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Nidhi Nagabhatla · Yusuf Mehta · Brijesh Kumar Yadav · Ambika Behl · Madhuri Kumari *Editors*

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Editors
Nidhi Nagabhatla
Institute on Comparative Regional
Integration Studies (CRIS)
United Nations University
Brugge, Belgium

Brijesh Kumar Yadav
Department of Hydrology
Indian Institute of Technology Roorkee
Roorkee, Uttarakhand, India

Madhuri Kumari
Amity School of Engineering
and Technology
Amity University Uttar Pradesh
Noida, Uttar Pradesh, India

Yusuf Mehta
Department of Civil and Environmental
Engineering, Center for Research
and Education in Advanced Transportation
Engineering Systems (CREATEs)
Rowan University
Glassboro, NJ, USA

Ambika Behl
Flexible Pavement Division
CSIR-Central Road Research Institute
New Delhi, Delhi, India

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About the Editors

Prof. Nidhi Nagabhatla is Senior Research Fellow and Cluster Coordinator: Climate Change and Natural Resources Program at United Nations University (CRIS). She is a Sustainability Science Specialist and System Analyst. With >23 years of work experience, she has led, coordinated, and implemented transdisciplinary projects in various geographical regions of Asia, Africa, Europe, and Americas working with international organizations, viz., IWMI, World Fish Centre, IUCN, Asia Pacific Climate Centre, and United Nations University (INWEH) leading research and capacity development initiatives. She is also affiliated with leading academic institutes: Oxford University (UK) and Leibniz University (Germany) in various roles, mostly related to sustainability research, science-policy interfacing, and mentoring young professionals. She is an Adjunct Professor at the School of Earth, Environment & Society McMaster University, Canada, and Guest Professor at Universidad Mayor de San Andrés, Bolivia. She served as Chair of The Partnership for Environment and Disaster Risk Reduction (UNEP) and co-leads the 'Water and Migration Working Group' of The Food and Agriculture Organization (FAO) of the United Nations. She also served on the Technical Committee of The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) from 2013 to 2018 and was the Lead Author in the Global Assessment Report. She also served as Vice-Chair and Chair of the Steering Board for Young Professional Platform for Agriculture Research and Development (YPARD), FAO from 2011 to 2018. Currently, she is actively involved with three expert working committees of the UN Decade on Ecosystem Restoration (2021–2030). She holds a doctoral degree from the Indian Space Research Organization in Environmental Science, post-doctoral experience working Consultative Group for International Agricultural Research (CGIAR), and a diploma in International Humanitarian Law from The National Academy of Legal Studies and Research, India. She holds executive education from Saïd Business School, University of Oxford, where she affiliates as a Chevening Fellow with the Future Leaders Programme of the Foreign and Commonwealth Office, UK. She has published more than 200 papers as peer-reviewed journal articles, chapters, conference papers, workshop contributions, and policy briefs and serves on the editorial and review committee of numerous international journals.

Prof. Yusuf Mehta is a Professor in Department of Civil Engineering of Henry M. Rowan College of Engineering and has extensive experience in pavement systems and management. He received his Ph.D. in Civil Engineering from The Pennsylvania State University in 1999 and M.S. in Civil Engineering from The Oklahoma University in 1995. He is a registered Professional Engineer in New Jersey. He has publications in refereed journals and international conferences. He has managed multiple projects of New Jersey Department of Transportation, Research and Innovative Technology Administration USDOT, and New York State Department of Transportation. He received Aviation Research Award and New Jersey DOT Research Implementation Award in the year 2012. He was recognized for his exemplary teaching by Mid-Atlantic American Society of Engineering Education in 2008. He received Louis J. Pignataro Memorial Transportation Engineering Education Award in 2013 for outstanding record of achievement in transportation engineering research, and undergraduate and graduate engineering education. He is an Associate Editor of American Society of Civil Engineers, Journal of Transportation Engineering. He is a part of Editorial Board, Modern Traffic and Transportation Engineering Research (MTTER). He is a Member of American Society of Civil Engineers, Transportation Research Board, American Society for Engineering Education, and Association of Asphalt Paving Technologist.

Prof. Brijesh Kumar Yadav is the Head of Hydrology Department of Indian Institute of Technology, Roorkee. He received his Ph.D. in 2008 from Indian Institute of Technology, Delhi, in collaboration with UNESCO-IHE Institute for Water Education, Delft, The Netherlands. He holds several memberships in established bodies of hydrology, International Association of Hydrological Sciences (IAHS); International Society for Porous Media (INTERPORE); American Geophysical Union (AGU); International Association of Engineers (IAENG), Indian Association of Hydrologists (IAH), Indian Association of Water Resources Society (IWRS), and Association of Global Groundwater Scientists (AGGS). He was awarded Ramanujan Fellow by Department of Science and Technology, Govt. of India. He is Chief Editor of quarterly E-journal of Association of Global Groundwater Scientists (AGGS) 'Journal of Ground Water Research (JGWR)' since 2021. He is the Editor of several renowned journals. He has guided a number of Ph.D. scholars. He is Active Researcher and has received several grants from Government of India for carrying out research and consultancy in area of bio-remediation, soil-water flow, and groundwater arsenic. He has published over 100+ publications in refereed journals and international conferences.

Dr. Ambika Behl is Head and Principal Scientist at Flexible Pavement Dept, Central Road Research Institute, Govt. of India. She obtained her Ph.D. from Indian Institute of Technology, Roorkee, in 2016 and M.Tech in 2004 from Punjab University. Her major areas of research interests include pavement engineering materials and sustainable road construction technologies. She has around two decades of experience in industry and academia in various capacities. She has several memberships of professional bodies like IRC, Transportation Group of India. She works actively on improvement of the materials and technologies to make long-lasting future ready roads. She has won several appreciation and accolades in the area of waste material application in pavement system. She has published several research articles in international peer-reviewed journals and conferences.

Prof. Madhuri Kumari received her Ph.D. from The Energy Resource Institute (TERI) for her work on geostatistical modeling for prediction of rainfall in Indian Himalayas. She completed her M.Tech. in Hydraulics and Water Resources Engineering from Institute of Technology, Banaras Hindu University, and B.E. in Civil Engineering from Andhra University and was awarded Gold Medal. She is working as Professor in Department of Civil Engineering, Amity School of Engineering and Technology, Amity University Uttar Pradesh, Noida, U.P. She has vast industry experience of 11 years and academic experience of around 11 years. Her research works in area of rainfall modeling have been published in reputed journals. Her research interests include data analytics, application of Geographic Information System and Remote Sensing (GIS&RS) for solving engineering problems, water resources engineering and management, hydrology, hydroinformatics, and irrigation engineering. She has been the Editor of two books published by Springer. She has worked as Co-PI for MoEF & CC-funded project on spatial decision support system for River Yamuna. She has worked as governing council member of Indian Building Congress. She is a registered Professional Engineer, Engineers Council of India. She is Member of several professional bodies like IEEE, Institution of Engineering and Technology (IET, UK), ISTE, Indian Society of Hydrologist, Indian Geotechnical Society, Indian Building Congress, and Women in Science and Engineering (WISE India). She is serving as Hon. Secretary of WISE India. She has attended several conferences, published technical papers, and delivered talks in the field of civil engineering.

Comprehensive Assessment of Simulation Tools for Analyzing Seepage Through Earthen Dams

Shravani Yadav, Shruti Jain, and Brijesh Kumar Yadav

Abstract Seepage is one of the primary reasons for the failure of earthen/embankment dams worldwide. As approximately 40% of earthen dams fail due to excessive and uncontrolled seepage, it is crucial to manage seepage in order to improve their stability and life. Numerical experiments are favored for predicting seepage flux under changing climatic conditions for earthen dams made of varying geological materials. In the present study, the application of numerical tools to analyze seepage through earthen dams is critically reviewed for popular software's such as SEEP/W, ANSYS, HYDRUS, PLAXIS, MODFLOW, SVFLUX, and FEFLOW. An overview of governing equations and limitations of these models is briefly explained along with their relative advantages. A comparative analysis is then carried out for a characteristic earthen dam using the simulation results of SEEP/W and FEFLOW. It has been found that the results obtained from FEFLOW are slightly accurate, and therefore, a detailed seepage study is finally being conducted for the Ambawali Dam, Haryana, India using FEFLOW. The results of this study can be used by field engineers in selecting the appropriate model(s) based on dam body and their surrounding conditions to manage the seepage flux effectively.

Keywords Earthen dams · Seepage analysis · Numerical modeling · Dams safety

S. Yadav · S. Jain · B. K. Yadav (✉)
Department of Hydrology, Indian Institute of Technology, Roorkee, India
e-mail: brijesh.yadav@hy.iitr.ac.in

S. Yadav
e-mail: shravani_y@hy.iitr.ac.in

S. Jain
e-mail: shruti_j@hy.iitr.ac.in

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1 Introduction

Earthen dams are the most prevalent form of dam, which are used to store water for irrigation, hydropower, municipal water supply, and to control floods and are built with naturally accessible materials. An earthen dam that has been appropriately constructed and designed will be stable against seepage and evaporation losses [7, 9, 19]. Although losses from evaporation cannot be controlled, and seepage losses can be reduced with proper construction methods. Seepage is the flow of water through the pores or fractures in the dam body and is one of the most important aspects of dam analysis and design. Thus, it is important to understand the seepage characteristics of dams to make sure the stability and performance of the dam.

The rate and direction of water flow through an embankment are determined by a seepage analysis. Controlling seepage through the embankment dam as well as its foundation is an essential factor for determining its safety. Typically, seepage occurs between a dam's upstream to downstream faces and phreatic surface describes the upper portion of this stream's percolating water. The seepage issue is the most frequently observed in earthen dams, and it has a direct effect on the stability of embankments, the sloughing of slopes as a result of increased pore water pressure, and internal erosion that may ultimately result in piping. According to literature, seepage failures such as piping and sloughing have caused approximately 40% of earthen dams to collapse [2]. Therefore, preventing seepage through dams is the key to creating safe dams that serve their intended purpose of storing water.

A significant aspect in the planning and building of dams is the detection of seepage through the foundations and embankment. For field engineers and researchers, the estimation and study of seepage flow behavior pose significant challenges. Researchers have used empirical, visual, and recently numerical approaches to quantify the water seepage under various boundary conditions [9]. Numerical models can help researchers to investigate seepage through earth-fill dams under varying hydrological and geological conditions at various sites.

For instance, physical models have been used in several studies to provide a basic overview of seepage behavior as well as rate of flow through dam body and top seepage line [7, 10, 14]. Numerical models are gaining popularity to overcome the limitations of physical modeling and to consider the complexity of the real-field situations. Thus, the main objective of this study is to provide a thorough overview of the various numerical tools available for earthen dam seepage analysis along with a case study using FEFLOW.

2 Methods of Analyzing Seepage

Seepage losses can be analyzed analytically, graphically and numerically for steady-state and transient flow conditions. Seepage flow can be obtained from the Darcy's law $Q = kiA$. The actual seepage for multi-dimensional flow can be analyzed using the Laplace Equation $\nabla^2 = 0$, the solution of this equation is quite complex and various considerations are made to solve this equation analytically. The solution of Laplace equation can also be represented graphically known as Flow Net, which is a set of equipotential lines and flow lines. The flow net can be used to calculate the seepage flow as $q = kH(N_F/N_D)$ or isotropic soils. While for non-isotropic, $q = \sqrt{K_H \cdot K_V} H \cdot N_F/N_D$ soil medium, dam section is drawn at same vertical scale but to a transformed horizontal scale (K_V/K_H).

Seepage through a heterogeneous, anisotropic, saturated–unsaturated soil can be given by governing a partial differential equation, which is derived by taking a representative elemental volume and conservation of mass [17]. The partial differential equation for transient process with the assumption that total stress remains constant that is given by Eq. (1).

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = \frac{S}{T}\frac{\partial h}{\partial t} \quad (1)$$

where k_x, k_y and k_z are the coefficients of permeability of soil in x, y and z direction, respectively, S is storativity and T is transitivity.

Causes of Uncontrolled Seepage

The problem of seepage occurs due to poor compaction of soil in foundation, embankment of dam and of its surrounding site. Poor foundation with rodent holes, tree roots, cracks, joints in earth rock, improper design of filter and drainage, shrinkage and settlement in soil media, excessive uplift pressure are the other reasons of seepage initiation. Due to these, dam failures by pipping through the body and foundation of the dam, generation of excess uplift pressure, erosion of embankment materials, and solubility of weak soluble rocks occur [12, 16, 18]. These failures will eventually lead to failure of the entire dam structure and cause catastrophic loss in terms of life and property.

3 Models for Seepage Analysis

Various numerical techniques of efficient computational period and enhanced visualization have emerged over the past decades for solving flow through complex porous media. Analytical solutions to seepage problems are also developed for seepage quantification. However, these solutions are based on assumptions of linear flow and are therefore only applicable to dams with simple geometries. The finite element method (FEM) is a numerical technique for solving partial differential equations (PDEs) by discretizing them into a set of finite elements. This method is used to analyze seepage problems in earthen dams by dividing the dam into small triangular or rectangular elements and solving the governing equations at each element. The finite difference method (FDM) is another numerical technique for solving PDEs by dividing the domain into a set of smaller cells and approximating the derivatives of the PDE at each cell. This method is used to analyze seepage problems in earthen dams by dividing the dam into small grids and solving the governing equations at each grid point. The most widely used numerical tools suitable for simulating seepage are described below.

FEFLOW is an acronym of Finite Element subsurface FLOW and transport system introduced in 1979. It is effective and interactive groundwater modeling system for variably saturated 3D and 2D transient or steady type flow. It can be effectively used for describing the spatial and temporal distribution and reactions of groundwater contaminants to model. FEFLOW is a powerful and comprehensive tool to model complex subsurface processes, yet it is easy to use. FEFLOW works with discrete feature approach, which provides the crucial link between the complex geometries for subsurface and surface continuum in modeling flow, containment mass and heat transport process. In the FEM context, the 3D mesh for the porous matrix can be enriched by both bar (channels, mine slopes) and areal (overland, fault) elements. FEFLOW provides 1D and 2D discrete feature elements, which can be mixed with the porous matrix elements in two and three elements. The basic balance equations used in FEFLOW are fluid mass conservation, fluid momentum conservation, contaminant mass conservation, and energy conservation. First step for creating a FEFLOW model is create soil geometry to a scale accounting maps and model boundaries, supermesh, finite element mesh and expansion of model to three dimensions. Secondly, inputs for model parameters are provided like, geometry, process variable, boundary conditions, material properties, auxiliary data, user data and discrete features. One of the limitations of this software is it is expensive and complex to learn. A case study illustrating the application of this software is mentioned in Sect. 4.

Geo-Studio-SEEP/W is a user-friendly software that is free for students, allowing them to conduct a variety of analyses linked to geotechnical investigations. For the analysis of seepage through earthen dams, SEEP/w program is used, which is a sub-program of Geo-studios software [14]. It is based on Darcy's Law, which describes movement of water through both saturated and unsaturated soils. Seepage analysis can be performed using SEEP/W. The likelihood of the dam failure because of seepage has been investigated analytically using the Geo-studio program. The limitation of SEEP/W is its restrictions related to the hardware's existing capabilities. SEEP/W is exclusively designed for flows that adhere to Darcy's Law adjacent to the ground surface. However, soil moisture may vaporize close to the surface and SEEP/W formulation does not include this element in its simulation [6].

MODFLOW is a 3-D groundwater flow model, which is developed by United States Geological Survey and works based on finite difference method. In the finite difference technique, terms that are derived from the variations in head values at different cells are used to replace the partial derivatives to represent study domain in a finite number of distinct points [11]. The model generates a set of simultaneous algebraic equations, whose solution provides the head values at particular times. These numbers represent an approximate representation of the time-varying head distribution, which would result from the groundwater flow equation of the partial differential nature. The MODFLOW models aquifer systems with saturated flow conditions by assuming constant groundwater density. The user has to enter aquifer attributes for each cell in the area of the aquifer system. In order to implement the solution, time steps are taken at each aquifer cell of the study domain [1]. The overall aquifer water budget is also simulated by MODFLOW in addition to the water levels. One of the limitations is that it does not take into consideration the capillary-induced infiltration that occurs at the beginning of wetting, when negative pressure difference might be substantial in comparison to gravity potential gradients. For considering density impacts, additional modules are integrated with MODFLOW model.

For the evaluation of the time-dependent, anisotropic and non-linear performance of soils and rocks, geotechnical solutions require sophisticated modeling techniques. In order to analyze deformation, stability, and groundwater flow in multi-dimensions, ***PLAXIS*** was developed based on geotechnical finite element method. The nonlinear behavior of soil and rock formations can be accurately modeled using PLAXIS software [5]. The findings of various studies reveal that the effectiveness of this software is capable of simulating behavior of embankment dams. One of the limitations of PLAXIS is that it is not able to define arbitrary geometries of the study area.

Likewise, ***ANSYS*** is a general-purpose finite-element modeling tool, which is used to numerically solve a wide range of mechanical issues. Similar to other finite element applications, ANSYS is organized into three major processors: pre-processor, solution processor, and postprocessor. The assessment of seepage using the Ansys software is performed using thermal methods [10]. To calculate the factor of safety, various methods such as Limit balance and Bishop methods are utilized. It has been noted that the rate of seepage obtained using ANSYS software usually underestimates in comparison with GEO-STUDIO.

A computer program called ***HYDRUS*** enables the modeling of water, mass, and heat movement in 3-D mediums with varying saturation levels. The finite element approach is used to calculate flow through soils with a mixed flow regime [15]. The model formation begins by defining the study area followed by discretization mesh developed. Seepage face boundary condition is employed along the air-side embankment. The software iteratively calculates the length of the seepage face using Picard's method. It uses Richard's equation to simulate flow through variably saturated medium. The quantitative assessment of water flow through the unsaturated soil zone is performed to estimate using the appropriate parameters of various soil types. One of the HYDRUS software's limitations is that it presumes the pressure head will always be steady and equivalent to zero along the seepage face.

PDEase2D is very adaptable and simple to use program that addresses issues in a variety of domains, including heat transfer, fluid and solid mechanics, electromagnetic, groundwater movement, and quantum physics. The time required to deal with nonlinear static and dynamic problems up to 32 constraints is quite less by its concise input language, automatic grid generation, and refining. Through PLAXIS 3D, the stability of dams and seepage is analyzed, and the results were appropriate [4].

SVFLUX software is employed to perform seepage analysis on both two- and three-dimensional domains. It can be employed in conjunction with the database tool 'Soil Vision' to do analysis without requiring a comprehensive laboratory process. The governing equation for seepage is obtained by solving the conservation of mass for a typical elemental volume. SVFlux solves a problem by enabling the input of complex geometry using survey information. In order to model water flow, reasonable boundary constraints are applied to the model, and flux sections are placed all throughout the area. Solution of non-linear equations converge well using this tool and it supports a wide range of formats for the input of material parameters including unsaturated soils.

This section provides a summary of the most widely used software programs for analyzing seepage through earthen dams. Additionally, a case study illustrating the use of these software's has been presented in Sect. 4.

Since most of the dam bodies are partially saturated/unsaturated, FEFLOW and SEEP/W seem capable of simulating these conditions effectively. Moreover, a significant variation in the water level in the dams during changing influx and outflux conditions can change the fraction of saturated/unsaturated portions of the dam's body. Initially, a characteristic dam site is used to compare the results of these two models followed by taking a real-field dam site.

4 Seepage Flow Through Earth Dams Using FEFLOW and SEEP/W

Seepage through earthen dams can be analyzed using above-mentioned tools and based on the limitations of some models, FEFLOW and SEEP/W are used for a comparative study as also suggested by Arshad et al. [3], Molla [13]. A case of homogeneous earth dam of 15 m height is taken and steady state is taken here for a constant hydraulic head of 12 m, and the results are shown in Fig. 1.

Figure 1 represents the variation of hydraulic head over the dam cross-section, the selected FEFLOW and SEEP/W models. The dashed line represents the phreatic

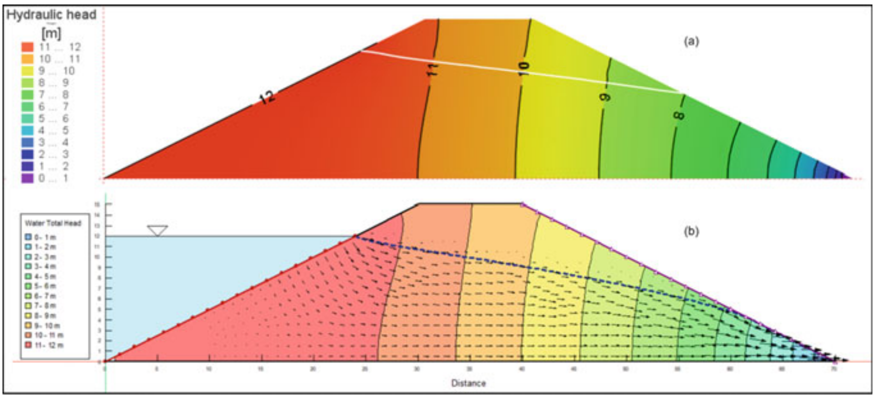

Fig. 1 Comparative study of seepage through earth dams using **a** FEFLOW, **b** SEEP/W for a homogeneous earth dam

line, i.e., zero pressure line (Fig. 1b), which may vary for case to case. After amassing the mass balance of this case study, it is found that FEFLOW predicts seepage more accurately than the SEEP/W model [8]. Thus, FEFLOW is used further to predict the rate of seepage flow and phreatic line for real field dam conditions.

For the seepage analysis, Ambawali Dam, Haryana is considered which is a zoned Earthen dam. FEFLOW is a numerical model that uses Darcy's equation for saturated zone and Richard's equation for the unsaturated zone. The Ambawali Dam is situated on Somb-Pathrala Nadi of Yamuna River Basin, having height of 23.25 m above the deepest bed (344 m), top width of 6 m, and length of dam is 550 m, as shown in Fig. 2. Seepage in the Earth dam occurs through dam body and foundation of the dam but for this study, the impervious layer in foundation is assumed at the 50 m from the deepest sea bed and a 2D flow model is constructed in FEFLOW. Further a steady-state stimulation is taken to obtain the seepage flow rate and phreatic line.

The finite element mesh is generated with a total of 44,458 elements of triangular type. The hydraulic boundary condition of the upstream side is given as FRL (363 m), i.e., hydraulic head of 19 m and downstream of the dam is seepage face side. For the seepage analysis, there are two main parameters, i.e., hydraulic conductivity and unsaturated flow porosity. Since Ambawali Dam is a zoned Earth dam, the parameters of different zones are taken according to the type of materials in the particular zone. The used parameters for this model run are listed in Table 1.

Parameters for solving an unsaturated model include empirical model parameters like saturation limits and Modified Van Genuchten Constants. In saturation limits, there are two parameters, i.e., maximum saturation and residual saturation. Considering the general values of maximum saturation as unity and residual saturation as 0.0025. Modified Van Genuchten model gives a relation for effective saturation and relative conductivity in terms of residual and maximum saturation levels. The value of constant parameters of the Modified Van Genuchten Model, i.e., α, n, m, and δ are listed in Table 1 and assigned in the model inputs based on the dam composition.

Steady-state stimulation is performed to find hydraulic head, pressure line, and rate of seepage flow. The imbalance in mass budget is 0.00030046 m^3/d, which is very small and its numerical model is quite accurate and can be used for further analysis.

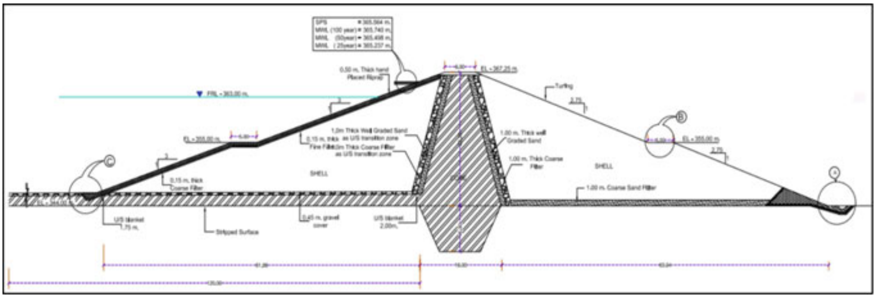

Fig. 2 Cross-sectional geometry of Ambawali Dam of Haryana (*Source* Completion Report of Ambawali Dam of Haryana)

Table 1 Hydraulic conductivity and unsaturated flow porosity of different zones

Serial number	Zone	Hydraulic conductivity (m/s)	Unsaturated flow porosity
1	Core of the dam	1.28×10^{-6}	0.374
2	Sand filter	9.23×10^{-5}	0.311
3	Coarse filter	6.6×10^{-3}	0.416
4	Shell (dam body)	2.21×10^{-5}	0.29
5	Foundation soil	5.23×10^{-6}	0.332

The seepage rate is computed as 4.16 m^3/d for the selected conditions Steady-state stimulation is performed for the hydraulic head of the upstream side as free reservoir level. The drops in hydraulic head and pressure distribution are shown in Figs. 3 and 4, respectively. The phreatic line that drastically lowered down at the core of the dam due to the presence of the clay formation is illustrated in these figures clearly. However, the phreatic line across the dam body is found not attenuated so sharply in left and right sides of the dam core. It is to be noted that the head loss in center of the body is more prominent as compared with the rest of the dam body as depicted by the interval of the isolines.

Thus, it can be concluded that the numerical model runs of the dam with FEFLOW are found quite accurate and are recommended to predict the rate of seepage flow and phreatic line under steady-state conditions for a dam made of different geological materials. It is observed that the composition of the earth dam body plays an important role in controlling piping and internal erosion. Further, it is found that the core body size of the earthen dam plays a crucial role in controlling the phreatic line and the head loss. Apart from this, proper seepage monitoring and instrumentation during and after the construction of the dam are recommended for identifying and controlling the dam seepage.

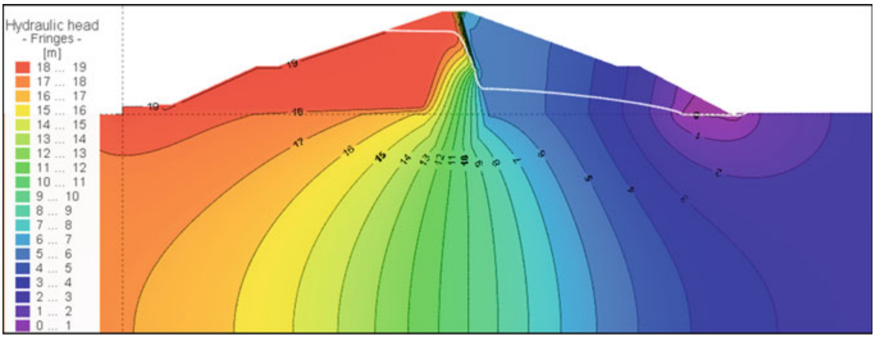

Fig. 3 Variation of hydraulic head over the cross-section of the dam

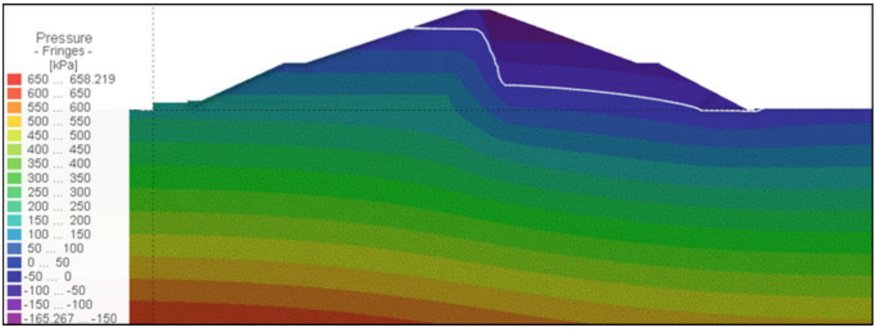

Fig. 4 Phreatic line (white) and variation of pressure over the cross-section of the dam

5 Conclusion

Numerical techniques are found powerful tools for simulating seepage in complex dam's bodies. Seepage analysis models employ numerical modeling techniques of finite element and the finite difference methods. Software such as SEEP/W, ANSYS, HYDRUS, PLAXIS, MODFLOW, and SVFLUX are employed by various designers and researchers for simulating various elements of seepage in earthen dams. Effectiveness of drains, internal soil stress, dam stability, settlement, prediction of seepage, and calculation of total seepage flow rate are some of the parameters that can be modeled using these numerical tools with some pros and cons. A comparative analysis for a homogenous earthen dam shows that FEFLOW conserves the mass more accurately than SEEP. The Ambawali Dam, Haryana that is a zoned earthen dam is used to show the capabilities of FEFLOW for seepage analysis and is recommended to use for analyzing seepage flow through earthen dams made of varying geological materials.

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References

1. Abhilasha M, Balan TGA (2014) Numerical analysis of seepage in Embankment dams. IOSR J Mech Civil Eng 1984:13–23
2. Ade P, Choudhary P, Dabhade S, Kad G, Changade JN (2019) Seepage analysis of earthen dam using geo-studio software - a case study. Int J Res Eng Sci Manag 2(6)
3. Arshad I, Muhammed, Muhammad Munir B (2014) Finite element analysis of seepage through an earthen dam by using geo-slope (SEEP/W) software. 6191
4. Athani SS, Shivamanth, Solanki CH, Dodagoudar GR (2015) Seepage and stability analyses of earth dam using finite element method. Aquatic Procedia 4(Icwrcoe):876–883. https://doi.org/10.1016/j.aqpro.2015.02.110

5. Bayat M, Eslamian S, Shams G, Hajiannia A (2019) The 3D analysis and estimation of transient seepage in earth dams through PLAXIS 3D software: neural network: case study: Kord-Oliya Dam, Isfahan province, Iran. Environ Earth Sci 78(18):1–7. https://doi.org/10.1007/s12665-019-8405-y
6. Calgary A (2012) Seepage modeling with SEEP/W 2015. In: GEO-SLOPE International Ltd. (Issue July)
7. Chahar BR (2006) Closure to "Determination of length of a horizontal drain in homogeneous earth dams" by Bhagu R. Chahar. J Irrig Drain Eng 132(1):89–90. https://doi.org/10.1061/(asce)0733-9437(2006)132:1(89)
8. Ersoy B, Haselsteiner R (2021) Aspects of 3D seepage analysis of dams and levees – case studies. 1:1–8
9. Fadaei-Kermani E, Shojaee S, Memarzadeh R, Barani GA (2019) Numerical simulation of seepage problem in porous media. Appl Water Sci 9(4):1–8. https://doi.org/10.1007/s13201-019-0965-1
10. Kamanbedast A, Delvari A (2012) Analysis of earth dam: seepage and stability using ansys and geo-studio software. World Appl Sci J 17(9):1087–1094
11. Langevin CD, Provost AM, Panda S, Hughes JD (2022) Documentation for the MODFLOW 6 groundwater transport model
12. Ma L, He C, Bian H, Sheng L (2016) MIKE SHE modeling of ecohydrological processes: merits, applications, and challenges. Ecol Eng 96(2016):137–149. https://doi.org/10.1016/j.ecoleng.2016.01.008
13. Molla DA (2019) Seepage through homogeneous earth dams provided with a vertical sheet pile and formed on impervious foundation. Ain Shams Eng J 10(3):529–539. https://doi.org/10.1016/j.asej.2018.12.008
14. Mostafa MM, Zhenzhong S (2021) A review on analysis of seepage in zoned earth dams. In: 2nd international conference on civil engineering: recent applications and future challenges, December, pp 137–146
15. Nieć J, Zawadzki P, Walczak Z, Spychała M (2017) Calculating earth dam seepage using hydrus software applications. Acta Sci Pol Form Circumiectus 3(December):43–56. https://doi.org/10.15576/asp.fc/2017.16.3.43
16. Omofunmi O, Kolo J, Oladipo A, Diabana P, Ojo A (2017) A review on effects and control of seepage through earth-fill dam. Current J Appl Sci Technol 22(5):1–11. https://doi.org/10.9734/cjast/2017/28538
17. Terbouche F, Hamza A, Gabi S (2021) Analysis of pore water pressures in an earth dam under operating conditions (case of Taksebt Dam, Algeria). World J Eng
18. Wan CF, Fell R (2004) Investigation of rate of erosion of soils in embankment dams. J Geotech Geoenviron Eng 130(4):373–380. https://doi.org/10.1061/(asce)1090-0241(2004)130:4(373)
19. Yaseen ZM, Ameen AMS, Aldlemy MS, Ali M, Afan HA, Zhu S, Al-Janabi AMS, Al-Ansari N, Tiyasha T, Tao H (2020) State-of-the art-powerhouse, dam structure, and turbine operation and vibrations. Sustainability (Switzerland) 12(4). https://doi.org/10.3390/su12041676

Nature-Based Solutions as a Pragmatic Approach Towards Flood Resilient Cities

Madhuri Kumari, Pranjal Pandey, Akanksha, and R. K. Tomar

Abstract Flooding is one of the most common and severe disasters that afflicts several Indian states every year, and it is frequently followed by the spread of epidemics. The cities along the banks of river or seashore face great pressure in dealing with flood disaster management and such experience will mount up in the coming decades due to the rising intensity and frequency of natural hazards triggered by climate change. Therefore, there is a need to develop an environment-friendly pragmatic approach for making such vulnerable cities into a flood resilient city. In recent decades, flood risk reduction and management strategies are seen to be supplementing the traditional technical and engineering methods with nature-based solutions (NBS). NBS brings in multiple benefits to people and the social system by contributing towards improvement in quality of life, strengthening, and promoting ecological balance. This paper presents a conceptual framework for the integration of NBS into current Flood Risk Mitigation and Management (FRM) strategies. This framework is intended as a tool to be adopted by decision-makers to operationalize the NBS integrated pragmatic approach and work towards developing flood-resilient cities.

Keywords Flood resilience · Nature based solutions · Flood risk mitigation · Disaster risk reduction · Urban flooding · NBS framework

M. Kumari (✉) · P. Pandey · Akanksha · R. K. Tomar
Department of Civil Engineering, Amity School of Engineering and Technology, Amity University Uttar Pradesh, Noida, Uttar Pradesh, India
e-mail: mkumari@amity.edu

R. K. Tomar
e-mail: rktomar@amity.edu

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1 Introduction

India experiences a variety of natural disasters and hazards, with flooding being the most significant. Flooding is defined as excessive surface runoff that inundates towns and farmland [1]. It is the most common natural catastrophe. The Intergovernmental Panel on Climate Change (IPCC) predicts that the region impacted by monsoon seasons will increase globally with rising precipitation levels, resulting in more flood events [2]. Flooding affects 14.6% of India's land area [3]. From 1978 to 2006, India had 2443 flood incidents causing 16 billion USD in damages [4]. During the monsoon season, which brings low to heavy rainfall, residents of Indian cities often experience flooded streets and waterlogged homes [5]. Monsoon season in India sees 80% of precipitation occur in a short time from June to September, leading to the highest number of flooding incidents (urban, rural, and coastal) in various regions of the country [6, 7]. Experts have long discussed the connection between climate-related disasters and their aftermath (socioeconomic losses and public health) [8]. Natural disasters such as flooding also pose a significant public health risk from water and air-borne infectious diseases, which have become increasingly prevalent over time [9]. Figure 1 shows that the states of Maharashtra, Tripura, West Bengal, and Bihar have had the highest number of flooding incidents in the last 15 years.

Flooding is classified into three types (ref. Table 1): rainfall-induced (pluvial), river flooding (fluvial), and tidal flooding (coastal) [10]. The preponderance of flood incidents during the monsoon season is triggered by prolonged rainfall and heavy downpours [11]. All river basins in India experience flood events; however, the Ganga and Brahmaputra River basins have the highest number and severity of flood events [12]. The Ganga River zone, the Brahmaputra River zone, the North-West River zone, and the Deccan (coastal) zone are the four principal flood zones in India [13].

Urban floods are common and have become serious issues around the world even in India as well [14]. Flooding happens most frequently in metropolitan areas due to substantial monsoon precipitation in a short period of time, causing significant damage to life and property. In India, 1561 urban local bodies out of 7935 are flood-prone [5, 15]. Figure 1 depicts the number of times flood occurred (flooding frequency) state-wise in India over the span of 15 years.

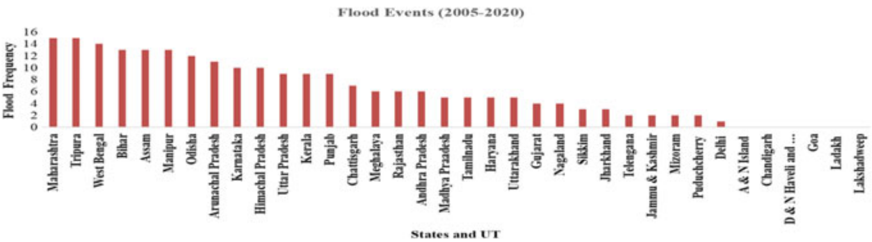

Fig. 1 Flood frequency in the last 15 years. (*Source* Annual disaster reports (2005–2020), Indian meteorological department (IMD))

Table 1 Types of floods in India

Type of flooding	Descriptions
Rainfall induced flooding	Heavy amount of rain over minutes to hours inundates creeks and dry valleys
River flooding	The floodplain is inundated when water from a river or drainage channel cannot be contained within its stream channel or by built structure. It occurs often seasonally. This is the most common flooding
Tidal flooding	Increasing sea level caused by storm surges generated by tropical cyclones and tsunami

The increasing urbanization in India has resulted in Indian cities being constructed hastily and in a haphazard manner, which has contributed significantly to the increased risk of an urban flood [16]. 30–40% more rainfall is observed in Indian urban cities than in rural areas [15]. Figure 2 shows the major flood prone regions in India. Metropolitan cities such as Mumbai, Delhi, Bangalore, Assam, Chennai, and many others are key examples of cities that face frequent urban flooding events, demonstrating the current state of flood management in Indian cities. Most of these cities are unplanned, have poor drainage systems [17]. Because of high population density and inadequate infrastructure, the socioeconomic losses and public health risk due to flooding aftermath are significantly greater in urban regions than in rural ones, resulting in the rapid growth of flood occurrences in metropolitan areas [18].

Significant socioeconomic and environmental consequence are the results of flooding, including the loss of living beings' lives, infrastructure destruction, and damage to the natural environment [20]. There are examples of recent flood events: Jammu and Kashmir flooded in 2014 because of constant rain. Even after the Indian army evacuated 11,000 people, 138 people died. River Jhelum and its tributaries flew above the danger mark. Due to this, the Vaishno Devi Yatra has been suspended [21]. Chennai had suffered 3 billion losses and live losses of 138 people in the 2015 flood. In 2018, Kerala faced massive flooding due to unusual rainfall and the sudden discharge of water from reservoirs [22]. Assam Flood 2020 refers to a major flood event of the Brahmaputra River. 5 million people were affected with the loss of 123 people [23].

In Indian cities, measures have been taken to prevent floods. Due to the diverse weather patterns across different regions in India, flood mitigation measures are tailored to each location based on its climate and rainfall pattern. These locations can range from areas near dams to hilly, marshy, and coastal regions. The measures are mainly divided into structural and non-structural categories. Non-structural measures include using automatic weather stations to gather real-time information on rainfall and flood warnings [24] and conducting flood vulnerability mapping to identify high-risk areas. Structural measures include enhancing the urban drainage system with sustainable solutions like detention ponds or storage channels to make cities more resilient to floods [25].

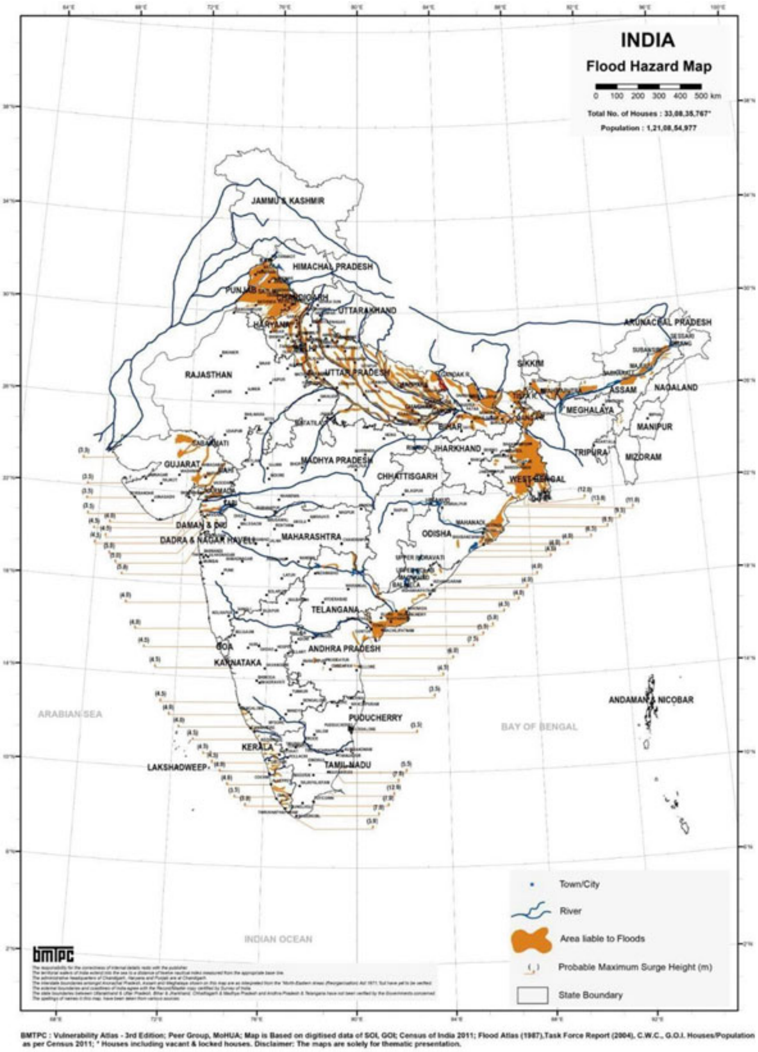

Fig. 2 Flood prone regions in India [19]

In addition to conventional strategies, nature-based solutions (NBS) are also being used for flood risk mitigation and prevention. NBS are strategies that address environmental challenges such as resource depletion, disaster risk reduction, and ecosystem degradation caused by urbanization and climate change [26]. This study focuses on the benefits of using NBS for socio-economic and public health purposes and proposes a framework for identifying and implementing nature-based projects in Indian cities to enhance flood resilience.

2 Nature-Based Solution for Flood Resilience Cities in India

According to the International Union for Conservation of Nature (IUCN), Nature-Based Solutions (NBS) are approaches to sustain, restore, and control natural or modified ecosystems in a sustainable manner, resulting in not only the elimination of environmental and social barriers but also the improvement of the physical and mental well-being of all living species through positive environmental externalities such as increased biodiversity [27]. The IUCN outlines eight principles that NBS activity should follow: embracing nature conservation, being integrated with other societal challenges, being determined by site-specific natural and cultural contexts, producing societal benefits fairly and equitably with transparency and broad participation, maintaining biological and cultural diversity and the ability of ecosystems to evolve over time, being applied at the landscape scale, recognizing trade-offs between immediate economic benefits and future ecosystem services, and being an integral part of overall design policies [28].

Traditional engineering solutions or structural ways of mitigating flood vulnerability have been used for centuries, such as building embankments, dams, levees, and canals [29]. These "hard" or "grey" infrastructure solutions have proven to be uneconomical and damaging to habitats and ecosystems, causing the loss of settlements, and forcing people to relocate without input or choice [30]. To address these drawbacks, there has been a growing interest in examining the role of nature-based projects as an alternative to traditional hard engineering solutions for flood risk mitigation in cities [31]. Concepts like "Nature-based solutions," "ecosystem-based adaptation," "eco-DRR," and "green infrastructure" have emerged as potential alternatives to traditional grey techniques, using natural processes and ecosystem services for purposes such as flood risk reduction and improved water quality [32].

In terms of flood management, NBS are divided into two categories: Natural Water Retention measures (NWRM) and Natural Flood Management (NFM) [33]. NWRM involves retaining water in and on plants, increasing plant transpiration, improving soil health, creating ponds and wetlands, and reconnecting floodplains. NFM uses landscape features to control flood risk by minimizing the maximum flow discharge and leveling it out [34]. These methods have the potential to remedy ecological hazards more effectively and NWRM can be used in various aspects of water management, such as water quality [31]. Floodplain restoration can also be considered an NBS that reduces the likelihood of flood-related disasters and can provide benefits for both ecosystem restoration and flood damage prevention [35, 36].

2.1 Ecosystem-Based Adaptation for Flood Impact Mitigation

Ecosystem-based adaptation initiatives generally focus on long-term adaptation to chronic and irreversible stressors, such as gradually warming temperatures, sea level rise, and glacial melting. Employing a range of biodiversity and ecosystem conservation approaches, such initiatives help people adapt to the adverse effects of climate change and mitigate climate-related hazards.

Ecosystem-based disaster risk reduction aims to reduce hazard events and/or communities' exposure and vulnerability to them. Disaster risk reduction is typically focused on near-future risk, such as landslides or floods. Such initiatives may involve, for example, the installation of early warning systems. But we can also reduce disaster risk through the planting of trees to stabilize slopes. Ecosystem-based disaster risk reduction addresses both non-climate-related events, such as earthquakes and tsunamis and climate-related events like hurricanes and heat waves, as well as other kinds of hazards. While different, these approaches share an emphasis on ecosystem management, restoration, and conservation and can be thought of as interventions that are implemented on a hazard continuum that ranges from near-term, often sudden events such as landslides, to longer term, generally gradual events such as sea level rise.

At the project or operational level, they are often indistinguishable. Environmental management is central to both approaches and can be combined with measures that explicitly reduce disasters and climate impacts. Such interventions have been around for decades, but it's only recently that we have started to emphasize disaster risk reduction and climate change adaptation.

3 Proposed Framework for Integrating NBS in Flood Resilience

Eco-engineering can have an impact on the structural components that support the ecosystem's functioning [37]. One notable example is the Azamenose Riverine Wetland Restoration Project in Saga, Japan, led by the Ministry of Land, Infrastructure, Transport, and Tourism in partnership with various stakeholders including local communities, NGOs, local governments, and academics, particularly Kyushu University [38]. In this project, a wing-shaped flood control basin was built along the curved part of the Matsura River to absorb overflow downstream [39].

These flood control basins not only reduce the risk of flooding but also provide habitats for biodiversity, as seen in wetland creation, which is a common approach in urban areas for flood control, improved drainage, and ecosystem restoration [40]. Wetlands, like those developed as part of an eco-neighborhood initiative in Geneva, Switzerland, serve to collect excess rainwater and provide a habitat for birds [41]. Ecological engineering plays a crucial role in incorporating modern technology, such as early warning systems for landslide movements and river height monitoring, or climate-smart agriculture, into these established and successful methods for promoting community resilience [42]. The concept of "building with nature" is often used to describe this process, but it should be used cautiously as many procedures, like using deep-rooted grasses to stabilize slopes, may be more accurately described as "weaving or knitting with nature" [43].

Ecological engineering is often described as "building with nature and people" due to its emphasis on involving local communities in its implementation [44]. It involves impacting the living tissue of ecosystems and the organisms that make them up, as well as the underlying structures such as mountains and valleys [45]. Efforts are underway to further the implementation of Nature-Based Solutions (NBS) for flood risk reduction through publications such as the World Bank's Implementing Nature-based Flood Protection (2017) and WWF's Guidelines on Natural and Nature-Based Flood Management: A Green Guide (2017).

The study suggests a framework for integrating NBS into current Flood Risk Mitigation and Management (FRM) methods in Indian urban cities. The framework begins by identifying flood hazards, categorizing them into three types: extreme weather events, riverine flooding, and tidal flooding. The next step involves determining the types of flood risk mitigation solutions, which are divided into non-structural and structural. Non-structural solutions involve policy development, public awareness, early-stage flood warning, and monitoring. Structural solutions include hard engineering solutions, soft solutions (i.e., nature-based solutions), and hybrid solutions combining both hard and soft approaches. To effectively reduce flood risk, it is recommended first to apply non-structural solutions and then consider structural solutions by prioritizing NBS whenever possible as part of an integrated approach. In the case of no other options, then gray solutions can be selected. With NBS in focus, the framework further focuses on the guiding principles describing key considerations [46] that are taken into consideration when planning Nature-based projects for flood risk mitigation. These majorly five principles to guide nature-based flood development in cities are as follows:

1. **System scale perspective**: Figure 3 depicts a system-wide review on the basis of spatial extent, time scale, local socio-economic, environmental, and institutional factors should be the first step in addressing nature-based solutions for climate change adaptation and disaster risk reduction.
2. **Risk and benefit assessment of a full range of solutions**: A complete assessment of the risks and benefits of the whole spectrum of possible measures, including risk reduction benefits as well as social and environmental consequences should be carried out.

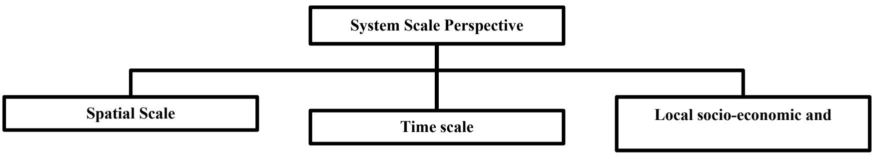

Fig. 3 Types of system scale perspective [47]

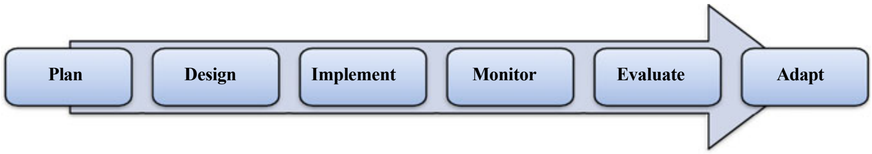

Fig. 4 Adaptive management process (CEDA, 2015)

3. **Standardized performance evaluation**: Nature-based solutions for flood risk management need to be tested, designed, and evaluated using quantitative criteria.
4. **Integration with ecosystem conservation and restoration**: Nature-based solutions for flood risk management should make use of existing ecosystems, native species, and comply with basic principles of ecological restoration and conservation.
5. **Adaptive management**: Nature-based solutions for flood risk management need adaptive management based on long-term monitoring. Figure 4 shows the process flow of adaptive management process, which contributes to ensuring NBS's sustainable performance.

The adaptive management cycle is based on an objective or outcome that may be predicted. Implementation, monitoring, data evaluation, decision-making, and adjustment of possible management measures are all parts of this process. This cycle should be performed at regular intervals throughout the measure's lifespan. The adaptive management cycle not only ensures constant management after the project is completed but also serves as a foundation for developing lessons learned for future projects. In addition to the principles, the World Bank (2017) [33] report outlines the processes for implementing a potential nature-based flood resilience project in the city. These eight implementation processes combine to form the framework's final step, resulting in a full and effective nature-based flood management project in both non-coastal and coastal communities. Figure 5 provides a summarised view of the proposed framework for integrating NBS as flood risk management tools in cities. The eight steps to successfully implementing any nature-based initiative are as follows (Fig. 6).

4 Discussion and Conclusion

Nature presents various answers to the multiple challenges humanity faces today, and there is still time to put these into practice. As the global climate crisis intensifies, natural disasters are becoming more frequent. These are partly due to climate change and partly due to poor land and resource management. The implementation of nature-based solutions for climate and disaster resilience is already taking place worldwide, and many have the potential to have a global impact. These solutions are sustainable, cost-effective, and bring multiple benefits. They can be used to tackle a variety of

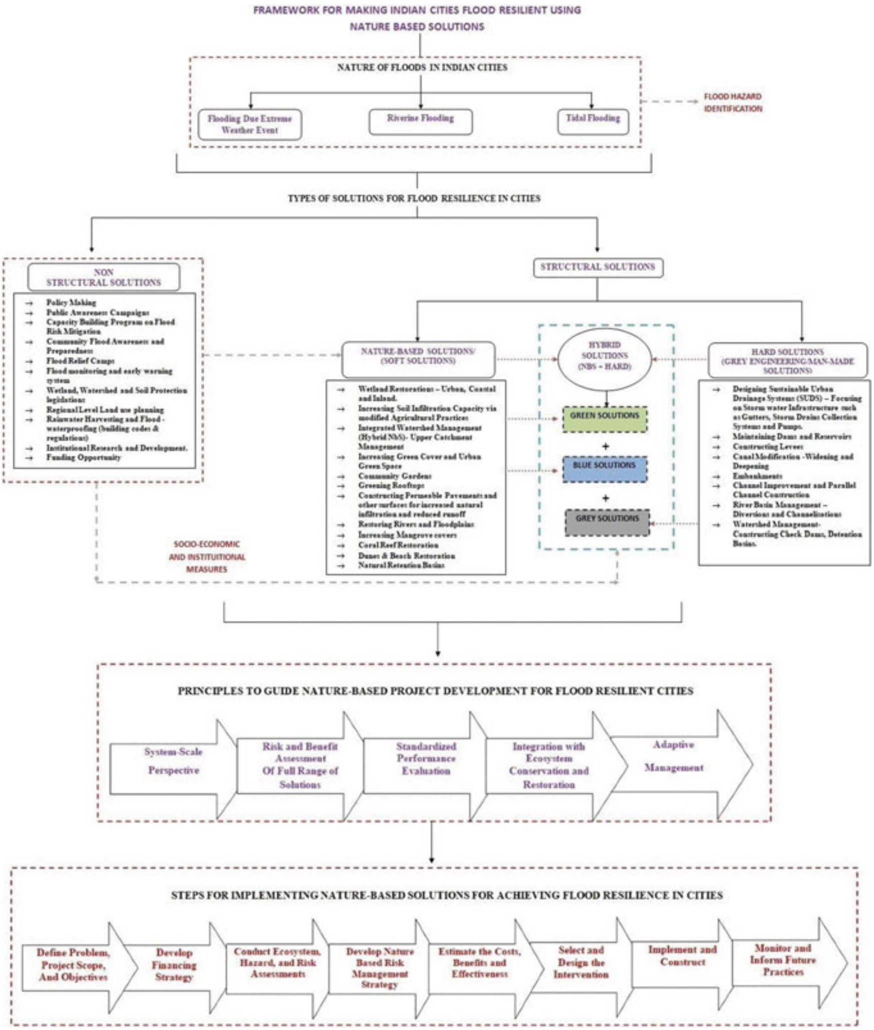

Fig. 5 Proposed framework for integrating NBS as flood risk management tools in cities

issues, from reducing carbon emissions to solving societal problems such as income inequality, food security, and other inequalities.

One main goal of nature-based solutions is to address problems caused by natural hazards such as earthquakes, floods, and landslides. People's decisions often contribute to hazards becoming disasters. For example, building in a floodplain increases a town's risk of flooding. Efforts such as planting trees on steep slopes to prevent landslides or relying on traditional flood management techniques such as water harvesting and conservation ponds can be made to reduce urban flooding [48].

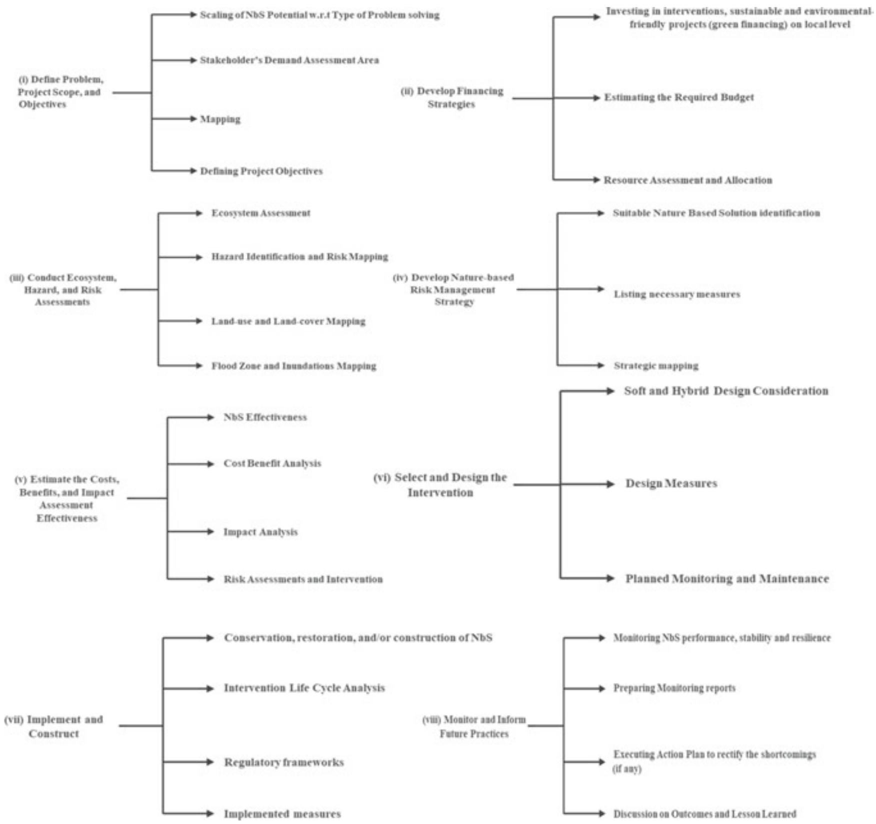

Fig. 6 The eight major steps to successfully implementing NBS for flood resilient cities

Nature-based solution is a term that encompasses a variety of ecosystem-based methods to tackle various social and economic issues. The concept is based on the ecosystem approach, which aims to manage land, water, and living resources in an integrated manner, promoting conservation, restoration, and sustainable use in an equitable way. Figure 7 summarizes the stages for successfully implementing the framework, which, when followed correctly, provides a comprehensive solution that addresses all critical categories: social and economic, institutional, and environmental, resulting in the development of an integrated Flood Risk Management tool.

It is crucial to consider both biophysical and socio-economic factors in a comprehensive manner in order to effectively implement Nature-Based Solutions (NBS) using the framework outlined in this study. To achieve this, a multi-disciplinary approach involving experts in fields such as water resources, environmental engineering and science, economics, and social studies must be taken. A participatory approach that involves all relevant stakeholders is also essential for designing

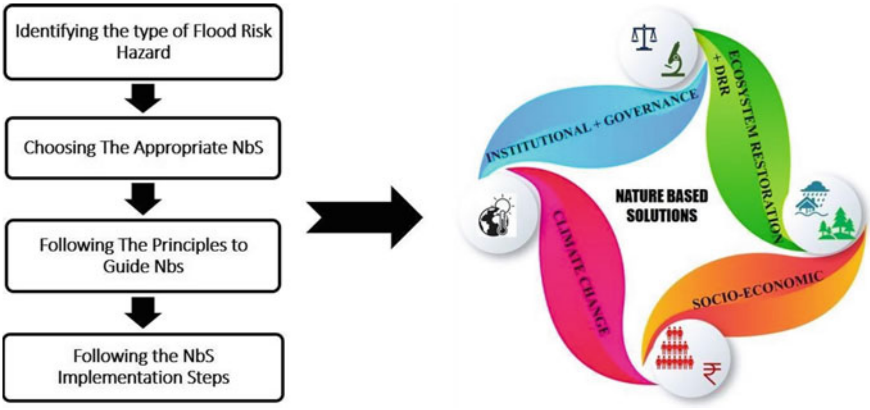

Fig. 7 Nature-based solution—an integrated approach for making cities flood resilient

and implementing effective nature-based programs for flood risk assessment and management.

Incorporating the socio-economic and institutional elements of non-structural flood risk reduction methods is vital to the success of any NBS project. NBS not only provides an environmental friendly approach to improving flood resilience in cities but also addresses flood risks while promoting conservation, development, and poverty reduction. The socioeconomic component of NBS can help to establish new partnerships and collaborations between government officials, local stakeholders, civil groups, and relevant private sector representatives. The concept of working with nature rather than against it is at the core of NBS, which seeks to address climate change through both adaptation and mitigation techniques. This approach prioritizes long-term environmental management and climate change mitigation.

References

1. Jha AK, Bloch R, Lamond J (2012) Cities and flooding: a guide to integrated urban flood risk management for the 21st century. The World Bank
2. Mal S, Singh RB, Huggel C, Grover A (2018) Introducing linkages between climate change, extreme events, and disaster risk reduction. In: Climate change, extreme events and disaster risk reduction. Springer, Cham, pp 1–14
3. Bisht S, Chaudhry S, Sharma S, Soni S (2018) Assessment of flash flood vulnerability zonation through geospatial technique in high altitude Himalayan watershed, Himachal Pradesh India. Remote Sens Appl Soc Environ 12:35–47
4. Singh O, Kumar M (2013) Flood events, fatalities and damages in India from 1978 to 2006. Nat Hazards 69(3):1815–1834
5. Ghosh A (2018) The great derangement: climate change and the unthinkable. Penguin, UK
6. Bhunia P, Das P, Maiti R (2020) Meteorological drought study through SPI in three drought prone districts of West Bengal, India. Earth Syst Environ 4(1):43–55

7. NDMA (National Disaster Management Authority Government of India) (2010) National disaster management guidelines: management of urban flooding
8. Alexander D (2018) Natural disasters. Routledge
9. Braide W, Justice-Alucho CH, Ohabughiro N, Adeleye SA (2020) Global climate change and changes in disease distribution: a review in retrospect. Int J Adv Res Biol Sci 7(2):32–46
10. Devi NN, Sridharan B, Kuiry SN (2019) Impact of urban sprawl on future flooding in Chennai city, India. J Hydrol 574:486–496
11. Swain M, Pattanayak S, Mohanty UC (2018) Characteristics of occurrence of heavy rainfall events over Odisha during summer monsoon season. Dyn Atmos Oceans 82:107–118
12. Mohanty MP, Mudgil S, Karmakar S (2020) Flood management in India: a focussed review on the current status and future challenges. Int J Disaster Risk Reduct 101660
13. Pandey K, Vishwakarma DK (2019) 7 flash floods cause and remedial measures for their control in hilly regions. Appl Agric Pract Mitig Clim Change 2:77
14. Datta A (2015) New urban utopias of postcolonial India: 'entrepreneurial urbanization' in Dholera smart city, Gujarat. Dialogues Human Geogr 5(1):3–22
15. Kadaverugu A, Rao CN, Viswanadh GK (2021) Quantification of flood mitigation services by urban green spaces using InVEST model: a case study of Hyderabad city, India. Model Earth Syst Environ 7(1):589–602
16. Waghwala RK, Agnihotri PG (2019) Flood risk assessment and resilience strategies for flood risk management: a case study of Surat City. Int J Disaster Risk Reduct 40:101155
17. Singh C, Madhavan M, Arvind J, Bazaz A (2021) Climate change adaptation in Indian cities: a review of existing actions and spaces for triple wins. Urban Clim 36:100783
18. Cutter SL, Emrich CT, Gall M, Reeves R (2018) Flash flood risk and the paradox of urban development. Nat Hazard Rev 19(1):05017005
19. Building Materials and Technology Promotion Council (BMTPC) (nd) Bamboo a material for cost effective and disaster resistant housing. Ministry of Urban Development and Poverty Alleviation, Government of India. BMTPC
20. Abubakar B, Umar H, Barde MM, Adamu S (2020) Socio-economic impact of flooding on the riverine communities of river Benue in Adamawa state, Nigeria. FUTY J Environ 14(2):116–124
21. Bhatt CM, Rao GS, Farooq M, Manjusree P, Shukla A, Sharma SVSP, Dadhwal VK et al (2017) Satellite-based assessment of the catastrophic Jhelum floods of September 2014, Jammu & Kashmir, India. Geomat Nat Haz Risk 8(2):309–327
22. Veerasingam S, Mugilarasan M, Venkatachalapathy R, Vethamony P (2016) Influence of 2015 flood on the distribution and occurrence of microplastic pellets along the Chennai coast, India. Mar Pollut Bull 109(1):196–204
23. Rao MP, Cook ER, Cook BI, D'Arrigo RD, Palmer JG, Lall U, Webster PJ et al (2020) Seven centuries of reconstructed Brahmaputra River discharge demonstrate underestimated high discharge and flood hazard frequency. Nat Commun 11(1):1–10
24. Gupta K, Nikam V (2014) Technological and innovative measures to improve flood disaster recovery following Mumbai 2005 Mega-flood. In: Disaster recovery. Springer, Tokyo, pp 287–297
25. Gupta K (2020) Challenges in developing urban flood resilience in India. Phil Trans R Soc A 378(2168):20190211
26. Lafortezza R, Chen J, Van Den Bosch CK, Randrup TB (2018) Nature-based solutions for resilient landscapes and cities. Environ Res 165:431–441
27. Cohen-Shacham E, Andrade A, Dalton J, Dudley N, Jones M, Kumar C, Walters G et al (2019) Core principles for successfully implementing and upscaling nature-based solutions. Environ Sci Policy 98:20–29
28. Guevara O, Rodriguez AV, van Breda A, Ilieva L, Cordero D, Podvin R, McQuistan C et al (2018) Adopting nature-based solutions for flood risk reduction in Latin America
29. Schoonees T, Mancheño AG, Scheres B, Bouma TJ, Silva R, Schlurmann T, Schüttrumpf H (2019) Hard structures for coastal protection, towards greener designs. Estuar Coasts 42(7):1709–1729

30. Anfuso G, Postacchini M, Di Luccio D, Benassai G (2021) Coastal sensitivity/vulnerability characterization and adaptation strategies: a review. J Mar Sci Eng 9(1):72
31. Morris RL, Konlechner TM, Ghisalberti M, Swearer SE (2018) From grey to green: efficacy of eco-engineering solutions for nature-based coastal defence. Glob Change Biol 24(5):1827–1842
32. Seddon N, Smith A, Smith P, Key I, Chausson A, Girardin C, Turner B et al (2021) Getting the message right on nature-based solutions to climate change. Glob Change Biol 27(8):1518–1546
33. Wilkinson ME, Addy S, Quinn PF, Stutter M (2019) Natural flood management: small-scale progress and larger-scale challenges. Scott Geogr J 135(1–2):23–32
34. Hartmann T, Slavíková L, McCarthy S (2019) Nature-based solutions in flood risk management. In: Nature-based flood risk management on private land. Springer, pp 3–8
35. Nugent N, Rhinard M (2015) The European commission. Bloomsbury Publishing
36. Moss T, Monstadt J (eds) (2008) Restoring floodplains in Europe. IWA Publishing
37. Tummers L (2016) The re-emergence of self-managed co-housing in Europe: a critical review of co-housing research. Urban Stud 53(10):2023–2040
38. Furuta N, Shimatani Y (2018) Integrating ecological perspectives into engineering practices–Perspectives and lessons from Japan. Int J Disaster Risk Reduct 32:87–94
39. Fujimoto T, Kagohashi K (2019) Community-Led micro-hydropower development and land-care: a case study of networking activities of local residents and farmers in the Gokase township (Japan). Energies 12(6):1033
40. Verol AP, Battemarco BP, Merlo ML, Machado ACM, Haddad AN, Miguez MG (2019) The urban river restoration index (URRIX)-A supportive tool to assess fluvial environment improvement in urban flood control projects. J Clean Prod 239:118058
41. Bachtold P (2013) The space-economic transformation of the city: towards sustainability. Springer Science & Business Media
42. Azadi H, Moghaddam SM, Burkart S, Mahmoudi H, Van Passel S, Kurban A, Lopez- Carr D (2021) Rethinking resilient agriculture: from climate-smart agriculture to vulnerable-smart agriculture. J Clean Prod 319:128602
43. Narayan S, Cuthbert RJ, Neale E, Humphries W, Ingram JC (2021) Protecting against coastal hazards in Manus and New Ireland provinces Papua New Guinea: an assessment of present and future options
44. Wijsman K, Auyeung DS, Brashear P, Branco B, Graziano K, Groffman P, Corbett D et al (2021) Operationalizing resilience: co-creating a framework to monitor hard, natural, and nature-based shoreline features in New York State. Ecol Soc 26(3)
45. Chakraborty SK (2021) Ecology and its relevance to environmental problems. In: Riverine ecology, vol 1. Springer, Cham, pp 57–165
46. World Bank (2017) Implementing nature based flood protection: principles and implementation guidance
47. Smith MP, Galloway G, van Wesenbeeck BK, Heynert K, Brideau J, Joseph T (2017) The path to a safe and sustainable future: mainstreaming nature-based approaches in comprehensive flood risk management. The Nature Conservancy. https://www.nature.org/content/dam/tnc/nature/en/documents/The_Path_to_a_Safe_Sustainable_Future_floodplains_report.pdf
48. Jennings T (2021) Oxford international primary geography: student book 6 ebook: Oxford international primary geography student book 6 ebook. Oxford University Press-Children

Analysing the Rigidity of Water Flows in Small Himalayan Towns: An Analysis of Water Accessibility and Availability in Champawat Town, Uttarakhand, India

Nishant Kharkwal and Kamal Kumar Murari

Abstract Water scarcity in Himalayan towns and cities has become a common phenomenon. Deforestation, urbanization, and heavy construction activities accompanied by climate change have impacted the availability and accessibility of water. In such a situation, water management becomes crucial to ensure water equitably. The remote Himalayan centres lack both research and assessment. The case study provides the condition of water accessibility and accessibility in small Himalayan urban centre of Champawat. The results show various indicators like quantity of water supplied, supply hours, quality standards are below state average. Local people use various coping mechanisms such as using multiple water sources, government water tankers, water rationing, multiple water containers to deal with persisting water scarcity.

Keywords Water accessibility and availability · Himalayas · Small towns · Coping mechanism

1 Introduction

Spanning across several countries in South Asia, the Himalayas are considered as "Water tower of Asia." The snow-clad mountains are the origin of 10 major river basins in South Asia and South-East Asia [1]. The region is witnessing changing rainfall patterns with extreme weather conditions, increasing average temperatures and receding glaciers [2–4]. Such a fragile and diverse topography, and changing rainfall patterns in the region create a challenge to water security [5–7]. The unplanned and

N. Kharkwal (✉)
Department of Sociology, Delhi School of Economics, University of Delhi, Delhi, India
e-mail: nishantkharkwal@gmail.com

K. K. Murari
Centre for Climate Change and Sustainability Studies, School of Habitat Studies, Tata Institute of Social Sciences, Mumbai, India
e-mail: kamal.murari@tiss.edu

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unregulated urbanization has further led to the depletion of resources [8]. The Hindu Kush region will cater for a population of 303.63 million by 2030 [1].

In between the lush green mountains of the Himalayas is the State of Uttarakhand which also experiences water crisis. Alarmingly 50% of the springs in the region are drying up [9]. In the past few decades, Uttarakhand has experienced an increase in population and rapid urban growth. The urban population in the state has risen by 44.8% between 1971 and 2011 [10]. There has been considerable out-migration in almost all the mountain districts. 66.2% of the out-migration from rural areas is towards urban centres within the state [11]. The urbanization in the region has also been accompanied by the shift from primary resource development sectors to secondary and tertiary sectors [1, 10]. Thus, burdening the urban centres which already have water accessibility and availability woes. Water woes have been persistent in the region due to poor water management practices [12, 13]. Uttarakhand scored lowest among all the states in the Composite Water Management Index, 2018 by the National Institute of Transforming India Aayog (NITI Aayog). One of the major reasons for the decline in the rankings was the fall in the reach of piped water supply (PWS) and the quality of the provision of drinking water in both rural and urban areas [14]. The United Nations Development Program (UNDP) in its Drill Down Vulnerability Risk Assessment report has highlighted severe water availability and accessibility issues in the state, especially during the summers [15].

The studies concerning water security in the Himalayan region have focused on the traditional water systems [16, 17], management and governance of water [12, 13, 18, 19], water quality [20, 21], resource management and spring rejuvenation [9, 22, 23]. Bharti and others [19] have worked on the dynamics of water supply in Mussoorie and Devprayag of Uttarakhand. Darjeeling, Devprayag, Mussoorie, Nainital, Shimla, and other such urban centres with high tourist footfall are different from the remote small towns. These small urban centres are mostly localized business centres [24], which lack both research and assessment [5, 9]. The present study uses the indicators of the quantity of water consumed, water sources, time taken for water provisioning, distance travelled, cost of provisioning, and dependency on secondary water sources to analyse the dynamics of water accessibility and availability in the remote town of Champawat in Kumaon Himalayas. The concept of accessibility and availability of water is attributed to the distance and time involved in obtaining water [25]. This distance and time change from place to place and thus the accessibility. Availability further depends on the quantity of water available for a certain period [26]. The accessibility also needs to be understood in terms of affordability. The unaffordability makes even the most common resource like water inaccessible [27]. Exploring these indicators becomes crucial to efficient water management practices [19, 28]. The study analyses the present water infrastructure system of Champawat. It navigates through the water flows in the town to understand the rigidity in the water supply by analysing water accessibility and availability through consumer's perspective or demand side.

2 Approach and Methodology

Survey Field: Champawat lies in the Kumaon division of Uttarakhand. It is a Municipal Council or Nagar Palika Parishad (NPP) consisting of nine wards. The town is at a height of 1650 m from the mean sea level [29]. As per the information provided by the NPP office, the administrative boundaries of the town were revised in 2012, and, in 2016, the town's population stands at 12,756. The district population growth rate is 15.6%, higher than the state average of 11.8% [11] (Fig. 1).

Methodology and Data Collection: The study uses mixed research methods. The mixed approach helped to better analyse the baseline situation of water availability and accessibility to analyse the consumption patterns in Champawat. The in-depth interviews of the resource persons and key stakeholders from both supply and demand sides were taken through purposeful sampling and snowball sampling. Interviews of the government officials largely consisted of questions concerning the technical aspects of the piped water supply system, its management and governance. Further, in-depth interviews of politicians, journalists, and social activists were taken to understand various intricacies of water accessibility and availability in the local context from the demand side. The information taken from the in-depth interviews was used to develop the questionnaire for consumption patterns. The consumption pattern survey needed secondary data about the piped water supply infrastructure, which was unavailable digitally and in any public domain. These data gaps were addressed through stakeholders' consultations. Total households in the town were analysed by dividing the population by 5, which came to around 2551. Uttarakhand has an average household size of 5 [11]. The ward-wise population data were provided by the office of NPP. Due to time constraints, 20 households from each ward of the nine wards were randomly taken. A consumer survey of 180 households was carried out using a structured questionnaire schedule. The questions in the schedule were prepared according to the joint World Health Organization (WHO) and United Nations Educational, Scientific & Cultural Organization (UNESCO) guidelines [31]

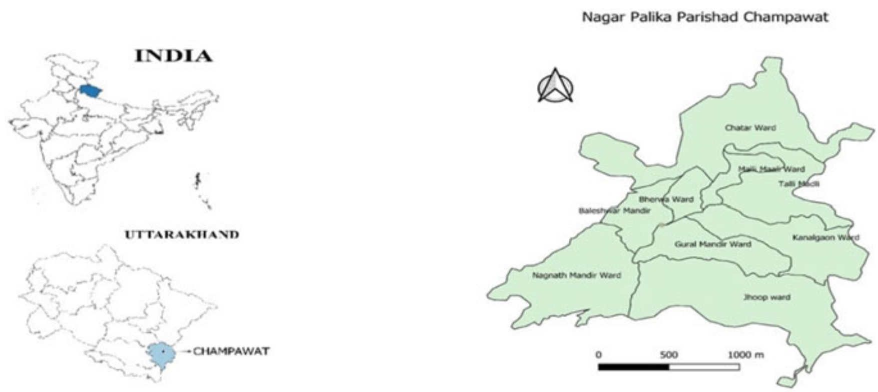

Fig. 1 Study area: Champawat NPP, Champawat, Uttarakhand, India [30]

and were modified according to local conditions. The descriptive analysis of the primary data was done on Microsoft Excel software. The graphs of various findings are in Sect. 3.

3 Findings and Analysis

3.1 Sources of Water

Piped Water Supply System (PWSS): Uttarakhand Jal Sansthan is the body responsible for the provisioning of the piped water system throughout the state. It is divided into two wings. First is Uttarakhand Jal Sansthan (UJS). It operates and maintains the PWSS. The second wing is Uttarakhand Pay Jal Nigam (UJN). It looks after the construction of water supply and sewerage infrastructure. Water in the PWSS comes from five different springs and streams (locally called "gaad" or "gadhera"). To cater for the increasing demand in the town and nearby areas a new scheme, Koirala Ghati Pariyojana is under construction. PWSS in Champawat is gravity main. No external pump is used in the main line to maintain the pressure. The distribution mains are laid throughout the town from where people connect pipelines to their dwellings. Water in a single ward can come from different springs. According to the UJS Champawat Office, the estimated demand for water is 2.3 million litres per day (MLD) for a population of 12,756, while the supply from sources is only 0.68 MLD. This deficit is high. The UJS provides water in different connections at different time intervals and operates PWSS for around 14 h. For calculation purposes, 15% of water leakage is considered according to Central Public Health and Environmental Engineering Organization (CPHEEO) Manual, 2019. There were no private water suppliers in the town.

Other Sources: People in urban and peri-urban access water from various other sources as there exists a lot of inequalities and unequal distribution of resources [32]. Narain [32] defines characteristics of peri-urban in terms of environment, social, institutional, land-use change, and livelihood practices. Being an emerging town with rural proximities, Champawat also shares such characteristics. 76% of the households are dependent upon piped water connections while 2% of the households also use standalone public water taps to access water. After PWS, people are mostly dependent on wells followed by hand pumps. Around 19% of the respondents use well as the primary source, while 44.5% of the respondents reported having well (see Figs. 2 and 3). Traditional water harvesting systems used for drinking and other domestic purposes in the region are Naula and Dhara. Naula is a small shallow well protected by walls and a shed. It generally has a temple-like architecture. Dhara is a natural spring. Construction is provided in its natural flow to use the water [12, 17, 30].

Periodic changes in availability, quality, and accessibility of water make people look out for more than a single source. The primary sources in the study are those on whom the respondents mostly rely, while secondary sources are those sources

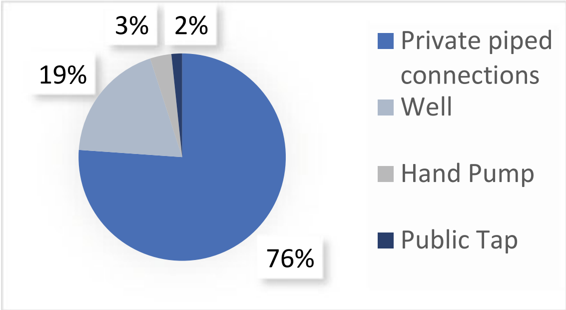

Fig. 2 Distribution of primary sources of water for households

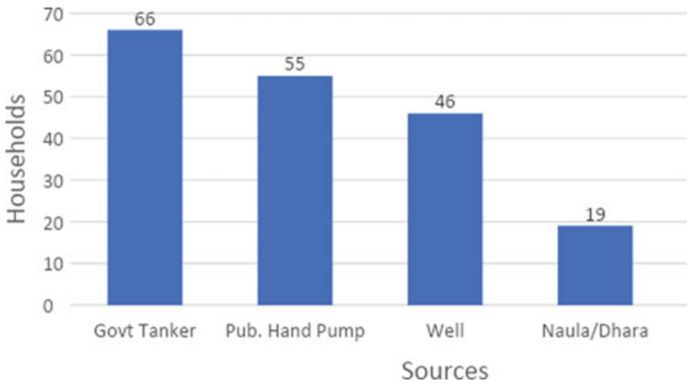

Fig. 3 Number of households using various secondary sources of water. A single household may use multiple sources

that are used for specific activities and during any fluctuation in the water availability. The dependence on secondary sources occurs during the summer season due to irregular supply in piped supply. There is low availability of water at their sources. Sometimes even wells might dry up. Poor water quality during rainy season also forces people to shift towards other secondary sources. 74.44% of surveyed households were dependent on at least one alternative source. 10.5% of respondents use Naula and Dhara around the year for different purposes. The reliance on traditional water harvesting systems has declined. The traditional sources of water were not a primary source of water for a single household. Only 19 surveyed households were utilizing them. Traditional water systems are in dilapidated condition, especially Naula. Though long queues around Naula and Dhara are a common sight during summer. Some people also depend on Naula and Dhara especially for drinking and religious purposes. Around 3% of such households were dependent on public hand pumps or Naula/Dhara. According to UJS office, 74 public hand pumps have been installed all over the town.

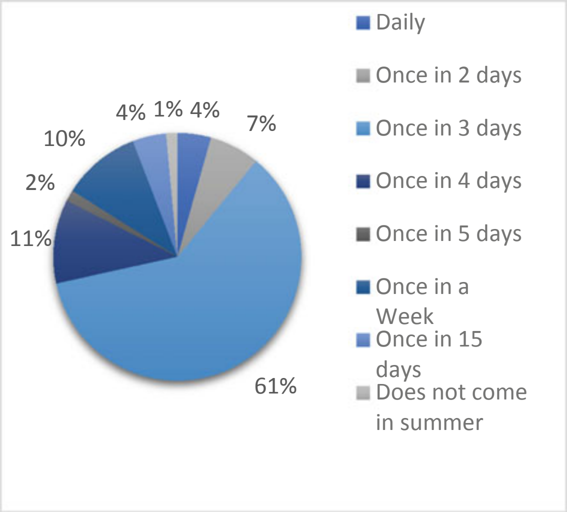

Fig. 4 Water supply frequency during summer

Fluctuations in Water Availability: Water levels in natural sources like springs, Naula, Dhara, and wells go down during summer. The region is highly prone to landslides and earthquakes [15]. Disruption in supply is common due to climatic and tectonic conditions of the region. Many times, pipelines, even the check dams get damaged during the heavy downpour of rain and snow. More than 90% of the surveyed households reported disturbance in the regular supply of water during summer. Almost 98% of surveyed households having piped connections experienced inconsistencies in the water supply. The situation in summer sometimes becomes too grim. 61% of surveyed households with piped water connections reported to get water every third day. Only 4% of surveyed households get daily water supply during summer. The situation in some households was very precarious, some even get water once in 7 days and even once in 15 days (see Fig. 4). Water tankers provided by UJS are the most important secondary source for households during dry summers. Further, hand pumps are the other important source of water.

3.2 Water Supply Timings of PWSS

Water supply timings play a pivotal role and decide the whole schedule of the day, especially for women and children who are engaged in water provisioning [33]. Beal and Stewart [28, 34] in their water end use studies have shown that the water consumption peaks have been observed in the morning hours. Most of the households in Champawat receive water during morning hours, which shows that the morning hours are the consumption peaks in the town. Respondents complained about odd water timings. The water supply before 6 a.m. and after 8 p.m. was considered odd

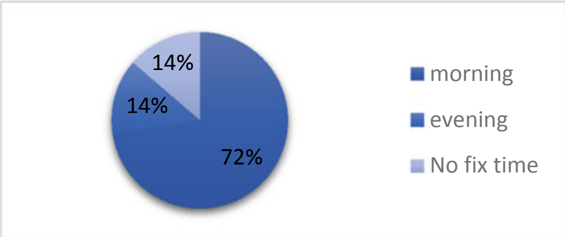

Fig. 5 Distribution of supply timings

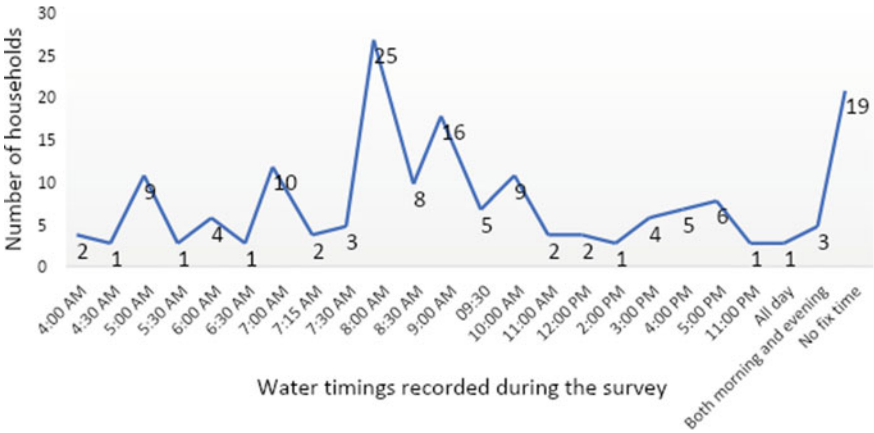

Fig. 6 Graph shows supply timings of PWSS

supply timings by the respondents (see Figs. 5 and 6). In 14% of the households, there were no fixed supply timings. Due to irregular timings, especially women have to adjust their sleeping patterns accordingly. It could impact their health and body cycles [35]. On average, the water supply is for a duration of approximately 119.42 min (around 2 h). The timings are less than the Asian Development Bank's (ADB) report [36]. It states that the present urban water supply duration in Uttarakhand is between 3 and 4 h [36]. Further, according to 34% of the respondents, their water supply timings and duration change in summer.

3.3 *Water Consumption Patterns*

In the survey, average water consumption levels in the town came to around 79.53 L per capita per day (LPCD). The average consumption of the piped water households came to around 83.42 LPCD. The average consumption of households with wells was the highest around 98.63 LPCD. The average consumption levels of households primarily dependent on hand pumps reduced drastically to 57.21 LPCD (see Fig. 7). From this, it can be inferred that the consumption of water in a household is linked to the availability of water from the source it receives water. Better availability provides more water at people's disposal; therefore, the consumption increases. The town does not have any sewage system so consumption levels may have been less. Also, according to URDPFI guidelines, the water provisioning standards differ for towns having sewerage lines [37]. The consumption levels also depend on the seasons [28]. According to the UJS, they are unable to meet the standard of 135 L per capita per day (LPCD) of water to the people. The national standards are according to the CPHEEO manual, 1999. Only 7% of households were consuming 135 LPCD. 37% of the surveyed households were consuming between 100 and 135 LPCD of water. The condition of most households seems to be precarious. 35% of households were consuming less than 70 LPCD of water. The consumption levels of 6% of households came to around 40 LPCD (see Fig. 8). 40 LPCD is less than the WHO's norms of the minimum requirement of water for a person, i.e., 50 LPCD [38]. According to Uttarakhand Vision 2030 report [39], just 23% of ULBs in the state provide the standard requirement.

Tankers: The availability of piped water goes down during lean patches, especially during the summer season. People reported that water sometimes comes after the third day and some even once a week. During such time, water tankers provided by UJS come to the rescue. The distribution of water from tankers is not uniform. Around 46.43% of households with piped water connections were able to access tanker services. The average water availability from tankers on a single visit came out to be 137.154 L a household while both mode and median came out to be 100 L. Approximately 72% of households were able to procure less than the calculated average of 137.45 L of water on a single visit of a tanker. Further people reported that the timings of water supply from tankers were very uncertain.

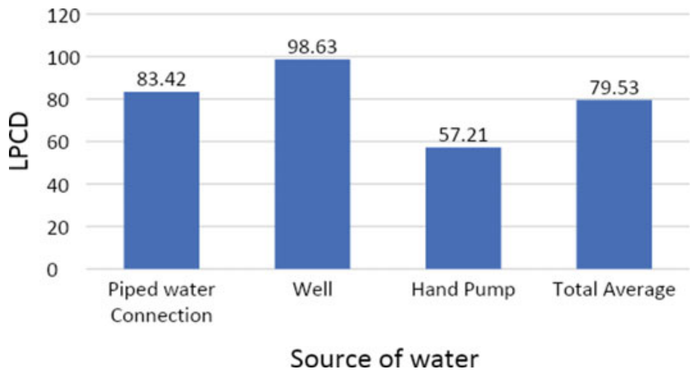

Fig. 7 Average water consumption levels of surveyed households

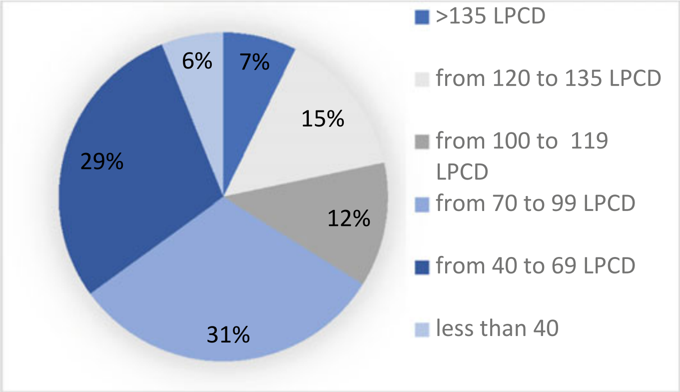

Fig. 8 Distribution of water consumption

3.4 Water Tariffs

Water tariffs in Uttarakhand are defined in the Uttar Pradesh Water Supply and Sewerage Act of 1975, which was amended in 2002 after the formation of the state. These are revised from time to time. Consumers are charged quarterly according to the property value with an annual revision of 15% [36]. The property tax data are taken from the office of NPP to calculate the water tariffs. Around 90% of people in Uttarakhand pay water tariffs [14]. This was also reflected in the survey as 93.43% of households were paying the tariffs. Some respondents who were living as tenants do not pay any tariffs as their owners do not take any kind of water charges from them. The average monthly water tariff came out to around Rs. 542.10. Respondents claimed that they were paying more than similar households in the nearby towns of Lohaghat and Pithoragarh. They blamed NPP for the high tariffs due to their faulty assessment of property values. The claims seem to be true as according to an ADB report [36] the average household in Uttarakhand pays a monthly tariff of Rs. 277.50.

3.5 Accessibility: A Walk to Water

Accessibility of water is affected by the time and distance a person travels to fetch water. Distance not only increases the time required to procure water but also puts physical strain [33]. Around 15.55% of the total surveyed households reported that during summers and in case of any disruption in regular supply, they walk between 100 and 200 m to fetch water. While 8% reported travelling more than 500 m. Households dependent on public hand pumps and traditional water harvesting system might even wash their clothes and even utensils at the sources. The situation of households living on the peripheries is more precarious. As their taps dry, they have

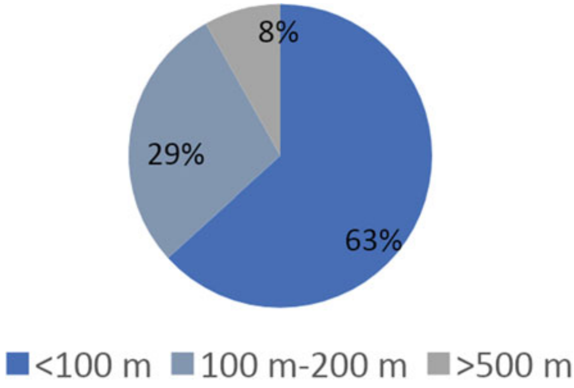

Fig. 9 Distribution of distance travelled by the people to fetch water

to cover longer distances to procure water (see Fig. 9). The time here is consumed in not only fetching water from source to home but also in waiting time while standing in the queue at the source.

3.6 Water Quality and Treatment

The perceptions of people regarding the water quality were taken for their respective sources. 87% of households reported receiving clean water from piped supply during normal seasons (other than monsoon) while 5% deemed it to be dirty and thought that it needed to be cleaned further. The water quality changes with the season and worsens during rainy seasons. Uttarakhand receives rainfall majorly twice a year, during monsoons and in winter due to western disturbance [40]. All the households reported receiving yellow to brown-coloured water during a heavy downpour, especially in monsoons. The water is muddy and unfit for domestic use. 14% of the households reported having found insects (see Fig. 10).

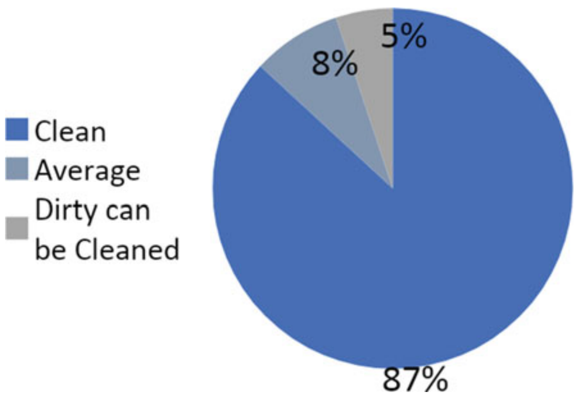

Fig. 10 Quality of piped water

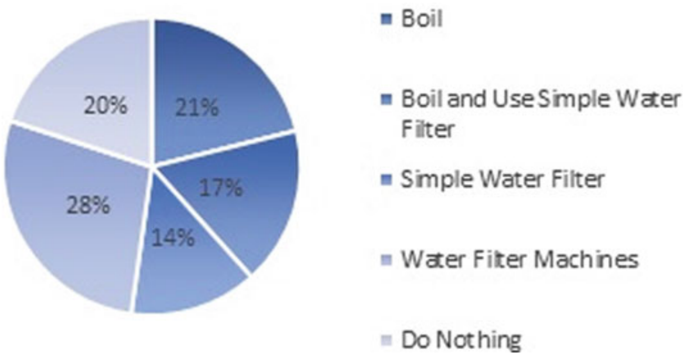

Fig. 11 Distribution of methods of water treatment among all the surveyed household

Water Treatment at Homes: 37% of households boil supply water for drinking and cooking purposes while 28% use home water treatment machines. 41% of households using well water do not use any treatment method. 20% of the households were found to be not using any treatment method (see Fig. 11). Using untreated water exposes a large population to various diseases. Studies in Kumaon have shown that untreated water especially of rivers may lead to various ailments and chronic diseases [21]. Though people do not treat water regularly, they clean and purify water mostly during rainy seasons. 16.11% of the surveyed households reported that their family members especially children suffer from some kind of waterborne disease every year.

3.7 Reasons for Water Scarcity

Even though the region experiences good precipitation around the year, the availability of water at the sources during summer goes down [7]. According to 76.67% of the respondent households, the reason for water scarcity was drying streams. There is low availability of water at sources like streams, springs and even wells in the summer season. Water harvesting in the town is highly neglected. Only a single household was using water harvesting system while only two were found rejuvenating groundwater. People further highlighted that the mismanagement by UJS increases their precarity. The rigidity in the system is more a component of water management than the unavailability of water. The structural persistence creates traps for the system, which impact its efficiency thus impacting the overall accessibility to the system. The system may not be adaptive and old, which leads to structural persistence [41]. Further, water reservoir tanks and check dams are also not maintained properly. Timely maintenance of PWSS could have reduced these persisting issues. One of the major worries in the system is old pipelines. Some of them are even 30–40 years old. With such a high water load, it's not easy to sustain the system. Water pressure at the supply line is not adequate and varies from place to place due to the topography, which further adds to the rigidity of the system. The under construction Koirala Ghati Pariyojana has been delayed for long due to land acquisition issues with the nearby rural areas. Addressing urban and rural conflicts is one of the important aspects for water governance to enhance the urban water security in the Himalayas [7].

3.8 Coping Mechanism

Local people have developed various coping mechanism to deal with water scarcity. People flock to handpumps and traditional water systems to procure water. For cooking and drinking purposes water from Naula and Dhara are preferred. During the lean water season, long queues around handpumps and traditional water systems is a common site. People do water rationing and store water in multiple containers. Households have a number of containers and tanks to save water as water supply fluctuates highly during summer and sometimes water may come on the third day. During dry season water tankers are also provided by UJS. Tankers bring water from Dhaun Dhara (spring) and Laluapani Spring, which are 15 km and 5 km away, respectively, from the town. In case of dire need, some households even bribe drivers of the tankers. Some people fetch water from neighbours and relatives who have personal wells and handpumps. One of the major issues that people face on a daily basis is the inadequate water pressure at taps due to variable topography. To maintain adequate pressure, some people also install water pumps directly to the supply line which may attract fines.

4 Conclusion

The analysis showed that towns like Champawat are not just dependent on PWSS but multiple sources. As the availability of water changes so do people change their water sources. The scarcity of water in summer season leads to a shift towards water tankers, handpumps and traditional water sources like Naula and Dhara. The piped water system is not able to provide water up to the standards of 135 LPCD. Water supply duration is below the state average levels and people are paying higher tariffs than the state average. The state government is slow in reforms. There is no metering in supply lines. The new scheme, Koirala Ghati Pariyojana has been delayed for years. With increasing population and changing rainfall patterns, the situation in future may worsen. Small remote towns like Champawat provide a different understanding of water accessibility and availability issues. Local geographical conditions, technical issues, and water governance impact the accessibility and availability, leading to persistent rigidity in the system. Local urban centres like Champawat have emerged by virtue of being administrative headquarters. Their growth is now not just limited to local circumstances but international and global socio-economic drivers and market forces. These areas need attention and further research. The issues of these remote towns cannot be seen through the lens of urbanization patterns of big cities and tourist centres.

References

1. Sharma E, Molden D, Rahman A, Khatiwada YR, Zhang L, Singh SP, Wester P (2019) Introduction to the Hindu Kush Himalaya Assessment. In: Wester P, Mishra A, Mukherjee A, Shrestha AB (eds) The Hindu Kush Himalayan Assessment. Springer, Switzerland, pp 1–16. https://doi.org/10.1007/978-3-319-92288-1_1
2. Xu J, Grumbine RE, Shrestha A, Eriksson M, Yang X, Wang Y, Wilkes A (2009) The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. Conserv Biol 23(3):520–530. https://doi.org/10.1111/j.1523-1739.2009.01237.x
3. Qing-Long Y, Guo-Yu R, Yu-Qing Z, Yu-Yu R, Xiu-Bao S, Yun-Jian Z, Raghavan K et al (2017) An overview of studies of observed climate change in the Hindu Kush Himalayan (HKH) region. Advances in Climate Research 1–7. https://doi.org/10.1016/j.accre.2017.04.001
4. Uniyal A, Rawat GS (2018) What is the future of water governance in the Himalayas? Econ Polit Wkly 53(35)
5. Mukherjee D (2013) Critical analysis of challenges of Darjeeling Himalaya: water, natural resources, hazards, and the implications of climate change. Int J Agric Innov Res 13–22
6. Shah R (2015) Understanding water availability and accessibility issues from a perspective of climate variability: a study in Darjelling. Mumbai: a project report submitted in partial Degree of Master of Science in Climate Change and Sustainability Studies, Tata Institute of Social Sciences
7. Ojha H, Neupane KR, Pandey CL, Singh V, Bajracharya R, Dahal AN (2020) Scarcity amidst plenty: lower Himalayan cities struggling for water security. MDPI Water 12:567. https://doi.org/10.3390/w12020567
8. Anbalagan R (1993) Environmental hazards of unplanned urbanization of mountainous terrains: a case study of a Himalayan town. Q J Eng Geol 26:179–184
9. Kulakarni H, Gupta A (2018) Report of working group I, inventory and revival of springs in the Himalayas for water security. NITI Aayog
10. Tiwari PC, Tiwari A, Joshi B (2018) Urban growth in Himalaya: understanding the process and options for sustainable development. J Urban Reg Stud Contemp India 4(2):15–27
11. Sati V (2016) Patterns and implications of rural-urban migration in Uttrakhand Himalaya, India. Ann Natl Sci 2(1):26–37
12. Bose A (2000) Reaching the unreached in Uttarakhand: demography, drinking water and technology. Econ Pol Wkly 35(25):2090–2092
13. Bahri A (2012) Integrated urban water management. Global Water Partnership, Stockholm
14. NITI Aayog (2018) Composite water management index. NITI Aayog, New Delhi
15. Sharma S (2018) Uttarakhand facing acute water crisis: UNDP report. Retrieved from The Times of India: https://timesofindia.indiatimes.com/city/dehradun/uttarakhand-facing-acute-water-ADB
16. Chopra R (2003) Survival lessons. People's Science Institute, Dehradun
17. Rawat AS, Sah R (2007) Traditional knowledge of water management in Kumaon Himalaya. Indian J Tradit Knowl 8(2):249–254
18. Bisht NS (2014) Economic valuation of the role of forests in providing water supply to the people of Kohima town, Nagaland. India SAARC For J III:47–64
19. Bharti N, Khandekar N, Sengupta P, Bhadwal S, Kochhar I (2019) Dynamics of urban water supply management of two Himalayan towns in India. Water Policy Corrected Proof 1–25. https://doi.org/10.2166/wp.2019.203
20. Dash RR, Mehrotra I, Kumar P, Grischek T (2008) Lake bank filtration at Nainital, India: water-quality evaluation. Hydrogeol J 2008(16):1089–1099. https://doi.org/10.1007/s10040-008-0295-0

21. Seth R, Mohan M, Singh P, Singh R, Dobhal R, Singh KP, Gupta S (2014) Water quality evaluation of Himalayan rivers of Kumaun region, Uttarakhand India. Indian J Gastroenterol
22. Sharma SK, Kansal ML, Tyagi A (2015) Resource assessment and strategic planning for improvement of water supply to Shimla city in India using geo-spatial techniques. Egypt J Remote Sens Space Sci 2015(18):85–97
23. Gautam D, Thapa BR, Prajapati RN (2017) Indigenous water management system in Nepal: cultural dimensions of water distribution, cascaded reuse. Springer
24. Wang Y, Wu N, Kunze C, Long R, Paerlik M (2019) Drivers of change to mountain sustainability in the Hindu Kush Himalaya. In: Wester P, Mishra A, Mukherji A, Shrestha AB (eds) The Hindu Kush Himalaya assessment. Springer, Kathmandu, Nepal, pp 17–55
25. Jones H, Parker J, Reed R (2002) Water supply and sanitation access and use by physically disabled people. WEDC Publications, Loughborough
26. Kaushik A (2011) Literature review on right to water for basic needs (drinking and domestic water, sanitation): forum for policy dialogue on water conflicts. Society for Promoting Participative Ecosystem Management (SOPPECOM), Maharashtra
27. Allen A, Davila J, Hoffman P (2006) Governance of water and sanitation services for the peri-urban poor, a framework for understanding and action in metropolitan regions. The Development Planning Unit, University College, London
28. Beal C, Stewart RA (2011) South East Queensland residential end use study: final report. Urban Water Security Research Alliance, Queensland. Australia
29. Census (2011) Census of India 2011, District Hand Book Champawat. Directorate of Census Operations, Uttarakhand, Dehradun
30. Kharkwal N (2020) Analysis of water accessibility and availability in Kumaon: case study of Champawat town, Uttarakhand, India. Masters dissertation. Tata Institute of Social Sciences, Mumbai
31. World Health Organization, United Nations Children's Fund (2006) Core questions on drinking water and sanitation for household surveys. World Health Organisation and UNICEF 2016. https://apps.who.int/iris/bitstream/handle/10665/43489/9789241563260_eng.pdf?sequence=1
32. Narain V (2010) Periurban water security in a context of urbanisation and climate change, a review of concepts and relationships. Peri Urban Water Security Discussion Paper Series, Paper No. 1, SaciWATERs
33. O'Leary H (2016) Between stagnancy and affluence: reinterpreting water poverty and domestic flows in Delhi, India. Soc Natl Resour 29(6):639–653. https://doi.org/10.1080/08941920.2016.1150534
34. Beal CD, Stewart RA (2014) Identifying residential water end uses underpinning peak day and peak hour demand. J Water Resour Plan Manag 140(7):04014008. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000357
35. Kher J, Aggarwal S, Punhani G (2015) Vulnerability of poor urban women to climate-linked water insecurities at the household level: a case study of slums in Delhi. Indian J Gend Stud 22(1):15–40. https://doi.org/10.1177/0971521514556943
36. ADB (2019) Sector assessment (summary): water and other urban infrastructure and services. Retrieved from Asian Development Banl. https://www.adb.org/sites/default/files/linked-documents/38272-044-ssa.pdf
37. URDPFI (2015) Urban and regional development plans formulation and implementation (URDPFI) guidelines, vol I, January 2015, Ministry of Urban Development, Government of India, town and Country Planning organization
38. UNO (2010) UN-water decade programme on advocacy and communication and water supply and sanitation collaborative council. Media Brief United Nations organisation. Retrieved from https://www.un.org/waterforlifedecade/pdf/human_right_to_water_and_sanitation_media_brief.pdf
39. Department of Planning, Government of Uttarakhand (2018) Uttarakhand vision 2030. Department of Planning, Government of Uttarakhand. Retrieved from Directorate of Economics and Statistics Planning Department, Government of Uttarakhand. https://des.uk.gov.in/files/Uttarakhand_Vision_2030.pdf

40. Sabin TB, Krishnan R, Vellore R, Priya P, Borgaonkar HP, Singh BB, Sagar A (2020) Climate change over the Himalayas. In: Krishnan R, Sanjay J, Gnanaseelan C, Majumdar M, Kulkarni A, Chakraborty S (eds) Assessment of climate change over the Indian region (1st ed, vol. I). Ministry of Earth Sciences, Government of India, New Delhi, pp 207–221. https://doi.org/10.1007/978-981-15-4327-2_11
41. Enqvist J, Tengo M, Boonstra WJ (2016) Against the current: rewiring the rigidity trap dynamics in urban water governance through engagement. Sutain Sci 11:919–933. https://doi.org/10.1007/s11625-016-0377-1

Identification of Flood-Inundated Areas Using HecRAS Model: A Case Study of Upper Sabarmati River Basin, Gujarat, India

Shibani Chourushi, Pradeep P. Lodha, and Indra Prakash

Abstract Identification of flood-inundated areas under different flood levels in a river basin is an important step to control and properly manage floods. Topography plays an important role in identifying vulnerable areas. River flood plain areas are most vulnerable to flooding requiring proper study. The flood management in any basin depends on the rain-fall events, surface runoffs, water surface elevation profiles, cross-section of the river basin, river bank profiles, elevation profiles, and ground level of low-lying areas. In the present study, downstream area of the Upper Sabarmati River basin between Dharoi Dam and Derol Bridge has been modeled using 1D HecRAS software for identifying inundation areas under different flood scenarios for proper flood management.

Keywords Digital elevation model · HecRAS model · Water surface elevation profiles

1 Introduction

The hydrological models are the model that describes the hydrological cycle or its major parts. Variations in climate, topography, land types, and land use as well as various man-made interferences with the system make it very difficult to construct

S. Chourushi (✉)
Government Engineering College, Rajkot, Gujarat 360005, India
e-mail: sschourushi@gecrajkot.ac.in

P. P. Lodha
Government Engineering College, Bharuch, Gujarat 392002, India

I. Prakash
Bhaskaracharya Institute for Space Applications and Geoinformatics, Gandhinagar, Gujarat 382010, India

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general models that treat the whole hydrological cycle in any given catchment. Hydrological modeling is the representation of the real hydrological system. In the case of any watershed or catchment area, there are two important models, namely, the hydrologic model such as ArcSWAT (Aeronautical Reconnaissance Coverage Soil & Water Assessment Tool), and the hydraulic model such as HecRAS (Hydrologic Engineering Center's River Analysis System). Hydrologic models are generally used to compute the quantity of flow discharge, sediment erosion and nutrients at a given point for a given period; and also used in flow frequency analysis. Hence, these types of models provide a basin-wide view. Whereas on the other hand, hydraulic models are generally used to compute water elevation, river cross-sections, inundation maps, etc. at a given point during a period. These types of models provide river length, cross-sections, etc. at reach level. In the present study, we have used the HecRAS model for the identification of the inundated area of the downstream part of the Upper Sabarmati River basin between Dharoi Dam and Derol, Gujarat, India.

The HecRAS is a hydraulic model developed by Brunner et al. [5] of US Army Corps of Engineers Hydrologic Engineering Center. This model helps in getting water surface profile, river cross-sections, river profile, flood inundation mapping, etc. The main five steps for the HecRAS model are as follows: (1) starting a new project, (2) entering geometric data, (3) entering flow data and boundary conditions, (4) performing the hydraulics calculations, and (5) viewing and printing the results. The HecRAS model can be used as DEM (Digital elevation model) input to facilitate the adaptation of suitable disaster mitigation measures from the water profile outputs [12]. This model can also be used for bridge hydraulics and their investigation studies [4].

The HecRAS models are of two types: one-dimensional and two-dimensional models [7]. The difference is between the meander's parts of the river configuration [14]. The HecRAS model helps in the editing of the elevations of the structures present within the flood boundary [11]. This model can be applied easily in different geological and topographical conditions [15], helpful in optimizing water resources for irrigation [17], predicting primary floods [16] and to decision-makers for environmental planning and flood control [17]. This model also helps in the generation of flood maps and stage-discharge curves for planning purposes [3, 8, 10]. RAS mapper tool added to the HecRAS model provides river distribution spatially [9] and overall visualization of the river [1].

The objective of the study is to create different flood inundated scenarios of the study area by carrying out a 1D steady flow analysis using the HecRAS model for the proper flood management. HecRAS and ArcGIS software were used for the data analysis and visualization.

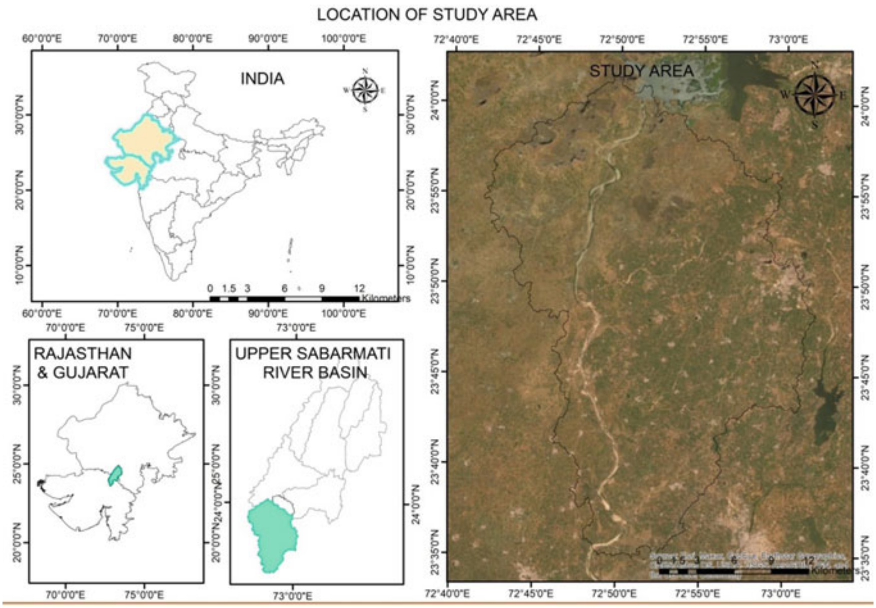


Fig. 1 Location map of study area

2 Study Area

In this study, the downstream region of the Upper Sabarmati River basin from Dharoi Dam to Derol Bridge is considered (Figs. 1 and 5). The catchment area of the Dharoi Dam is 5475 km^2. The total length of the river from the Dharoi Dam to Derol Bridge is 58 km, which is up to the endpoint of the study area. The Dharoi gravity dam (24°0′16”N, 72°51′13”E) was constructed on the Sabarmati River in1978 year near Dharoi, Satlasana Taluka, Mehsana, district, Gujarat, India (Fig. 1).

3 HecRAS Model

HecRAS (Hydrologic Engineering Center’s River Analysis System) is a hydraulic model developed by Brunner et al. [5] US Army Corps of Engineers Hydrologic Engineering Center. The HecRAS is a hydraulic model used for identifying critical areas in flood-like situations as well as in high-intensity rainfall events. This model helps in getting water surface profile, river cross-sections, river profile, flood inundation mapping, etc. The HecRAS model is broadly of two types: 1D steady flow analysis and 2D unsteady flow analysis. The 1D steady flow analysis uses the kinematic flow of water under study. This kinematic flow is a static flow that varies slowly. This flow helps in identifying flood-inundated areas effectively along the river’s length and further helps in proposing the appropriate structure required to be constructed in the future for solving the flood problem. On the other side 2D, unsteady flow analysis uses the dynamic flow of water which varies rapidly. This flow helps in identifying flood-inundated areas area-wise. The decision-making using dynamic flow is difficult as compared to 1D steady flow. Hence, we have selected the 1D HecRAS method for identifying flood-inundated areas.

3.1 Methodology of HecRAS Model

The hydraulic modeling was performed using the HecRAS model, where a DEM map for generating terrain layers. Then HecRAS model setup was done; the Mapper tool in the HecRAS model was used to generate real-time river profiles, river bank lines, cross-sections, flood lines, etc. using Google Satellite image. For the parameter input for the HecRAS model, various profiles were generated based on calibrated discharge obtained from the ArcSWAT model considering different discharges. These profiles were used in steady flow analysis performed in HecRAS to generate inundated maps.

The present study was carried out in five steps: (1) starting a new project, (2) entering geometric data using HecRAS Mapper tool, (3) entering flow data and boundary conditions, (4) performing the hydraulic calculations, and (5) viewing and printing the results.

3.2 HecRAS Model Parameters

The steady flow analysis was performed in the HecRAS model using four model scenarios using monthly discharge data. The monthly flow data was used in the HecRAS model for the entire month. The monthly flow becomes steady due to the average speed of the flow in river cross-sections, which helps in modeling permanent flow as compared to the daily event, which is turbulent as well as unsteady in nature. In steady flow analysis, decision-making becomes easy due to the day's margin for permanent structural solutions.

4 HecRAS Model: Results and Discussions

In total, 13 cross-sections were generated using the RAS-Mapper tool in the HecRAS model. After that steady flow analysis of the model was performed with all four profiles (H1–H4) along the Sabarmati River in between Dharoi dam and Derol bridge station in the downstream region for all 13 cross-sections.

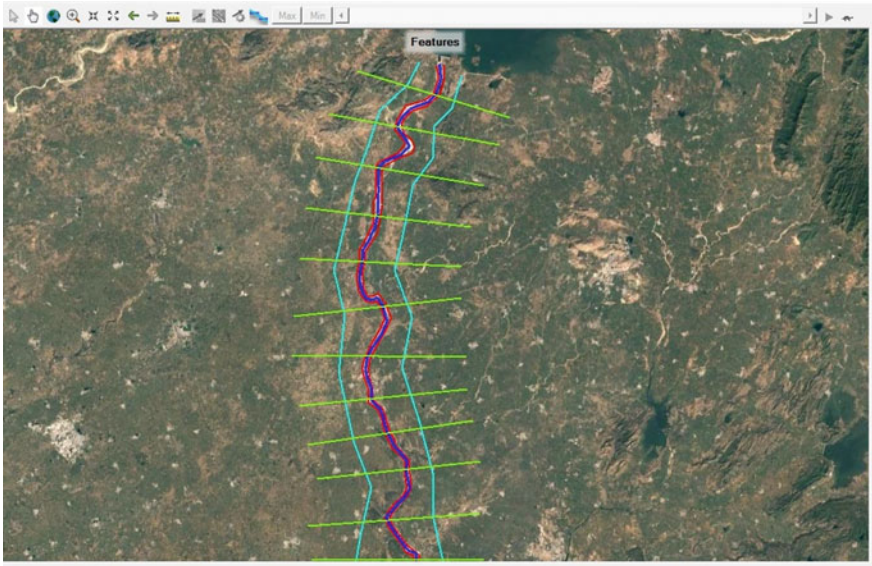


Fig. 2 Map showing river line, bank lines, bank stations, and various cross-sections

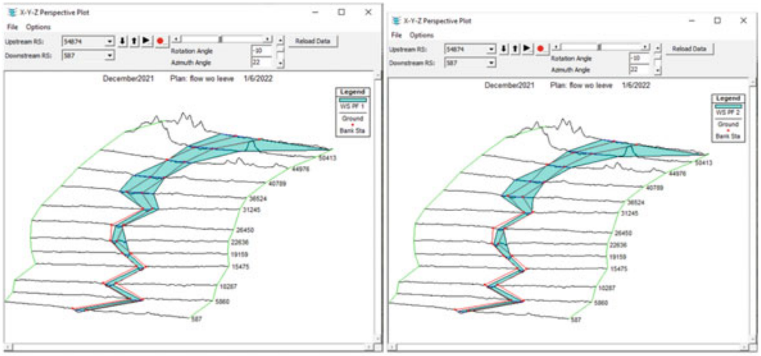
In Fig. 2, the Blue line represents the river centerline, the red lines represent the limit of river banks, the red dots represent river banks, the sky blue lines represent the flow area marked for the study and the green lines represent various cross-sections on the river. For natural main channels (clean, straight, deep pools with more stones and weeds), manning's n value is 0.035. And for flood plains (scattered brush with heavy weeds), manning's n value is 0.05 (Source: Open channel hydraulics by Ven T. Chow [6]).

Figure 3 shows X-Y-Z perspectives of four profiles, respectively. The X-Y-Z-perspectives represent various cross-sections in three dimensions, which show six vulnerable cross-sections after steady flow analysis in all profiles.

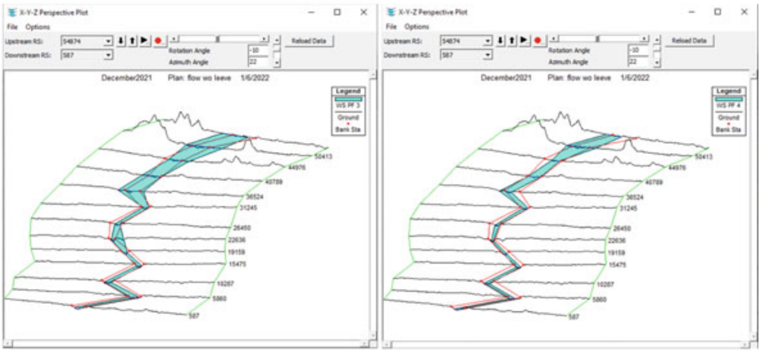
Figure 4 shows flood inundation maps of four profiles, respectively. The flood inundation maps represent flood-inundated areas near vulnerable cross-sections after a steady flow analysis is used.

Figure 5 shows that Chandap village is at high risk due to the probability of floods as per profiles 1 and 2.

The HecRAS Mapper tool in the HecRAS model was used to generate a river longitudinal profile and cross-sectional profile from the terrain map created from the DEM map of the Sabarmati basin. A total of 13 cross-sections were generated using the 'Generate tool' (Fig. 2). The HecRAS model was run on a monthly basis to estimate the flood inundated maps from real-time Google Satellite images. The



(a) And (b)



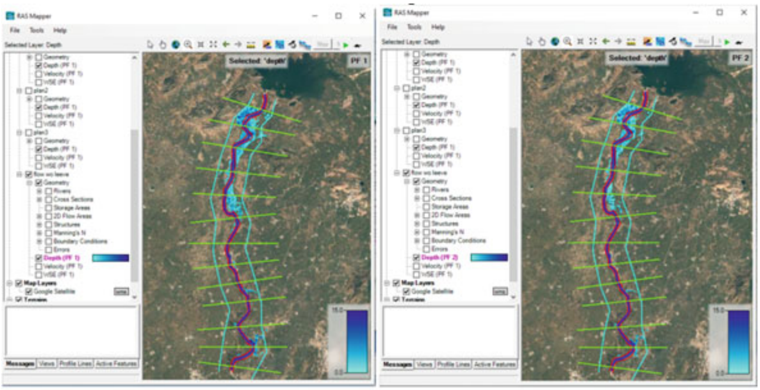
(c) and (d)

Fig. 3 Map showing X-Y-Z perspectives of profiles 1(**a**), 2(**b**), 3(**c**), and 4(**d**)

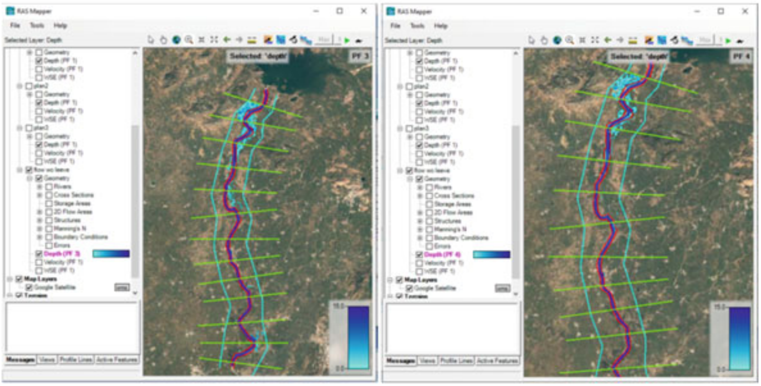
steady flow analysis was performed using four profiles: PF 1, PF 2, PF 3, and PF 4 were generated considering different flood scenarios (Table 1). Flood risk area of Chandap, Village (Fig. 5) was identified. From the Steady flow analysis, the water profiles and their X-Y-Z perspectives (Fig. 3) of four profiles were obtained in the downstream area, which is represented in flood inundated maps (Fig. 4). 1-D HecRAS model studies have also been carried out successfully for downstream flood modeling in other parts of the river basins such as Shetrunji River, Gujarat, India [13], Pahang River, Malaysia and Jhelum River, Jammu and Kashmir [2].

5 Conclusions

There are different hydrological models available for flood studies in a river basin. In the present study, we have used the HecRAS model, which is simple to apply for the identification of flood-prone areas. We have carried out a 1D steady flow analysis



(a) and (b)



(c) and (d)

Fig. 4 Flood inundation maps for profile PF1 (**a**), PF2 (**b**), PF3 (**c**) and PF4 (**d**)

for the generation of different flood scenarios and identified flood-inundated areas in the downstream part of the Upper Sabarmati River, Gujarat, India. This study will be helpful in proper flood management of the probable flood areas to prevent flood damages and in saving human lives. It is proposed to carry out a 2D analysis in future for the comparison of results of the 1D analysis.

Source: google.com/maps/@23.9301352,72.8559057,12z

Fig. 5 Location map of a village at flood risk.

Table 1 HecRAS model parameters

Serial number		Profiles	Monthly Discharges (cumec)
Different scenarios	H1	Profile 1	32,000
	H2	Profile 2	23,000
	H3	Profile 3	17,000
	H4	Profile 4	8000

References

1. Ackerman CT, Jensen MR, Brunner GW (2010) Geospatial capabilities of Hec-RAS for model development and mapping. In: 2nd joint federal interagency conference. Las Vegas, New York, pp 1–6
2. Ahmad HF, Alam A, Bhat MS, Ahmad S (2016) One dimensional steady flow analysis using HecRAS-A case of River Jhelum, Jammu and Kashmir. Eur Sci J 12(32): 340–350
3. Al-Zahrani M, Al-Areeq A, Shareef H (2016) Flood analysis using HEC-RAS model: a case study for Hafir Al-Batin, Saudi Arabia. In: Flood risk 2016–3rd European conference on flood risk management, pp 1–5
4. Bonner VR (1996) Bridge hydraulic analysis with HEC-RAS. In: Association of state flood plain managers 20th Annual conference. ASCE, San-Diego, CA, California, pp 1–17
5. Brunner VR (1994) HEC-river analysis system (HEC-RAS). In: National conference of hydraulic engineering. ASCE, New York, California, pp 1–8
6. Chow VT (1959) Open channel hydraulics. Mc Graw Hill, United States of America
7. Dasallas L, Kim Y, An H (2019) Case study of Hec-RAS 1D–2D coupling simulations: 2002 Baeksan flood event in Korea. Water, MDPI J 11(2048):1–14

8. Hydroc (2017) Report on hydraulic modelling. Assessment of suitable flood mitigation measures (based on Dukiskhevi river extreme flood analysis) in Tbilisi, Georgia. Hydroc GmbH, German
9. Khan, Pathan AKI, Agnihotri PG (2020) 2 D unsteady flow modelling and inundation mapping for lower region of purna basin using HEC-RAS. Nat Environ Pollut Technol J 19(1): 277–285
10. Mistry KV, Prajapati P, Chaudhari B (2018) Determination of the stage discharge curve using HEC-RAS. Int J Adv Eng Res Dev 5(5):645–649
11. Ogras S, Onen F (2020) Flood analysis with Hec-RAS: a case study of Tigris river. Adv Civil Eng, Hindawi J 1:1–13
12. Pallavi H, Ravikumar AS (2021) Analysis of steady flow using HecRAS and GIS techniques. Int J Eng Technol 1(1):36–41
13. Patel AD, Patel DP, Prakash I (2016) Flood madeling using HecRAS and geo-informatics technologies in lower reaches of Shetrunji river, Gujarat, India. In: National conference on water resources and flood management with special reference to flood modeling, October 14–15. SVNIT, Surat, pp 1–11
14. Shahiriparsa A, Noori M, Heydari M, Rashidi M (2016) Floodplain zoning simulation by using Hec-Ras and CCHE2D models in the Sungai Maka River. Air, Soil Water Res J 9:55–62
15. Sun P, Wang S, Gan H, Liu B, Jha L (2017) Applications of HEC-RAS for flood forecasting in perched river—a case study of hilly region, China. In: IOP conference series: earth and environmental science. IOP publication, pp 1–7
16. Thol T, Kim L, Ly S, Heng S, Sun S (2016) Applications of HEC-RAS for a flood study of a river reach in Cambodia. In: Proceedings of 4th international young researchers workshop on river basin environment and management, pp 16–20
17. Traore VB, Soussou S, Sambou H, Diaw AT (2015) Steady flow simulation in Anambe river basin using HEC-RAS. Int J Dev Res 5(7): 4968–4979

Socio-Economic Impact Assessment of Dam Break: A Case Study of Hulu Perak Dams in Malaysia

Rohani Salleh, Lariyah Mohd Sidek, Rafidah Abdul Rashid, Hidayah Basri, Vicky Kumar, Siti Nooriza Abd Razak, Khalidah Khalid Ali, and Priyanka Singh

Abstract In Malaysia, embankment dams are frequently constructed because they benefit the local population, particularly in agricultural activities and flood control. However, flood disasters caused by dam breaks have catastrophic consequences on human lives and immensely damage the environment, infrastructure, and socio-economic stability, especially in downstream areas. Despite the rapid advancement of risk analysis in dam engineering, there is limited research on the socio-economic impact of dam failure. This paper is deemed to provide a critical review of the socio-economic risks affected by dam breaks in Hulu Perak district, Malaysia. The findings have highlighted the communities, key facilities, and heritage sites are at high risk

R. Salleh (✉) · R. Abdul Rashid · K. Khalid Ali
Department of Management and Humanities, Universiti Teknologi PETRONAS, Seri Iskandar, Malaysia
e-mail: rohanisalleh@utp.edu.my

R. Abdul Rashid
e-mail: rafidah_20002048@utp.edu.my

K. Khalid Ali
e-mail: khalidahkhalidali56@gmail.com

L. Mohd Sidek · H. Basri
Department of Civil Engineering, Universiti Tenaga Nasional, Kajang, Malaysia
e-mail: lariyah@uniten.edu.my

H. Basri
e-mail: bhidayah@uniten.edu.my

V. Kumar · S. N. Abd Razak
Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Seri Iskandar, Malaysia
e-mail: vicky_19000193@utp.edu.my

S. N. Abd Razak
e-mail: siti_0008995@utp.edu.my

P. Singh
Department of Civil Engineering, Faculty, Amity University Uttar Pradesh, Noida, India
e-mail: priyanka24978@gmail.com

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if there are dam breaks in the Hulu Perak district. İt is recommended that appropriate risk management measures be undertaken to reduce human catastrophy and negative socio-economic impacts. Hence, there is a need to conduct an empirical study to assess dam break threats to humans and the socio-economy and formulate a framework to mitigate the risks of flood disasters due to dam failures.

Keywords Dam break · Socio-economic impact · Flood · Perak · Malaysia

1 Introduction

Dams have long been acknowledged as a key infrastructure that has benefited mankind for centuries. Numerous studies revered that dams have been built for various purposes, accommodating daily human needs, for instance, domestic and industrial water supply, irrigation, aquaculture, hydropower, and recreation [1–4]. Besides, dams are pertinent components of economic, environmental and societal development from a single investment [5, 6]. Other than that, the key point to retain in constructing the dam is for water retention and flood mitigation to minimize risk to the local population in the downstream area and environment. Despite its benefits and being well-structured, dams worldwide are aging and will have reached the end of their intended lifespan as their design lifespan is only around 50–100 years [7, 8]. Besides, climate change, particularly unforeseen heavy rainfall and landslide, earthquake, and fault movements, can be the basis of dam breaks [9, 10]. There has been a growing interest in dam break studies, largely due to the catastrophic impacts of dam failures. While a dam failure immensely leads to fatal cases and loss of lives, it also causes devastating effects on the general environment and incurs high social and economic costs that must be borne by the community members, particularly those living in the downstream areas [11, 12]. The associated cost will increase if the breach parameters cannot be predicted with reasonable accuracy. Thus, any emergency and unusual events that occur at the dam could impose a huge risk on the downstream population. As a consequence, some researchers (e.g. [2, 13, 14]) were keen to investigate the effects of flash floods due to the dam break occurrence from social, economic, and environmental perspectives.

It is therefore pertinent to prudently identify conditions that could lead to the implementation of the necessary mitigative measures. With proper preparations through the implementation of an early flood warning system and emergency action plan, it is possible to obviate or at least reduce the loss of lives to a great extent, even in the case of a dam failure. For the purpose of emergency action planning, obtaining information about areas that would be inundated is a must. Nevertheless, studies that focus on assessing potential damages due to dam breaks from a socio-economic perspective are somewhat limited, especially in developing countries. Therefore, this study aims to assess the socio-economic impact of flooding due to dam breaks in Hulu Perak district, Perak State, Malaysia. Hence, the objective of the study is to quantify the extent of damage and displacement caused by floods and their immediate impact on the communities in residential areas, public infrastructures/facilities, and heritage/cultural sites.

2 Literature Review

2.1 Overview of Dam Break Incidents

Over many centuries, thousands of dams have been built worldwide. For example, China had over 98,000 dams in 2013, making it the country with the most dams in the world [15], followed by the United States and India. Due to high river flows, sea storm surges, and other factors, hundreds of dams have failed, and numerous dikes breach each year, frequently with disastrous results. According to previous dam failure risk assessments, the breaching risk and dam failure process could be predicted based on past dam failure events. Furthermore, such studies provide valuable insights into how to improve dam safety. There have been a number of incidents that occurred a long time ago, such as three dam failure cases in Italy: the Marib dam (Yemen) in A.D. 575, the earthen dam near Grenoble (France) in 1219, and the earthen dam near Grenoble (France) in 1923, 1935, and 1985 all caused the death of hundreds of people in the regions of Gleno, Molare, and Stava [16]. Around 200 people were killed in Mascara, Algeria, in 1881 by a dam known as "Fergoug I" [17]. Furthermore, The Banqiao Dam and the Shimantan Dam catastrophically failed in August 1975 in Henan Province, China, as a result of the overtopping brought about by torrential rains, making it by far the worst dam disaster in history. Flooding claimed the lives of about 85,000 people, and thousands more perished from subsequent epidemics and starvation. Millions of people also lost their homes [18]. Additionally, a high-tide storm in the Netherlands in February 1953 resulted in the highest recorded water levels and breached the dikes in over 450 locations, killing nearly 1,900 people and causing enormous economic damage [19]. In Indonesia, there have been two dam breaks in the past 10 years. The first instance happened in 2009 when the 1933-built Gintung Dam suddenly burst, releasing about 2 million cubic meters of water into its downstream region. In contrast, the second incident took place in 2013, when the Way Ela Dam, which had been naturally formed in 2012 as a result of the cliff landslide that blocked the main river, suddenly broke and released about 20 million cubic meters of water to its downstream area [20]. Although the reasons for each dam's failure are unique, data showed that overtopping, toe erosion, loss of storage contents, failure of the auxiliary structure, earthquake, foundation failure, and movement or cracking in the dam structure have been highlighted as the leading causes of dam failures [21].

2.2 The Implication of Dam Breaks

The goal of dam breaks social impact evaluation is to examine the effects of a dam break from a variety of macro factors. The main factors considered in this assessment are the number of casualties (including mortality cases), the political impact (i.e. how it may have a negative impact on the nation's and society's stability), the decline in living standards and quality of life, and the disappearance of irreparable cultural artifacts, priceless works of art, flora, and fauna. According to [22], social risk can be assessed through an index system, as depicted in Fig. 1. The social impact consists of people at risk, town level (i.e. community settlement), important facilities, agriculture, public facilities, cultural heritage, etc.

An earth-rock dam break has put people at risk. Generally, the larger the number of people at risk, the greater the risk of a dam break causing death and the greater the social impact. The town level is critical to the region's development and stability. In addition to important facilities, a number of social concerns also need to be addressed. A few examples of important facilities include transportation, power transmission, oil and gas pipelines, factories, mines, enterprises, and military facilities. Relics of culture, art treasures, and rare animals and plants are examples of cultural heritage. Social attention is paid to cultural heritage, but its monetary value is hard to estimate. Cultural heritage must be repaired when damaged.

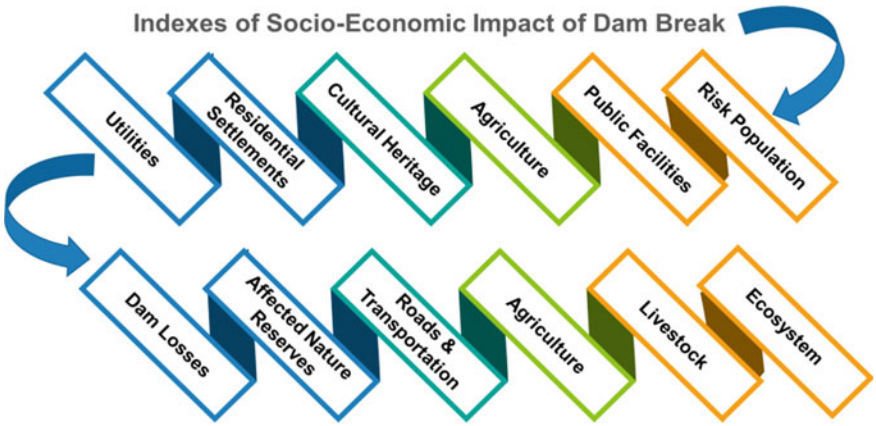


Fig. 1 Index system of the social impact of dam break

3 Methodology

3.1 Study Area

Perak is one of the 13 states of Malaysia and is located on the west coast of Peninsular Malaysia. The Perak River (Sungai Perak 4.040651° 100.858159°), approximately 400 km in length, is the second longest river in Peninsular Malaysia and serves as the main river that makes up most of the drainage system in Perak, which forms the backbone of socio-economic activities and development of Perak. It starts from the Hulu Perak district that borders Thailand and the State of Kelantan and ends at the Straits of Melaka in Bagan Datoh. These rivers have been primary sources of water supply for the state population. However, these rivers have also resulted in massive floods arising from excessive rainfalls.

3.2 Geographic Location and Dam Characteristics in Hulu Perak

There are three dams in the Hulu Perak district: Bersia, Kenering, and Temenggor. The Temenggor Dam is situated in Gerik, Perak, Malaysia. It is located on the Perak River, about 200 km northeast of Ipoh. Construction of the dam impounded Temenggor Lake. The power station is a hydroelectric power station, using four Hitachi turbines of 87 MW installed capacity, and the average annual energy generation is 900 million units. The Bersia Dam is the second dam in the Sungai Perak hydropower cascade system. It is located about 20 km away from the Temenggor Dam, at an elevation of 143 m above sea level. It is about 16 km East of Gerik, Sungai Perak, Perak. This infrastructure is of TYPE Hydro Power Plant with a design capacity of 72 MWe. Lastly, the third dam in the hydropower cascade system is the Kenering Dam, located about 45 km downstream of the Bersia Dam. It is situated 110m above sea level. Figures 2, 3, and 4 show the study area location and a zoomed view of the dams.

Fig. 2 Temenggor Dam in Hulu Perak (5.406234° 101.300704°) *Source* Google EarthPro

Fig. 3 Bersia Dam in Hulu Perak (5.429616° 101.208815°) *Source* Google EarthPro

Fig. 4 Kenering Dam in Hulu Perak (5.215335° 101.097910°) *Source* Google EarthPro

4 Findings and Discussion

4.1 Risk Assessment on the Social Impacts of Dam Break

Hulu Perak has a total population of 89,926, Gerik has a population of 29,391, the highest among the sub-districts, followed by Pengkalan Hulu, with a population of 16,150 people. In terms of gender, it was observed that a higher number of male population than females in respective sub-districts of Hulu Perak is indicated in Fig. 5. A mix of ethnic groups represents the Hulu Perak community. Besides Malays, Chinese, Indians and non-citizens, there are 11,271 indigenous people (Orang Asli) in Hulu Perak, who make up 13% of the total population in this district (Figs. 6 and 7).

Hulu Perak is one of the most populated districts in Perak state and contains three dams. It can be seen topographically that the series of dams are interconnected with sub-districts within Hulu Perak. According to each sub-district, Tables 1, 2, and 3 present the main public facilities, which are promptly used by local communities. Similarly, Tables 4 and 5 show the public utilities and infrastructure, such as transportation, which is an important means of import and export. Such places with dense populations at high risk can be affected due to dam break/failure.

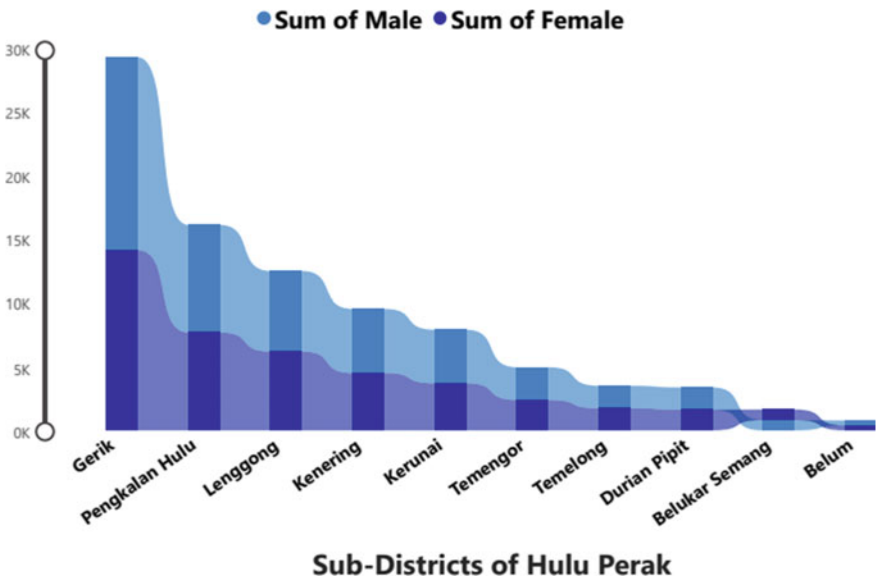
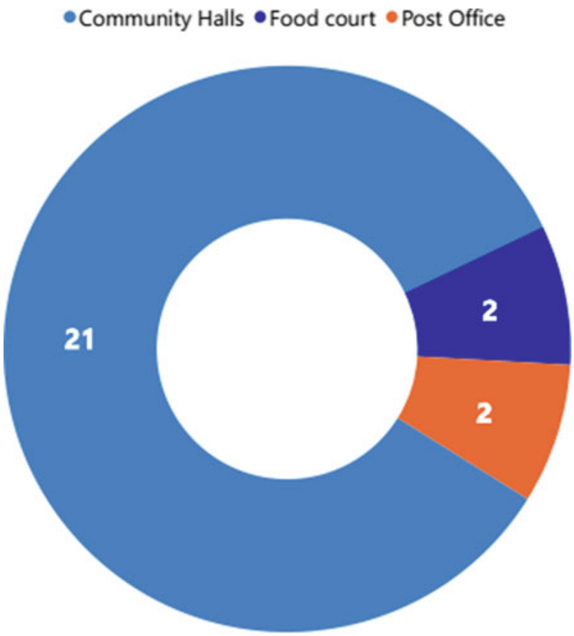


Fig. 5 Hulu Perak sub-districts population

Fig. 6 Total Public facilities in sub-districts in Hulu Perak



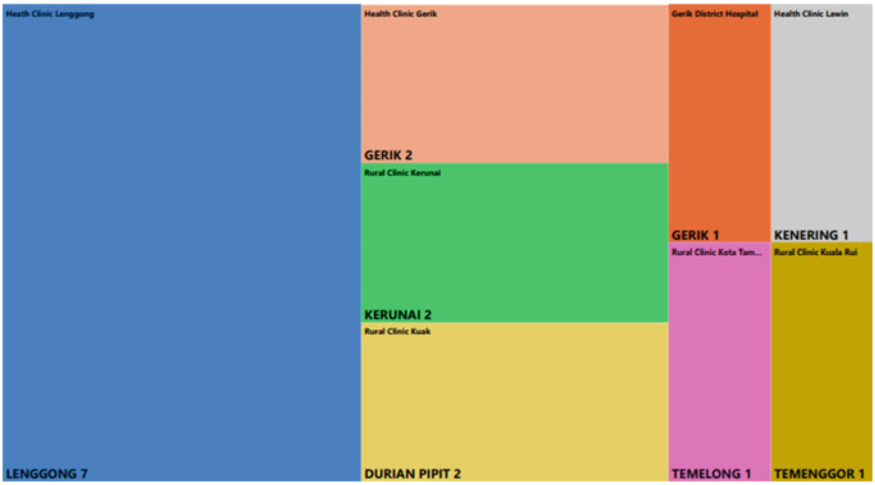


Fig. 7 Health facilities in sub-districts in Hulu Perak

4.2 Cultural Sites

Tourism-attractive places and resources in the district of Hulu Perak are divided into two main categories: natural and artificial attractions. The main tourism products

Table 1 Main public facilities in sub-districts in Hulu Perak

Public facility	Details	Total	Sub-district
Community Hall	Community hall Kota tampan air Pavillion Taman Kota Tampan Multi-purpose Hall Kota Tampan Community service center Kampung Luat	4	Temelong
	Merdeka hall Lenggong	1	Lenggong
	Community hall Kampung Kuak	1	Durian Pipit
	District community Hall Lawin Community hall Kg. Air Jeda Aman Jaya square Lawin	3	Kenering
	Community hall Bandariang UMNO Community hall Kg. Bersia Baru Public hall Kuala Kenderong Public hall Kg. Padang	4	Temenggor
	Community hall Kg. Jong Multi-purpose Kg. Pahit Tgh Community hall Kg. Pahat	4	Kerunai
	Multi-purpose Majlis Daerah Gerik Multi-purpose Gerik Community hall Kg. Gerik	4	Gerik
	Total	**21**	
Post Office	Post office Lenggong	1	Lenggong
	Mini post office Lawin	1	Kenering
	Total	**2**	
Food court	Pavillion Lenggong	1	Lenggong
	Pavillion Tasik Raban	1	Kenering
	Total	**2**	

in Hulu Perak District include eco-tourism and historical heritage tourism. Each sub-district presents tourism activities and categories as shown in Tables 6, 7 and Fig. 8.

4.3 Economic Impacts of Dam Breaks

Research on the economic activities of each district in Perak is obtained from official government documents. The analysis of these secondary documents is important to

Table 2 Health facilities in sub-district in Hulu Perak

Health facilities	Location	Total	Sub-district
Clinic	Rural clinic Kota Tampan	1	Temelong
	Heath clinic Lenggong Rural clinic Kg. Chepor Dental clinic Lenggong Rural clinic Kg. Gelok Rural clinic Kg. Sumpitan Clinic Ok Ong Polyclinic Dr. Azhar	7	Lenggong
	Rural clinic Kuak Rural clinic Kg. Beng	2	Durian pipit
	Health clinic Lawin	1	Kenering
	Rural clinic Kuala Rui	1	Temenggor
	Rural clinic Kerunai Health clinic Plang	2	Kerunai
	Health clinic Gerik Health clinic Ibu Dan Anak Gerik	2	Gerik
Government hospital	Gerik district hospital	1	
	Total	**17**	

deepen and understand the strength and main focus of the district. The documents referred to include materials from the official website of the NCER Strategic Development Plan 2021–2025 and the Perak State Structure Plan 2040. Referring to the table below (Table 8), in 2012, agriculture, being the main economic activity in Hulu Perak, contributed 45.42% of gross domestic product (GDP), followed by industry/mining (38.77 % of GDP), business, and services (15.81% of GDP).

The main economic activities in Hulu Perak are eco-tourism, tin mining, and agriculture, focusing on plantation/crops (mainly rubber, oil palm and paddy), livestock farming, and fisheries. Indeed, these income-generating activities will be directly affected during flash floods and dam break incidents. Such uncalled hazards will affect the socio-economic of the living communities with loss of income, employment, shelter, and personal belongings. Hence, to reduce the damage and negative impacts, it is critical for mitigative measures to be identified as alerts to the living communities for their survival and socio-economic sustainability.

Table 3 Public authorities in sub-districts in Hulu Perak

Public authorities	Location	Sub-district
Mosque	Mosque Al Aliah Kg. Cha Ain Mosque Kota Tampan Mosque Warisan Kg. Temelong	Temelong
Police station	Lenggong police station	Lenggong
Government offices	Magistrate court Lenggong district office Lenggong district council Co-operative development department Lenggong chief office Lenggong RISDA office LPP quarters Lenggong national registration department Puskep mara (student leadership center) Lenggong Farmers organization office	Lenggong
Government offices	Durian Pipit chief district office	Durian Pipit
Police station	Kuak police station	
Police station	Lawin police station	Kenering
Police station	Gerik district police headquarters Police station Kg. Lalang	Kerunai
Fire station	Gerik fire station	
Government offices	Bandariang forest ranger office Teacher quarters Bersia	Temenggor
Police station	Police station Bersia	
Government offices	Hulu Perak veterinary office Department of indigenous affairs Department of work (JKR) Gerik Road Transport Office (JPJ) Office Gerik Bn303 Gerik military camp Lembaga Air (Water) Perak Gerik Gerik magistrate court Gerik Shariah lower court Gerik district council Gerik religious office Youth and sports office Hulu Perak district and land office Tawai felda office Gerik forest office Gerik social welfare office Gerik KWSP office District education offices Gerik agriculture office Hulu Perak district RISDA office	GERIK

Table 4 Utility facilities in sub-districts in Hulu Perak

Utility facilities	Location	Total	Sub-district
Gas station	Caltex Lenggong BHP Lenggong PETRONAS Lenggong	3	Lenggong
	Shell	1	Kenering
	Petron Bandariang Shell Bandariang BHP Desa Baiduri Buraq oil Simpang Perah Buraq oil Bersia Lama Oil Felda Bersia	6	Temenggor
	Shell Gerik Petron Gerik	2	Gerik
Water treatment plant	Water treatment plant	1	Kenering
Water supply	Water pump house	1	
Electric infrastructure	Power generation sultan Azlan Shah Kenering Hydro power dam Kenering	2	
Water supply	Metrological Kuala Kenderong	1	Temenggor
Electric infrastructure	Power generation Temenggor PMU Temenggor	2	

Table 5 Transportation infrastructure in Hulu Perak

Transportation infrastructure	Location	TOTAL	Sub-district
Bus station	Lenggong bus terminal	1	Lenggong
	Gerik bus station	1	Gerik
	Total	**2**	
Bridge	Raja Muda Nazrin bridge	1	Durian Pipit
	Belum Baru bridge	1	Kenering
	Total	**2**	
Jetty	Trojan Tnb Jetty	1	Temenggor
	Kg. Air Ganda Jetty	1	
	Total	**2**	
Airport	Gerik Military airport	1	Gerik
	Total	**1**	

Table 6 Sub-district and main focus of tourism activity

Sub-district	Sector/activity
Pengkalan Hulu	Mining heritage
Gerik	Natural heritage
Lenggong	World historical heritage

Table 7 List of categories and tourism places in sub-districts in Hulu Perak

Category	Type of products	Number of products		
		Pengkalan Hulu	Gerik	Lenggong
Natural attractions	Eco-tourism	4	18	4
Man-made	Sports and recreation	1	–	1
	Historical heritage	4	2	1
	Cultural heritage	1	–	1
	Shopping	1	1	–
	mining heritage	1	–	-
	Agro tourism	–	–	2
	Homestay	–	–	1
	Total	**12**	**21**	**10**

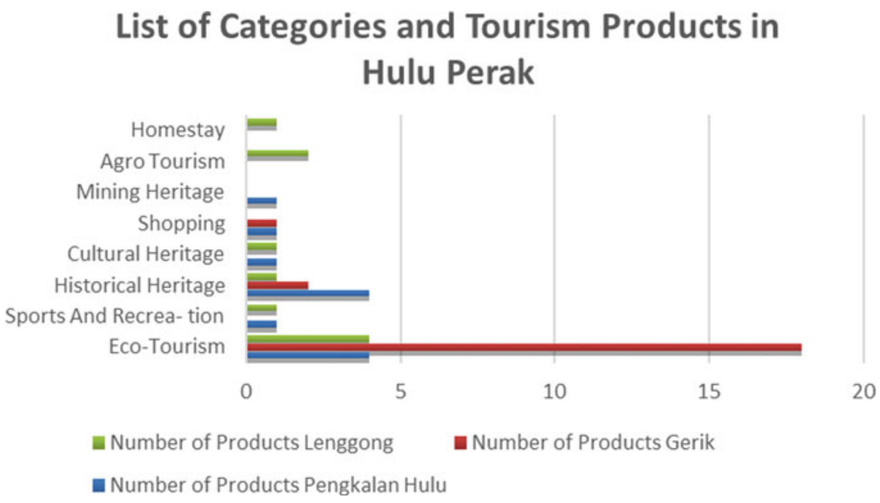


Fig. 8 Total number of tourism products in sub-districts in Hulu Perak

Table 8 Hulu Perak's GDP contribution

Type of land use	Hulu Perak district		Perak state	
	Estimated GDP (RM)	Percentage (%)	Estimated GDP (RM)	Percentage (%)
Industry/ mining	483.33	38.77	6,831.97	17.51
Business and services	197.11	15.81	26,425.00	67.71
Agricultural	566.18	45.42	5,770.00	14.78
Total	1,246.62	100.00	39,026.97	100.00

5 Conclusion

Hulu Perak is located in one of the districts with significant contributions to socio-economic activities, especially in eco-tourism and forest activities by indigenous communities. Temenggor, Bersia, and Kenering dams are located in Hulu Perak and the confluence with the joined river Sungai Perak. Hulu Perak has been identified as one of the districts with a frequent record of flood disasters. It recorded 11 cases of flood in 2020, mainly due to flash floods that happened because of heavy rain. Hence, this district has been identified as a high-risk area in Perak. Previous flood disaster, as reported, shows the failure to notify the communities with sufficient preparation and evacuation. Therefore, the impact of the occurrence of the flood might cause heavy damage to the socio-economy of Hulu Perak.

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References

1. Hood K, Perez RA, Cieplinski HE, Hromadka TV, Moglen GE, McInvale HD (2019) Development of an earthen dam break database. JAWRA J Am Water Resour Assoc 55(1):89–101
2. Mao J, Wang S, Ni J, Xi C, Wang J (2017) Management system for dam-break hazard mapping in a complex basin environment. ISPRS Int J Geo- Inf 6(6):162
3. Shahrim MF, Ros FC (2020) Dam break analysis of Temenggor dam using hecras. In: IOP conference series: earth and environmental science, vol 479, no 1, p 012041. IOP Publishing
4. Lariyah MS, Faizah CR, Mohd Noh A, Rahsidi SM, Azwin Zailti AR, Intan Shafilah AA, Development of Probable Maximum Flood (PMF) for Sultan Abu Bakar Dam
5. Sidek LM, Ros FC, Aziz NHA (2011) Numerical modelling of dam failure for hydropower development in Cameron Highlands–Batang Padang Scheme, Pahang Malaysia. In: Student

conference on research and development. Author H., A Book New York Publisher, Year (pp. 1–200). Foster, I., Kesselman, C.: The grid: blueprint for a new computing infrastructure. Morgan Kaufmann, San Francisco (1999)
6. International Commission of Large Dams, ICOLD (2011) "Role ofDams" www. Icold- cigb.net
7. Ho M, Lall U, Allaire M, Devineni N, Kwon HH, Pal I, Raff D, Wegner D (2017) The future role of dams in the United States of America. Water Resour Res 53(2): 982–998
8. Perera D, North T (2021) The socio-economic impacts of aged-dam removal: a review. J Geosci Environ Protect 9(10):62–78
9. Gaagai A, Aouissi HA, Krauklis AE, Burlakovs J, Athamena A, Zekker I, Benaabidate L, Chenchouni H (2022) Modeling and risk analysis of dam-break flooding in a semi-arid montane watershed: a case study of the Yabous Dam, Northeastern Algeria. Water 14(5): 767
10. Tavus B, Kocaman S, Gokceoglu C (2021) Assessment of flooded areas caused by a dam break (Sardoba dam, Uzbekistan). The Int Archiv Photogrammetry, Remote Sens Spatial Inf Sci 43:291–297
11. Kumar S, Jaswal A, Pandey A, Sharma N (2017) Literature review of dam break studies and inundation mapping using hydraulic models and GIS. Int Res J Eng Technol 4(5):55–61
12. Muda RS, Khidzir ABM, Amin MFM (2021) Dam break flood mapping analysis and impact assessment. In: Water management and sustainability in Asia. Emerald publishing limited.
13. Glotov VE, Chlachula J, Glotova LP, Little E (2018) Causes and environmental impact of the gold-tailings dam failure at Karamken, the Russian Far East. Eng Geol 245:236–247
14. Shabu T, Musa SD (2015) Downstream socio-economic impact of dam failure: a case study of 2012 river flooding in Benue State, Nigeria. J Environ Issues Agric Dev Countries 7(3):19
15. Ge W, Li Z, Liang RY, Li W, Cai Y (2017) Methodology for establishing risk criteria for dams in developing countries, case study of China. Water Resour Manage 31(13):4063–4074
16. Luino F, Tosatti G, Bonaria V (2014) Dam failures in the 20th century: nearly 1000 avoidable victims in Italy alone. J Environ Sci Eng 3(1):19–31
17. Gaagai A, Boudoukha A, Benaabidate L (2020) Failure simulation of Babar dam—Algeria and its impact on the valley downstream section. J Water Land Dev
18. Qing D, Thibodeau JG, Williams MR, Dai Q, Yi M, Topping AR (2016) The river dragon has come!: three gorges dam and the fate of China's Yangtze river and its people: three gorges dam and the fate of China's Yangtze river and its people. Routledge
19. Gerritsen H (2005) What happened in 1953? The big flood in the Netherlands in retrospect. Philos Trans Royal Soc A: Math, Phys Eng Sci 363(1831):1271–1291
20. Yudianto D, Ginting BM, Sanjaya S, Rusli SR, Wicaksono A (2021) A framework of dam-break hazard risk mapping for a data-sparse region in Indonesia. ISPRS Int J Geo Inf 10(3):110
21. Chen SS, Zhong QM, Shen GZ (2019) Numerical modeling of earthen dam breach due to piping failure. Water Sci Eng 12(3):169–178
22. Gu H, Fu X, Zhu Y, Chen Y, Huang L (2020) Analysis of social and environmental impact of earth-rock dam breaks based on a fuzzy comprehensive evaluation method. Sustainability 12(15):6239

Study of the Conjunctive Water Use: A Case Study of Kankai Irrigation System, Jhapa, Nepal

Krishna Sedai, Debi Prasad Bhattarai, Jawed Alam, and Bhola Nath Sharma Ghimire

Abstract More canal water is provided to farmers in the head end reaches of the canal. Consecutively, the farmers at the tail end have to pump more groundwater due to insufficient irrigation canal supply. As a result, it causes over exploitation of groundwater assets. If coordinated use of surface water and groundwater supplies is done in a planned way, then water demands for the crops can meet which ultimately increases water supply reliability. This research study focuses on enhancing irrigation water distribution by simultaneously using surface water and groundwater. Kankai Irrigation System having a command area of 7000 hectares (ha) of agricultural land in Jhapa district of Nepal is selected as the study area. Our main focus is on the tail end of the main canal at the command region of the secondary canals S_{19}, S_{20} and S_{21} having a total area of 500 ha. The optimal plan for allotting canal water and groundwater was achieved using the LINDO 6.1 optimizing software. LINDO input model has been developed for allocation of water on existing and proposed cropping patterns. After extensive study on the different cases, the optimal plan giving maximum net benefits of NPR 9612 million, utilization of surface water and groundwater 266.15 ha-m and 152.67 ha-m respectively whereas the optimal of land use 95% monsoon rice for monsoon season, 40% wheat +20% green beans +20% pulses +15% tomatoes for winter season and 95% spring rice for spring season is suggested to be adopted and implemented for the study area.

Keywords Allocation of water · LINDO · Net benefits · Optimization · Cropping pattern

K. Sedai (✉) · J. Alam
Department of Agricultural Engineering, Purwanchal Campus, Institute of Engineering, Tribhuvan University, Dharan, Nepal
e-mail: sedai.krishna@ioepc.edu.np

D. P. Bhattarai · B. N. S. Ghimire
Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Lalitpur, Nepal

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1 Introduction

The joint utilization of groundwater and surface water resources is crucial. Individual water supplies could not be sufficient for a long period of time or in a particular location to fulfill all irrigation requirements [1, 2]. Compared to separately managed groundwater and surface water systems, a properly managed conjunctive use system will produce more water [3]. For both head and tail reach command region, optimization model will establish several operational policies for maximization of benefits. These types of researches on water allocation options are inadequate in Nepal [4]. Combined use of Surface water and groundwater irrigation in a planned manner is relatively a recent technique in Nepal [5]. Operation of both surface water and groundwater sources provides for greater Water Conservation. Groundwater storage can provide for water requirements of the crops during a series of dry years [6]. Simulation–Optimization for joint management of water resources was conducted in the Kushabhadra-Bhargavi river delta in eastern India. According to the optimization results, especially during the non-monsoon season by reducing agricultural rice farming and boosting crop diversification will boost farmer livelihoods and promote the sustainable use of water resources [7]. Likewise, sustainable conjunctive water management in irrigated agriculture in Yaqui Valley, Mexico was conducted in the year 2006. The main conclusions of the study were that fluctuations in the prices of crops and production costs, as well as water availability, affect agricultural profit in the Yaqui Valley [8]. Similarly, the research was carried out on the joint use of surface and groundwater resources for reliable water management in Varada river basin in southern India. The researchers came to the conclusion that in order to fulfill the basin's water needs and avoid groundwater mining in the study region, it is essential to provide canal water [9]. Paudyal and Gupta (1990) performed Irrigation planning by multilevel optimization in Tinao River Basin, Nepal. They found that considering the most critical year, the water distribution strategy for best cropping pattern suggests that the net yearly return will be significantly lowered i.e. NPR.160 million (M). Likewise, [10] performed assessment of combined use of canal water and groundwater in Sapon Irrigation System, Indonesia. In this study, conjunctive use model was solved for current cropping practices under the present circumstances and then different scenarios were developed for suggested cropping patterns. The findings demonstrate the viability and simplicity of conjunctive usage alternatives, which would increase the overall incomes from the cropping conditions. Similar to this, [11] carried out an optimal distribution of water for an irrigation in Pingtung county, Taiwan. The simulation's results show that the water requirements for crops in the region can be satisfied by the area's current agricultural practices through combined use of surface water and groundwater.

2 Materials and Methods

2.1 Study Area

For most of the irrigation system in Nepal, irregular irrigation supplies, ineffective water management, and lack of awareness of how the water should be managed and utilized is the major concern. This research study focuses on improving irrigation water allocation by judiciously using surface water and groundwater. Hereby minor attempt has been made as a case study in the Kankai Irrigation System (KIS) in Jhapa, Nepal to determine how to resolve present issues by placing an emphasis on the study of conjunctive water use. KIS having a command area of 7000 ha of agricultural land in Jhapa district of Nepal is selected as the study area. The water source of KIS is the Kankai river, a perennially flowing river having a catchment area of 1190 km^2. The command area is located in the flat land of the terai of Nepal having mildly slope from north to south. Generally, crops are planted in monsoon, winter and spring seasons. Our main focus is on the tail reach end of the main canal at the command area of the secondary canals S_{19}, S_{20} and S_{21}. The total block area is 500 ha for the case study purpose. The map of Nepal with Jhapa district and command area of KIS along with tail reach command area is illustrated in Fig. 1.

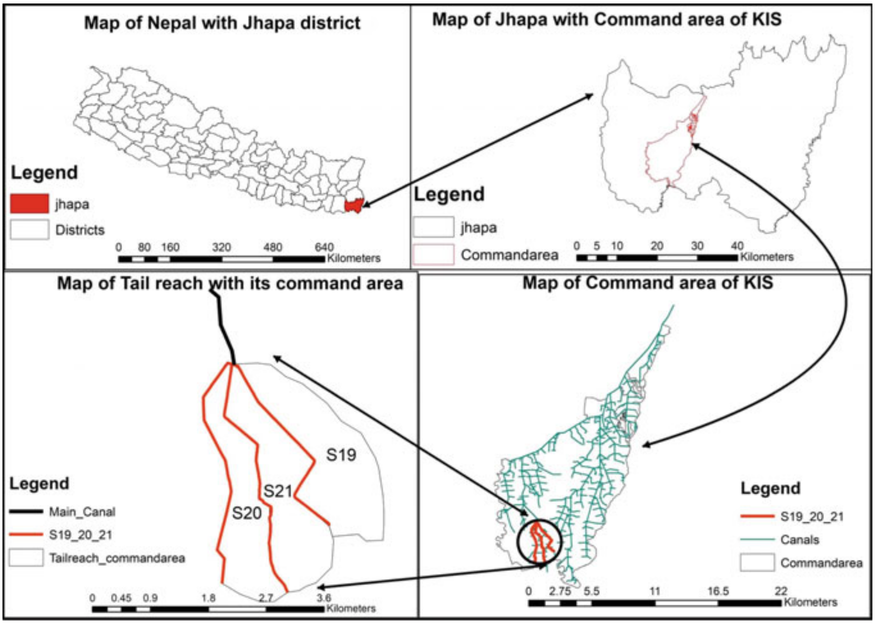

Fig. 1 Research area map of the tail reach command area

2.2 Data Collection

The data on canal, groundwater, crop, weather, soil, water charges, cost and benefit parameters were obtained from numerous sources like governmental agencies, international organizations, local organizations, local farmers, literature review, and from personal contact, such as Department of Hydrology and Meteorology (DHM), Kankai Irrigation Management Office, Ground Water Resource Development Board (GWRDB), Agriculture Knowledge Center, Food and Agriculture Organization (FAO), Water User Associations (WUAs), etc.

2.3 Soil Characteristics

The soil data of the study area required for analysis of this study is obtained from FAO Irrigation and Drainage Engineering paper number 56 and soil map which is obtained from the soil grids of the year 2017. The soil type of Kankai command area was determined using ArcGIS. It was found that Kankai command area is covered by loamy, sandy clayey loamy and sandy loamy soil.

2.4 Climate and Rainfall

The average monthly highest temperature and average monthly lowest temperature of the study area are 33.46 °C and 8.29 °C respectively. The minimum and maximum relative humidity is 54.9% and 82.73% respectively. Rainfall is most abundant during the monsoon season i.e. in the period of June to October. The average annual rainfall in the area from 1990–1999, 2000–2009 and 2010–2019 is 2848.55 mm, 2398.67 mm and 2462.99 mm respectively.

2.5 Existing and Proposed Cropping Pattern

The existing cropping scenario of the study area is mainly paddy crop oriented. The paddy is planted twice a year in monsoon and spring seasons whereas mustard and maize are planted in winter season in less quantity by some farmers in the study area. The proposed cropping pattern will be suggested based on the food requirement, suitability of the soil for cultivation, present practices on nearby zones, restrictions on the availability of resources and socio-economic features of the command area.

As far as there, 85–90% of the total command area is cultivated by paddy as socio-economic prospectus of the farmers. Hence, we can have the following proposed cropping pattern in the study area: monsoon rice in monsoon season, wheat/ mustard/ maize/ potato/ pulses/ green beans/ cauliflower/ tomato/ small vegetables in winter season and spring rice in spring season.

2.6 Surface Water Availability

The Kankai river is the primary source of surface water (SW) for canal irrigation system in its command zone. There are altogether 21 secondary canals branched from the main canal. The water at the tail reach (reach V) i.e. S_{19}, S_{20} and S_{21} of the KIS shall run from the start of May to the end of November at full supply discharge of design capacity. Thereafter, from December to April i.e. in the main dry season of the year, there is no water in the canal. Similarly, the canal shall not have water in the spring season as well in the succeeding year if it has delivered water in the preceding year due to the provision of the KIS office to deliver water to the alternate region of the reach V because of scarcity of water. The detail regarding the monthly canal head discharge available is given in Table 1. The lowest discharge available among the three canals has been used in the optimization model as a restriction for SW availability.

Table 1 Monthly Canal head discharge

S. no.	Period	Water available at canal head (ha-m)		
		S_{19}	S_{20}	S_{21}
i	Jan	0	0	0
ii	Feb	0	0	0
iii	Mar	0	0	0
iv	Apr	0	0	0
v	May	50	57	51
vi	Jun	50	57	51
vii	Jul	50	57	51
viii	Aug	50	57	51
ix	Sep	50	57	51
x	Oct	50	57	51
xi	Nov	50	57	51
Xii	Dec	0	0	0

2.7 Groundwater Availability

The monthly static water level data that are recorded by the GWRDB, Biratnagar, Morang, Nepal office have been used to observe the mean groundwater (GW) level trend from the year 2005 to 2013. The water table in the month of May is taken as pre-monsoon water table (WT) levels. Similarly, the WT in the month of September is taken as post-monsoon WT levels. Pre-monsoon and post-monsoon depth of WT are used for the recharge calculation of the research area. Changes in groundwater table level and specific yield data are used for the recharge calculation. Shallow cavity tube wells are applicable over the whole research area as per the investigation carried out on the shallow tube wells by UNDP/GWRDB in the year 1987–1992. The average value of the specific yield is taken as 0.15 for terai region [12]. The GW recharge in the study area is found to be 1.527 cubic million meters. This available GW can safely be adopted as this is the safe yield for pumping purposes.

2.8 Crop Water Requirements (CWR) for Different Crops

One of the fundamental criteria for crop planning in a command region is the evaluation of the water requirements for various crops, which plays a significant role in crop selection. Using FAO recommendations for the optimal amount of crop production, the CWR for the study area was estimated from CROPWAT 8.0. Table 2 lists the various crops' monthly water needs in meters for each crop.

2.9 Water Charges

The development and operation of surface water from canal with operation and maintenance (O and M) charges are computed as 10,382.34 NPR/ha-m. Similarly, groundwater pumping cost including O and M charges is computed as 5496 NPR/ha-m.

2.10 Cost and Benefits Considerations

Considering the agricultural input and crop productivity in the research area, net returns to the farmers per hectare (given in Table 3) from various crops are computed. The mean grain yield data of the three fiscal years viz. 2074/75, 2075/76 and 2076/77 B.S (Bikram Sambat) from the Agriculture Knowledge Center, Jhapa, Nepal has been used.

Table 2 CWR of various crops in meters (m)

S. no.	Crops	Months												Total
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
A	Monsoon season													
1	Rice	–	–	–	–	–	0.234	0.352	0.404	0.344	0.267	–	–	1.601
B	Winter season													
1	Wheat	0.190	0.178	0.045	–	–	–	–	–	–	–	0.066	0.127	0.606
2	Mustard	0.170	0.224	0.307	0.092	–	–	–	–	–	0.011	0.094	0.140	1.038
3	Maize	0.197	0.165	0.023	–	–	–	–	–	–	–	0.074	0.163	0.623
4	Potato	0.191	0.199	0.083	–	–	–	–	–	–	–	0.112	0.163	0.747
5	Pulses	0.191	0.085	–	–	–	–	–	–	–	–	0.096	0.173	0.545
6	Green beans	0.164	–	–	–	–	–	–	–	–	–	0.116	0.164	0.443
7	Cauliflower	0.153	0.198	0.334	0.179	–	–	–	–	–	–	0.155	0.133	1.151
8	Tomato	0.188	0.217	0.245	–	–	–	–	–	–	–	0.133	0.144	0.926
9	Small vegetables	0.172	0.023	–	–	–	–	–	–	–	–	0.158	0.173	0.526
C	Spring season													
1	Spring rice	0.116	0.212	0.371	0.437	0.434	–	–	–	–	–	–	–	1.569

Table 3 Net returns per ha of various crops

S. no.	Crops	Yield of grains (mt/ha)	Unit market price (NPR/mt)	Total earnings (NPR/ha)	Production cost (NPR/ha)	Net returns (NPR/ha)
1	Monsoon rice	4.6	27,500	126,500	65,678	60,823
2	Wheat	3	28,000	84,000	55,624	28,376
3	Mustard	1.3	95,000	123,500	43,890	79,610
4	Maize	6.5	18,000	117,000	52,553	64,448
5	Potato	15.3	15,000	229,500	140,595	88,905
6	Pulses	1.5	80,000	120,000	37,317	82,683
7	Green beans	5.8	30,000	174,000	73,448	100,553
8	Cauliflower	19	15,000	285,000	37,317	247,683
9	Tomato	20.8	30,000	624,000	71,308	552,692
v	Small Vegetables	14	15,000	210,000	50,190	159,810
11	Spring rice	5.2	22,000	114,400	65,678	48,723

2.10.1 Research Design

The crop water requirements for various crops in the study area are computed by CROPWAT 8.0 using the FAO guidelines for the optimum level of crop production. The discharge at the head of respective canals and groundwater extraction in the research area are evaluated considering SW and GW availability. Then, a simple optimization input conjunctive use model is created to investigate the potential joint use of SW and GW using linear programming. The objective function is limited to a variety of hydrological and management constraints. The LINDO 6.1 optimizing software is used to create the best SW and GW allocation plan. Finally, the best cropping arrangement for the best use of water resources is obtained maximizing the net returns from the crop production. Detail flowchart of the research design is given in Fig. 2.

2.10.2 Conjunctive Use Model

The formulation of objective function for maximizing the net returns generated from the crop production in the research area was done. Considering the three components viz. net benefits from cropping activity, surface water charge and groundwater charge, the objective function can be expressed as:

$$\text{MaxZ} = \sum_{p=1}^{nz}\sum_{q=1}^{nc} A_q XNB_q - \sum_{p=1}^{nz}\sum_{r=1}^{12} SWCXSW_r - \sum_{p=1}^{nz}\sum_{r=1}^{12} GWCXGW_r \quad (1)$$

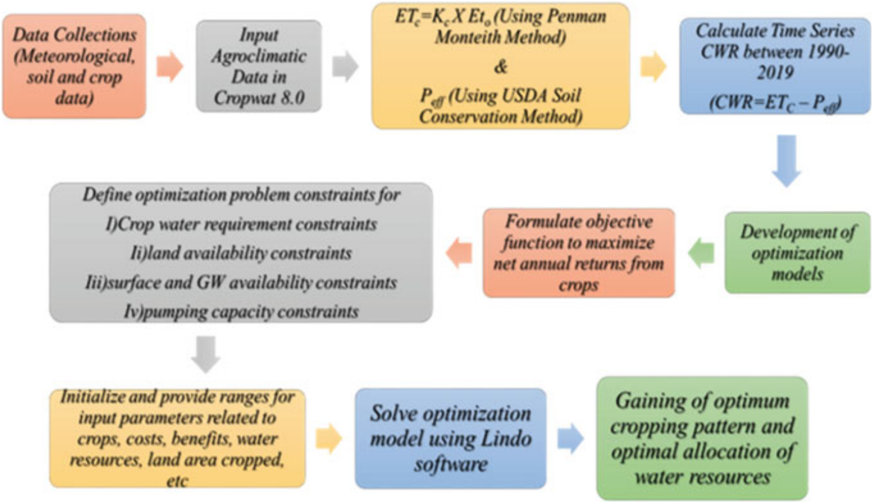

Fig. 2 Flowchart of research design

where,

nz = Number of zones,

nc = Number of crops,

A_{pq} = Area of qth crop for pth zone (ha),

NB_q = Net benefits for qth crop excluding irrigation water charges (NPR),

SWC_p = Surface water charge for pth zone (NPR/ha-m),

SW_{pr} = Surface water allocation for pth zone during rth time interval (ha-m),

GWC_i = Groundwater charge for pth zone (NPR/ha-m),

GW_{pr} = Groundwater allocation for pth zone during rth time interval (ha-m).

This objective function, Eq. (1) is subjected to a number of restrictions, including restrictions on agricultural water needs, restrictions on surface water availability, restrictions on groundwater availability, restrictions on area availability and restrictions on crop area.

3 Results and Discussions

Different cases for conjunctive use planning have been investigated using the conjunctive use model. The following cases have been investigated in the present study: Cropping patterns that are now in practice and proposed cropping patterns with four scenarios for joint utilization of surface water and groundwater.

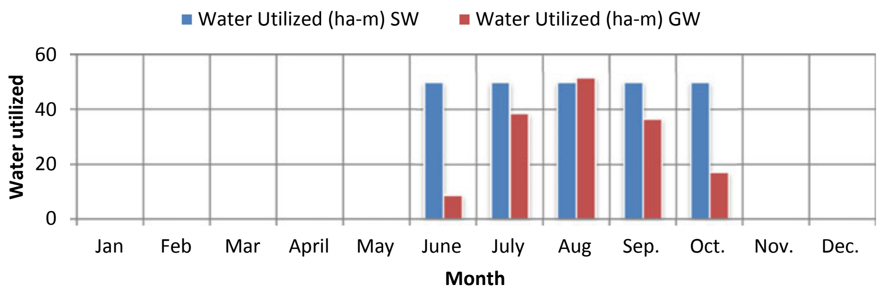

Fig. 3 Optimal water use for current cropping pattern

3.1 Existing Cropping Pattern

This case was taken up to determine the most favorable cropping pattern in the study area, if surface water is available in monsoon season and groundwater supply is available in winter and spring seasons as prevailed in the study area. In this trial run, no crops area constraint was considered. The objective function value is NPR 6574 million and SW and GW utilization are 250 ha-m and 152.66 ha-m respectively. Whereas optimal cropping pattern is found to be paddy only in the monsoon season. Details of water allocation are provided in Fig. 3.

3.2 Proposed Cropping Pattern

Various cases on the suggested cropping strategy were developed and tested on the model considering the existing practices and conditions, market prices of crops, productivity of crops, cropping intensity of the whole KIS system, etc. Here, the model was run for different percentages of crops mainly in the winter season.

Case I: **Proposed cropping pattern 95% rice in monsoon season, 40% wheat + 40% mustard + 15% maize in winter season and 95% spring rice in spring season.** The objective function value is NPR 7403 million and SW and GW utilization are 273.15 ha-m and 152.67 ha-m respectively. Whereas optimal cropping pattern is found to be monsoon rice–spring rice. Details for this case are provided in Fig. 4.

Case II: **Proposed cropping pattern 95% rice in monsoon season, 40% mustard + 20% potato + 20% pulses + 15% small vegetables in winter season and 95% spring rice in spring season.** The objective function value is NPR 7740 million and SW and GW utilization are 274.46 ha-m and 152.66 ha-m respectively. Whereas optimal cropping pattern is found to be monsoon rice—small vegetables-spring rice. The monthly optimal allocation of SW and GW for this case is in Fig. 5.

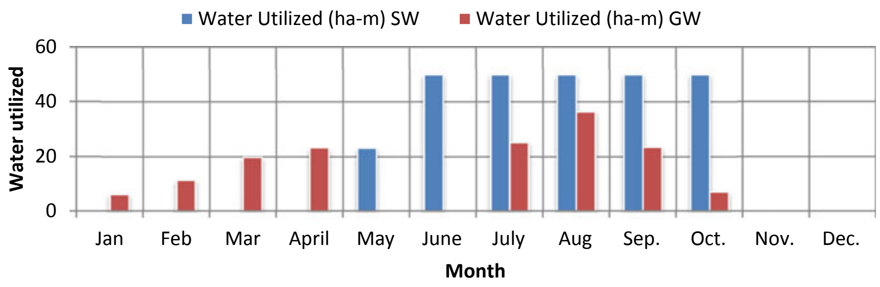

Fig. 4 Optimal water allocation for proposed cropping pattern case I

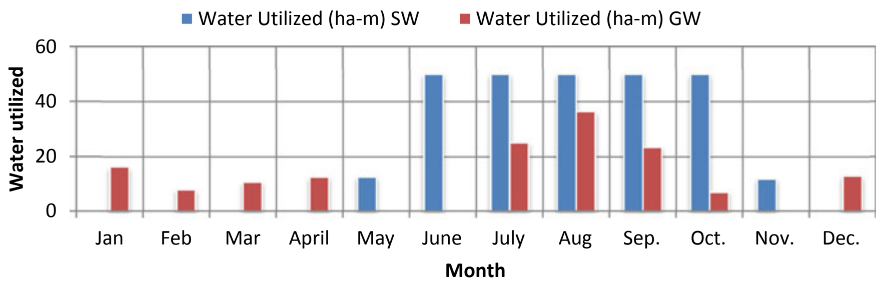

Fig. 5 Optimal water allocation for proposed cropping pattern case II

Case III: **Proposed cropping pattern 95% rice in monsoon season, 40% wheat + 20% green beans + 20% pulses + 15% tomatoes in winter season and 95% spring rice in spring season.** The objective function value is NPR. 9612 million and SW and GW utilization are 266.15 ha-m and 152.67 ha-m respectively. Whereas optimal cropping pattern is found to be monsoon rice—green beans- tomatoes. The overall results of this run are given in Fig. 6.

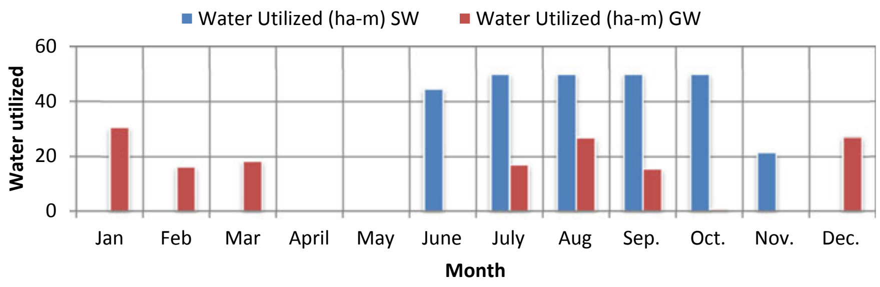

Fig. 6 Optimal water allocation for proposed cropping pattern case III

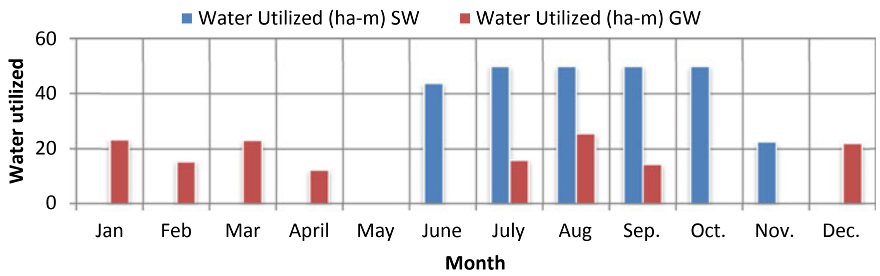

Fig. 7 Optimal water allocation for proposed cropping pattern case IV

Case IV: **Proposed cropping pattern 95% rice in monsoon season, 20% mustard + 20% potato + 20% pulses + 20% cauliflower + 15% small vegetables in winter season and 95% spring rice in spring season.** The objective function value is NPR 8321 million and SW and GW utilization are 266.41 ha-m and 152.65 ha-m respectively. Whereas optimal cropping pattern is found to be monsoon rice—cauliflower—small vegetables. Results on water allocation for this case IV of proposed cropping are given in Fig. 7.

4 Summary and Conclusions

The maximum water use (SW and GW) is found in case II of the proposed cropping pattern. Likewise, minimum water use (SW and GW) is found in the existing cropping pattern. Similarly, maximum net returns from crop production are found in case III of the proposed cropping pattern and minimum net returns from crop production are found in the existing cropping pattern. It is found that groundwater utilization is approximately same whereas minor change of canal water is there for various cases. Similarly, when different cases are compared, it indicated that the suggested cropping pattern in case III gives the maximum net return from the crop production. The current cropping practices and utilization of SW and GW yields minimum benefits i.e. NPR 6574 million. Various alternatives for changing crop area constraints in the winter season suggested enough scope for improvement of benefits. On the basis of many cases discussed, adopting the proposed cropping pattern III is a suggestion that may be made i.e. 95% rice in monsoon season, 40% wheat + 20% green beans + 20% pulses + 15% tomatoes in winter season and 95% spring rice in spring season, which yield maximum benefit of NPR. 9612 million. The maximum net benefits achieved from best proposed cropping pattern are found to be approximately 1.5 times more than net returns obtained from the existing cropping pattern. For the best suited case i.e. Case III, it has been seen that 244.57 ha-m SW and 60.33 ha-m GW in monsoon season, 21.58 ha-m SW and 92.34 ha-m GW in winter season and 65.14 ha-m GW in spring season is to be released. The parameters that are sensitive towards the net benefits are market price of the crops, energy cost for GW pumping, grain yield capacity, cost of cultivation, etc.

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References

1. Harmancioglu NB, Barbaros F, Cetinkaya CP (2013) Sustainability issues in water management. Water Resour Manage 27(6):1867–1891
2. Tyagi NK, Agrawal A, Sakthivadivel R, Ambast SK (2005) Water management decisions on small farms: a case study from northwest India. Agric Water Manag 77(1–3):180–195
3. Wrachien DD, Fasso CA (2002) Conjunctive use of surface and groundwater: overview and perspective. Irrig Drain 51(1):1–15
4. Bhattarai DP, Shakya NM (2019) Conjunctive use of water resources in sustainable development of agriculture in terai Nepal. J Inst Eng 15(2):210–217. https://doi.org/10.3126/jie.v15i2.27668
5. Brewer JD, Sharma KR (2000) Conjunctive management in the hardinath irrigation system, Nepal
6. Todd DK (1980) Groundwater hydrology, 2nd edn. xiii + 535 pp., numerous figs and tables, vol 118, no 4. Wiley, New York, Chichester, Brisbane, Toronto. ISBN 0 471 87616 X. Price £13.00
7. Jha MK, Peralta RC, Sahoo S (2020) Simulation-optimization for conjunctive water resources management and optimal crop planning in kushabhadra-bhargavi river delta of eastern india. Int J Environ Res Public Health 17(10):1–20. https://doi.org/10.3390/ijerph17103521
8. Schoups G et al (2006) Sustainable conjunctive water management in irrigated agriculture: model formulation and application to the Yaqui Valley, Mexico. Water Resour Res 42(10):1–19. https://doi.org/10.1029/2006WR004922
9. Ramesh H, Mahesh A (2012) 'Conjunctive use of surface water and groundwater for sustainable water management. In: Sustainable development—energy, engineering and technologies - manufacturing and environment. InTech. https://doi.org/10.5772/29493
10. Khare D, Jat MK (2006) Assessment of counjunctive use planning options: a case study of Sapon irrigation command area of Indonesia. J Hydrol 328(3–4): 764–777.https://doi.org/10.1016/j.jhydrol.2006.01.018
11. Cheng Y et al (2009) An optimal water allocation for an irrigation district in pingtung county, Taiwan. Irrig Drain 58(3):287–306. https://doi.org/10.1002/ird.411
12. Shrestha SR, Tripathi GN, Laudari D (2018) Groundwater resources of nepal: an overview. Springer Singapore. https://doi.org/10.1007/978-981-10-3889-1_11
13. Paudyal GN, Gupta AD (1990) Irrigation planning by multilevel optimization. J Irrig Drain Eng 116(2):273–291. https://doi.org/10.1061/(asce)0733-9437(1990)116:2(273)
14. Paudyal GN, Gupta DA (1990) A nonlinear chance constrainedmodel for irrigation planning. Agric Water Manage 18(2): 87–100
15. Paul S, Panda SN, Kumar DN (2000) Optimal irrigation allocation: a multilevel approach. J Irrig Drain Eng 126: 3(149), 149–156. https://doi.org/10.1061/(ASCE) 0733-9437
16. Tyagi NK (1986) Optimal water management strategies for salinity control. J Irrig Drain Eng. https://doi.org/10.1061/(ASCE)0733-9437(1986)112:2(81),81-97

17. Tyagi NK, Narayana VVD (1981) Conjunctive use of canals and aquifers in alkali soils of Karnal. J Agric Eng 18(3–4):78–91
18. Tyagi NK, Narayana VVD (1984) Water use planning for alkali soils under reclamation. J Irrig Drain Eng. https://doi.org/10.1061/(ASCE)0733-9437(1984)110:2(192),192-207

Dam Break Flood Hazard Mapping and Vulnerability Analysis in Kulekhani Dam, Nepal

Nabin Shrestha, Upendra Dev Bhatta, Bhola Nath Sharma Ghimire, and Akhilesh Kumar Karna

Abstract Construction of dam serves numerous purposes. Despite all the advantages, failure of dam structures could result in enormous losses in downstream areas due to unexpected floods. So, dam break study is important to reduce threats of flood in downstream areas during dam failure. The present study was conducted in the year 2021–2022 for Kulekhani Dam in Nepal and it helps to prepare dam break flood hazard map, to identify the vulnerability of downstream and to estimate the time for peak discharge to reach at different sections of the river from Kulekhani Dam to Bagmati River. The equations proposed by Froehlich in 2008 and 1995 were used to calculate dam breach parameters and peak outflow respectively. The maximum flood discharge was calculated as 15,303.61 m^3/s. HEC-RAS two-dimensional unsteady flow analysis was performed from which approximately 2.03 km^2 of the downstream area was found to be inundated with maximum flood depth of 31.60 m. The cultivable lands, vegetation, roads, bridges, buildings, electric poles and other infrastructures were found to be vulnerable during flood. The peak flood during the dam breach was estimated to reach different settlements in a time period between 60 and 100 min. The model was validated by comparing simulated flood depth and calculated flood depth using the coefficient of determination, Nash–Sutcliffe Simulation Efficiency, RMSE-observation for Standard Deviation Ratio and Percent BIAS which were found to be 1.00, 0.81, 0.44 and −7.81% respectively, all remaining within a prescribed range. Using flood hazard map and vulnerability of the downstream areas, the local government have to identify areas of risk and only then design and extension of market towns, infrastructures, buildings, etc. should be allowed. Concerned authority, local government and national government together have to perform dam break study and prepare flood hazard map, emergency action plan and standard operating procedure, proper evacuation route and open spaces during a disaster.

N. Shrestha (✉) · U. D. Bhatta · B. N. S. Ghimire · A. K. Karna
Tribhuvan University, Pulchwok, Nepal
e-mail: sthasthnabin@gmail.com

B. N. S. Ghimire
e-mail: bholag@ioe.edu.np

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Keywords Dam breach modeling · HEC-RAS · Kulekhani dam · Flood hazard map · Vulnerability

1 Introduction

Natural hazards vary in magnitude and intensity in time and space [1]. Under certain conditions and influenced by triggering factors, they may cause loss of life, destroy infrastructures and properties, impede economic and social activities and cause destruction to the environment and other infrastructures [2]. Flood is defined as an overflow of water that can submerge the land that is usually dry [3]. Floods usually occur during heavy rainfall but there might be situations when dams or water-flowing-path-obstructing structures are suddenly broken down. Floods usually affect the downstream the most but in the context of water reservoirs, they will affect the people at upstream as well [4]. Dams are constructed to address the necessities in the fields of agriculture, water supply and hydropower. According to adverse incremental consequences of failure or misoperation of dams, they can be categorized into three hazard potential classifications as low, significant and high [5]. The structural damage of dam is limited to areas of immediate vicinity of the structure but the failure of dam and sudden release of impounded reservoir water cause destruction over large areas at downstream of the dam [6]. Planning for disasters, providing emergency assistance and issuing flood warnings are the benefits from systematic assessment of the risks presented by potential dam failure [7]. The catastrophic consequences of dam break events urge the need for dam break modeling analysis so as to provide inundation maps at a scale sufficient to determine the extent of flooding, timing of the arrival and peak of flood wave [8]. However, researches on risk management, warning mechanisms and loss assessment considering dam failures have not yet been properly established.

When compared to other types of flooding, floods by failure of dams are distinguished by their sudden occurrence, enormous volume of water flow and strong water forces. High flood, caused by dam failure, travels downstream of the dam and damages people's lives and properties along the flood wave's path [9]. Flood routing is the technique of determining flood hydrograph at a section of river by utilizing the data of flood flow at one or more upstream sections [10] to determine flood protection, flood forecasting, spillway design and reservoir design and estimate peak discharges and stage of discharge in river channel [11]. The hydrologic approach (Muskingum method) and hydrodynamic approach (Saint–Venant equations) are the two methods of flood routing [12]. Flood routing and flood level forecasting can be easily performed using HEC-RAS model as it saves time in calibration of model to determine flood level forecasts [13]. HEC-RAS river network model provides upgraded simulations with better computational routing and supports in importing and exporting GIS data to prepare flood hazard map [14]. Simulated flood depth and observed flood depth were used to validate the HEC-RAS unsteady flow model prepared for Lower Tapi river [15]. HEC-RAS in combination with ArcGIS can be used for flood plain mapping, which provides results that are more realistic and same can be used to prepare decision support system for possible disaster [16].

For effective land-use planning in flood-prone areas and for preparing communities at downstream areas, flood hazard mapping can play a vital role as it creates easily readable, rapidly accessible charts and maps, thus facilitating the identification of areas at risk of flooding and helping in prioritizing mitigation and response efforts during disaster events [17]. Flood hazard maps are prepared to increase awareness of the likelihood of flooding among public, local authorities and other organizations, which encourage people living and working in flood-prone areas to take appropriate actions [18]. The flood hazard map can be used to identify affected areas, flood depth and time of arrival of flood in order to determine flood risk and flood risk management activities [19].

United Nations International Strategy for Disaster Reduction (UNISDR) describes vulnerability as the characteristics and circumstances of a community, system or asset that make it susceptible to damaging effects of hazard [20]. Vulnerability to floods is determined by several factors such as levels of economic status, control over assets and controlling power of hazard or disaster, and livelihood opportunities [21].

Nepal is one of the high potential nation regarding water resources [22]. In Nepal, monsoon brings much of rainfall, which are the main source of water for the rivers [23]. Dams exceeding 15 m in height have been built for tapping the water resource potential. Young geology and active tectonic region with steep topography are contributing factors for disasters like landslides in mountainous terrain, which might trigger the overtopping of natural or artificial dams [24]. During the construction of Kulekhani hydropower power station, heavy rains in 1984 and 1986 triggered slope failures, collapses and landslides around the project area affecting roads, bridges and houses, causing casualties of people [25]. Nepal Electricity Authority initiated Kulekhani Disaster Prevention Project after diversion from dam in its project and has no proper interest in main stretch of Kulekhani River [26] so, the study of river channel and its vicinity is lacking in context of downstream of Kulekhani Dam. Department of Humanitarian Affairs (1994) has recommended for the study of possible dam break of Kulekhani Dam in future and for the assessment of vulnerability, evacuation plans and training for evacuation during possible dam breach condition.

The goal of this study is to develop flood modeling and to prepare flood hazard map in downstream of Kulekhani Dam due to its outbreak condition. The study also helps to identify areas of downstream vulnerable to dam break flood and to estimate probable travel time for peak discharge to reach at different parts downstream of Kulekhani dam located in Indrasarowar Rural Municipality, Nepal.

2 Study Area and Dataset

2.1 Study Area

Location and Physiography

The Kulekhani watershed covers the area of Thaha Municipality and Indrasarowar Rural Municipality in Makwanpur District of Nepal. The watershed is of national importance as it is the source for one and only reservoir type of hydel plant in the country. The hydel plant has rock filled earthen dam of length 406.00 m and height of 114.00 m with gross storage of 94.26 million cubic meters. The study area lies in Mahabharat range consisting of rugged terrain with sharp crests and steep slopes [27]. The study area covers the area from Kulekhani Dam to Bagmati River within Indrasarowar Rural Municipality. Indrasarowar rural municipality lies in north-eastern part of Makwanpur district of Bagmati province in Nepal (Fig. 1). Palung River feeds the watershed from west to east and Chitlang River from north to south. River tributaries like Tistung River, Chitlang River, Thado River, Chalku River and Bisingkhel River combine to form Kulekhani River. The study area can be divided into two zones as warm temperate humid zone and cool temperate humid zone. The average temperature of warm temperate humid zone ranges between 15 and 20 °C and for cool temperate humid zone, it ranges between 10 and 15 °C. The average annual precipitation over the watershed is about 1500 mm [28].

Kulekhani Dam

The Kulekhani dam is located at a latitude of 27°35′26″N and at a longitude of 85°09′20″E. Kulekhani dam is zoned rock-fill dam with inclined core zones, filter core zones, quarry rock zones and random rock zones. The dam is 114.00 m high with 10.00 m wide and 406.00 m long crest. The crest lies at an elevation of 1534.00 m. The foundation has been made impervious by excavating the bedrock and grouting in the foundation to eliminate seepage. In 2018, from bathymetric survey the sedimentation rate of Kulekhani reservoir was measured to be 5216 m^3/km^3/year with minimum bed level near the intake of Kulekhani I hydropower project of 1459.83 m [29].

2.2 Dataset

Data from governmental and non-governmental sources were acquired for the study (Table 1).

Meteorological Data

Flood and its behavior are dependent on the characteristics of catchment area, hydro-meteorological conditions, soil characteristics and terrain of the catchment area [30].

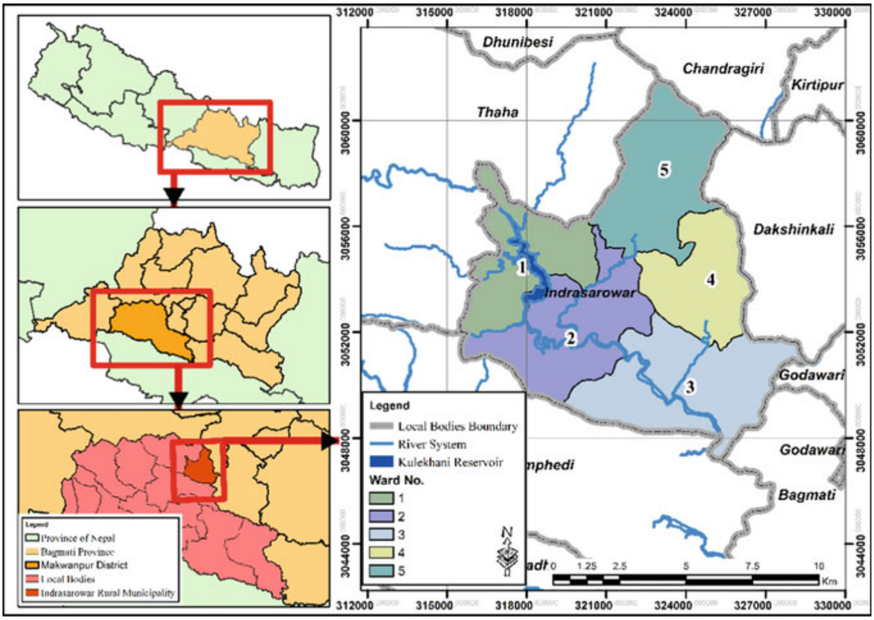

Fig. 1 Location map of indrasarowar rural municipality

Table 1 Dataset used for study

Dataset	Data type	Source
Digital elevation model (DEM)	Raster	Earthdata
Precipitation	Excel file	Department of hydrology and meteorology, Nepal
Landcover	Vector file	Department of survey, Nepal
Satellite image	Raster	Google earth

Rainfall intensity and duration of rainfall also play a vital role in the flood development in any watershed [31]. In case of dam break flood, hydro-meteorological conditions and soil and terrain characteristics are important [32]. There is one meteorological station within the catchment of study area at Markhugaun. Precipitation data of the station was obtained from Department of Hydrology and Meteorology, Nepal. The meteorological data were used to generate hydrograph at the dam site.

Digital Elevation Model (DEM)

Elevation data are important in each flood modeling technique [33]. DEM data of 12.5 × 12.5 m grid have been obtained from ALOS palsar (Fig. 2). The elevation data were used to create Triangular Irregular Network (TIN) for the preparation of geometric data.

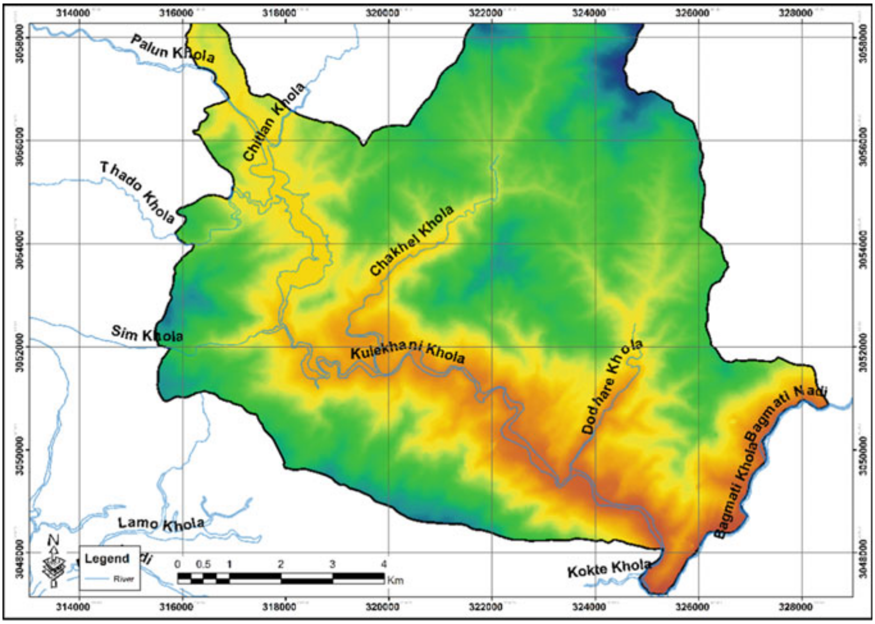

Fig. 2 DEM of study area

Landcover, Settlement Name

Landcover information is important in modeling of floods and assessing the vulnerability of the communities at downstream [34]. Landcover data and name of settlement were obtained from Department of Survey of year 2000, which was updated using satellite image captured on April 2021 (Fig. 3). Landcover data are important in determining Manning's coefficient of the study area.

3 Methodology

For the preparation of flood hazard mapping and vulnerability analysis in downstream of Kulekhani Dam due to dam break situation, the Kulekhani dam was initially classified according to dam hazard potential using FEMA Dam Safety guidelines. There are numerous causes of dam failure among which overtopping failure and piping or leakage failure are the most dominant type of failure than spillway erosion, sliding, faulty construction, gate failure, excessive deformation and earthquake instability. The Kulekhani Dam failure was analyzed for overtopping failing scenario. Dam breach parameters were estimated using available empirical equations for the final breach depth of the dam taken as 60 m. Using flow regression equation, the peak flow at different breach depths were computed at different intervals of time, which

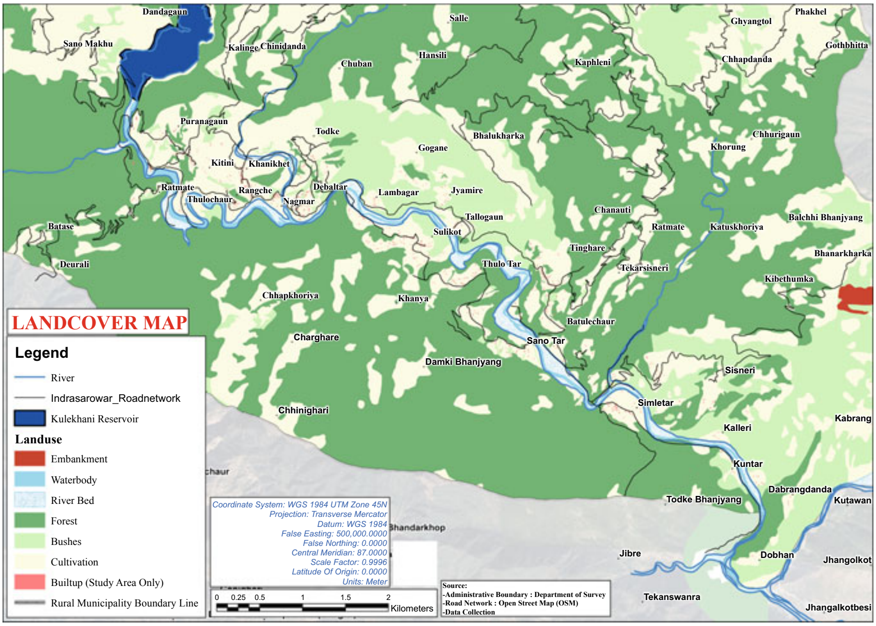

Fig. 3 Landcover map of study area

was used to prepare dam breach hydrograph. The dam breach outflow hydrograph was used for the modeling, which was routed for downstream areas to determine peak flood wave and time of travel of flood wave. With all available data which include DEM, Manning's roughness coefficient and dam breach hydrograph, HEC-RAS model was prepared and then analyzed for obtaining the flood hazard map. The flood hazard map was finalized after validation of the model and vulnerability analysis of the downstream was performed. The flowchart of the methodology is described in Fig. 4.

3.1 *Dam Hazard Potential Classification*

Flood has a great influence on its vicinity area and has effects on settlements, households and land-use. According to the probability of loss of human life and economic, environmental and lifeline losses, the dams can be classified into three hazard potentials i.e., low, moderate and high [3].

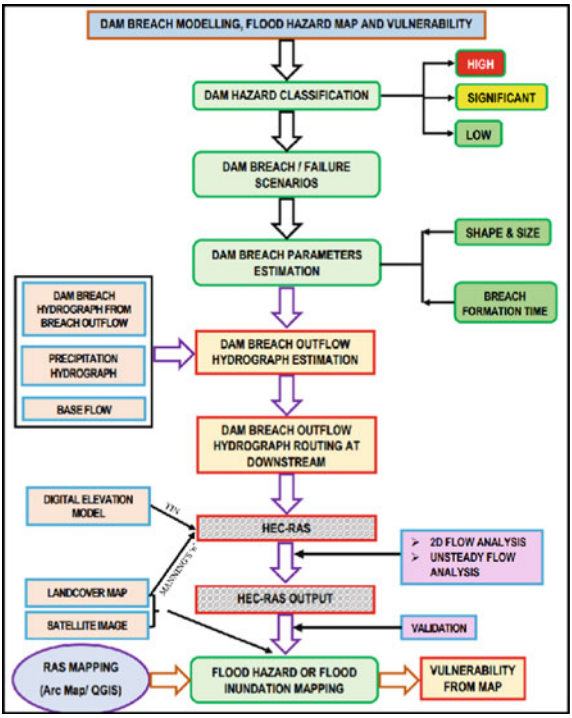

Fig. 4 Flowchart of methodology

3.2 Dam Breach Parameters and Peak Outflow

During dam break modeling, dam breach parameters have to be identified to predict breach width and breach development time. Formation of breach in dam and shape of breach govern the impact of flood wave at downstream. Numerous empirical formulae have been proposed for the determination of final breach width and breach formation time. Froehlich has studied numerous earth dams and proposed empirical formula to determine breach parameters. Equation provided by Froehlich (2008) was used to determine the final dam breach width and breach formation time. Among the proposed empirical formula, regression equation provided by Froehlich (1995) was used for estimating peak discharge. The variation of peak flow with respect to time was computed to prepare dam breach hydrograph. The superposition of dam breach hydrograph, precipitation hydrograph and base flow of the river were used to prepare final dam breach hydrograph. The final dam breach hydrograph was routed using Muskingum routing equation based on specification of the space and time intervals to determine the peak flow and travel time of flood wave at downstream areas.

Table 2 Manning's coefficient

Categories	Range	Adopted value
Buildings	0.050–0.120	0.050
Bushes and cultivation	0.025–0.050	0.030
Forest	0.045–0.150	0.045
Riverbed and waterbody	0.025–0.050	0.025

3.3 HEC-RAS Analysis

HEC-RAS 6.0 software was used for flood simulation. For the study area, Manning's roughness coefficient was adopted according to changes in landcover data (Table 2). Final flood hydrograph and frictional slope were used as upstream and downstream boundary conditions. With all data and information required for the model, two-dimensional unsteady analysis was performed.

3.4 Model Validation

Model validation was performed by comparison between simulated depth and calculated depth using statistical equations. Coefficient of determination (R^2), Nash–Sutcliffe Simulation Efficiency (NSE), RMSE-observations standard deviation ratio (RSR) and Percent Bias (PBIAS) were used to evaluate model prediction.

3.5 Flood Hazard Mapping and Flood Vulnerability

Flood hazard map was prepared after the validation of the model. The map was prepared to provide information about inundation areas, inundation extents and inundation depths [35]. Flood vulnerability due to outbreak of Kulekhani dam was analyzed with guidance from flood hazard map. For ease of the study and to prepare plans for future disaster risk reduction and management activities, the vulnerability levels were classified into five levels, namely, very low, low, moderate, high and very high with respect to flood depths (Table 3).

Table 3 Vulnerability level for classification

Hazard and vulnerability level	Flood depth (m)
Very low	<0.5
Low	0.5–1.5
Moderate	1.5–2.5
High	2.5–5.0
Very high	>5.0

4 Results and Discussion

4.1 Dam Breach Analysis

During overtopping failure of Kulekhani Dam, the final breach width of the dam was calculated as 140.32 m with breach formation time of 0.84 h. The maximum discharge of 15,303.61 m^3/s was attained at 50 min from the start of dam breach. The final hydrograph at dam was prepared which was used as input boundary condition. The probable time for peak discharge to reach at 1.00 km, 2.00 km, 5.00 km, 7.00 km, 10.00 km and 12.00 km downstream were estimated to be about 52 min, 55 min, 67 min, 75 min, 88 min and 96 min respectively (Fig. 5). The probable time for peak discharge to reach at 5.30 km, 6.70 km, 8.86 km, 9.51 km, 10.45 km and 11.06 km downstream were estimated to be about 68 min, 74 min, 83 min, 86 min, 90 min and 92 min respectively. HEC-RAS two-dimensional unsteady flow analysis was performed to measure simulation depth at different chainages. The flood depths at 5.30 km, 6.70 km, 8.86 km, 9.51 km, 10.45 km and 11.06 km were simulated to be 12.41 m, 11.19 m, 6.91 m, 6.90 m, 11.39 m and 12.66 m respectively (Table 4).

4.2 Model Validation

The simulated depths and calculated depths (Table 4) were compared for the validation of model. The computed result of $R^2 = 1$ (which is >0.5) depicts flood depths from model can be predicted at any chainage at downstream without error. NSE = 0.81 (which lies between 0.0 and 1.0) implies that model is superior and accurate representation of real system. The RSR = 0.44 (which lies between 0.0 and 0.5) indicates that model simulation performance is better. The PBIAS = −7.81% (which is negative and <10%) indicates that the model is overestimation bias but lies within acceptable range indicating very good performance rating. From the statistical calculation, all four values remain within the prescribed range indicating validation of the model.

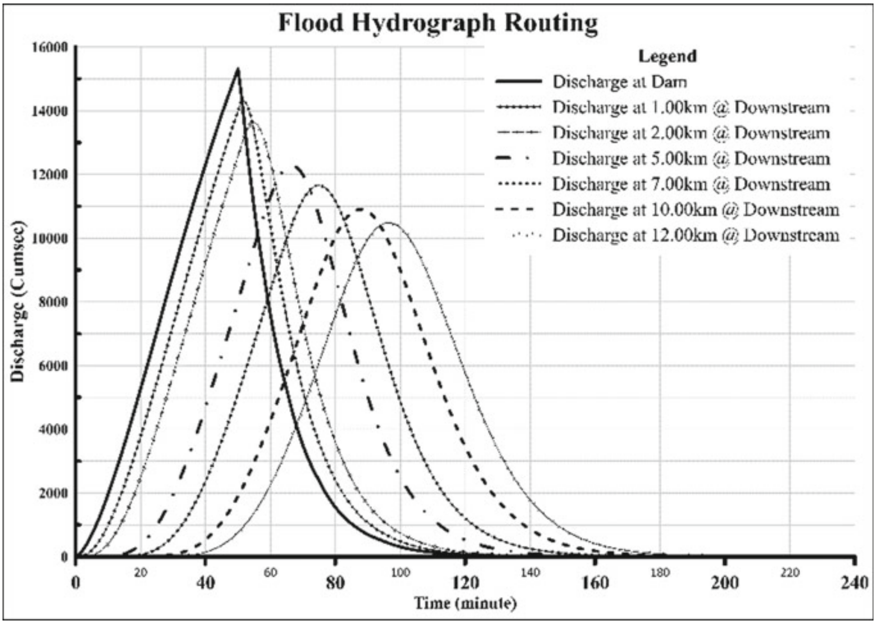

Fig. 5 Flood routing of Kulekhani dam outbreak flood

Table 4 HEC-RAS model flood depth and calculated flood depth at different sections

Chainage	HEC-RAS depth (m)	Calculated depth (m)
5 + 300	12.41	11.30
6 + 700	11.19	10.34
8 + 860	6.91	6.72
9 + 510	6.90	6.79
10 + 450	11.39	10.43
11 + 060	12.66	11.39

4.3 Flood Hazard Mapping and Flood Vulnerability

The flood hazard mapping was done after validation of model. The flood map shows approximately 2.03 km^2 of downstream land areas to be inundated with varied flood depths with maximum depth being 31.60 m. The major settlements at Thulochaur, Nagmar, Debaltar, Lambagar, Tallagoun, Sanotar, Simletar and Kuntar are inundated during flood events (Fig. 6). As shown in Fig. 6, the Pharping-Kulekhani road (at the vicinity of dam and at section 8.85–10.50 km downstream) and other feeder roads will be inundated during flood. There is a high possibility of failure of bridge at the base of dam, bridge over Chakhel River and circular pipe bridge at Simletar. The flood will also affect the electric poles installed at the banks of river. Approximately 292

Fig. 6 Flood hazard mapping of dam outbreak (*Source flood hazard analysis*)

buildings were found to be vulnerable (Fig. 7) during the flood which might displace approximately 1262 people. From the study, 35.95% of buildings lie in "very highly vulnerable" areas followed by 29.10% in "highly vulnerable" areas. Only 9.93% of buildings are located in "very low vulnerable" areas. About 364,055 m^2 of vegetation and 571,614 m^2 of cultivable areas were found to be inundated (Fig. 8). Among these calculated areas, maximum areas of vegetation and cultivable areas were found to lie in "very high vulnerable" region while least areas of vegetation and cultivable areas were found to lie in "very low vulnerable" regions.

5 Conclusion and Recommendations

From numerous available empirical equations, Froehlich equation provides the most satisfactory result for earthen dams. During overtopping failure of dam, the final breach width was calculated to be 140.32 m. The estimated peak discharge was computed to be 15,303.61 m^3/s which was attained after 50 min of starting of breach of dam. The simulation results in inundation of 2.030 km^2 downstream, which inundates settlements of Thulochaur, Nagmar, Debaltar, Lambagar, Tallagoun, Sanotar, Simletar and Kuntar. The roads, bridges, buildings, electric poles, etc. are the vulnerable infrastructures during disastrous flood events. The peak discharges after

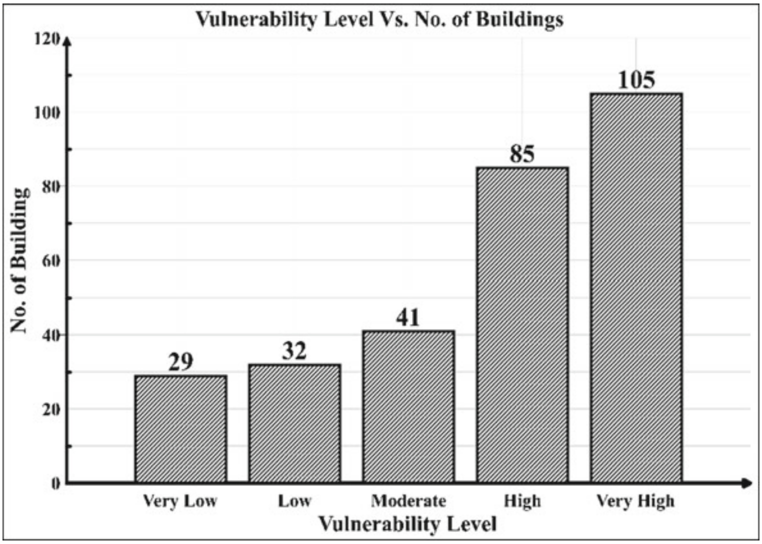

Fig. 7 Vulnerability level and building count

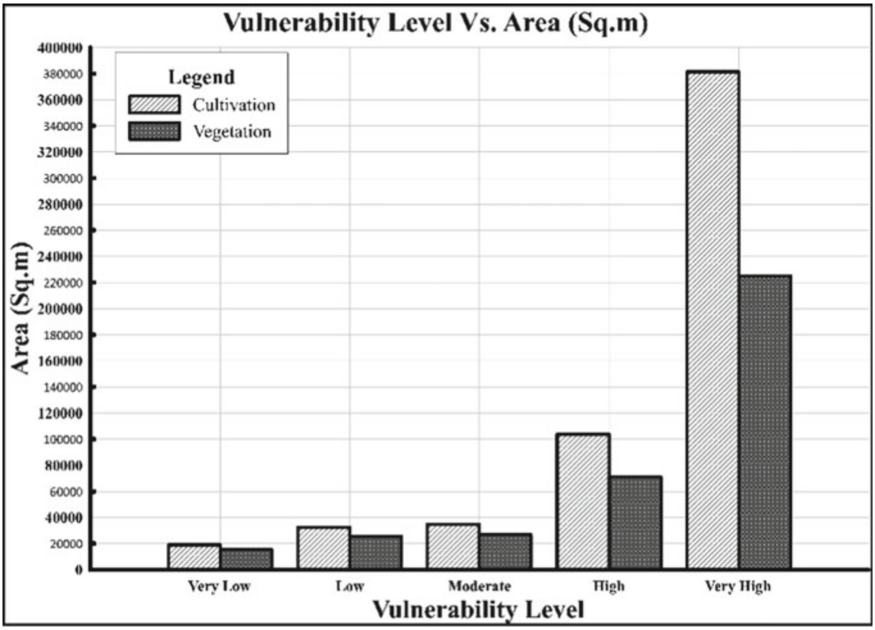

Fig. 8 Vulnerability level and vegetative and cultivable areas (*Source* Flood Hazard Map and Landuse Map)

breach of dam reaches different settlements between 60 and 100 min. Use of two-dimensional unsteady flow analysis in HEC-RAS is suitable to prepare flood hazard map during flood events. Concerned authorities, local governments and national government should perform dam break study for constructed dams or dams being constructed to identify risk areas for disastrous events then only extension of infrastructures and development activities should be allowed. Emergency action plans and standard operating procedures have to be prepared for possible disastrous events.

References

1. UNDRR (2022) Understanding disaster risk. Prevention Web. https://www.preventionweb.net/understanding-disaster-risk/component-risk/hazard
2. Dutta D, Teng J, Vaze J, Lerat J, Hughes J, Marvanek S (2013) Storage-based approaches to build floodplain inundation modelling capability in river system models for water resources planning and accounting. J Hydrol 504:12–28
3. WHO (2022) World Health Organization. https://www.who.int/health-topics/floods#tab=tab_1
4. Fread DL (1996) Dam-breach floods. In: Hydrology of disasters. Springer, Dordrecht, pp 85–126
5. FEMA (2004) Federal guidelines for dam safety: hazard potential classification system for dams. U.S department of homeland security federal emergency management agency
6. Charles JA (2011) Delivering benefits through evidence: lessons from historical dam incidents. Project
7. Michaud J, Johnson C, Iokepa J, Marohnic J (2005) Methods for estimating the impact of hypothetical dam break floods. In: Chemistry for the protection of the environment, vol 4. Springer, Boston, MA, pp 195–199
8. Zagonjolli M (2003) Dambreak modelling analysis
9. Katopodes ND, Strelkoff T (1978) Computing two-dimensional dam-break flood waves. J Hydraul Div 104(9):1269–1288
10. Hossain MM (2014) Analysis of flood routing. Dhaka Univ J Sci 62(2):69–73
11. Ogbonna D, Okoro BC, Osuagwu JC (2017) Application of flood routing model for flood mitigation in Orashi river, south-east Nigeria. J Geosci Environ Protect 5(03):31
12. Cunge JA (1969) On the subject of a flood propagation computation method (Musklngum method). J Hydraul Res 7(2):205–230
13. Hicks FE, Peacock T (2005) Suitability of HEC-RAS for flood forecasting. Can Water Resour J 30(2):159–174
14. Yang J, Townsend RD, Daneshfar B (2006) Applying the HEC-RAS model and GIS techniques in river network floodplain delineation. Can J Civ Eng 33(1):19–28
15. Timbadiya PV, Patel PL, Porey PD (2011) HEC-RAS based hydrodynamic model in prediction of stages of lower Tapi River. ISH J Hydraul Eng 17(2):110–117
16. Khattak MS, Anwar F, Saeed TU, Sharif M, Sheraz K, Ahmed A (2016) Floodplain mapping using HEC-RAS and ArcGIS: a case study of Kabul River. Arab J Sci Eng 41(4):1375–1390
17. Bapalu GV, Sinha R (2005) GIS in flood hazard mapping: a case study of Kosi River Basin, India. GIS Dev Weekly 1(13):1–3
18. Environment Agency (2010) Flood Map—your questions answered. Environment Agency, Rotherham
19. Mao J, Wang S, Ni J, Xi C, Wang J (2017) Management system for dam-break hazard mapping in a complex basin environment. ISPRS Int J Geo Inf 6(6):162
20. UNISDR (2021) https://www.unisdr.org/files/7817_UNISDRTerminologyEnglish.pdf

21. Pelling M (1997) What determines vulnerability to floods; a case study in Georgetown, Guyana. Environ Urban 9(1):203–226
22. Upadhyay SN, Gaudel P (2018) Water resources development in Nepal: myths and realities. Hydro Nepal: J Water, Energy Environ 23:22–29
23. WECS (2011) Water resources of Nepal in the context of climate change. Government of Nepal, Singha Durbar, Kathmandu
24. NDRR Portal (2021) Nepal disaster risk reduction portal. Retrieved from Nepal Disaster Risk Reduction Portal. http://drrportal.gov.np/risk-profile-of-nepal
25. JICA (2002) Kulekhani disaster prevention project. https://www.jica.go.jp/english/our_work/evaluation/oda_loan/post/2002/pdf/113_full.pdf
26. NEA (2016) Nepal electricity authority a year in review-fiscal year 2015/2016. Nepal electricity authority, Durbarmarg, Kathmandu
27. Pradhan AMS, Dawadi A, Kim YT (2012) Use of different bivariate statistical landslide susceptibility methods: a case study of Khulekhani watershed, Nepal. J Nepal Geol Soc 44:1–12
28. Shrestha S, Khatiwada M, Babel MS, Parajuli K (2014) Impact of climate change on river flow and hydropower production in Kulekhani hydropower project of Nepal. Environ Process 1(3):231–250
29. NEA (2018) Bathometric survey of Kulekhani reservoir. Nepal Electricity Authority, Kathmandu
30. Stein L, Clark MP, Knoben WJ, Pianosi F, Woods RA (2021) How do climate and catchment attributes influence flood generating processes? A large-sample study for 671 catchments across the contiguous USA. Water Resour Res 57(4): e2020WR028300
31. Cheng Y, Sang Y, Wang Z, Guo Y, Tang Y (2021) Effects of rainfall and underlying surface on flood recession—the upper Huaihe river basin case. Int J Dis Risk Sci 12(1):111–120
32. Tedla MG, Cho Y, Jun K (2021) Flood mapping from dam break due to peak inflow: a coupled rainfall-runoff and hydraulic models approach. Hydrology 8(2):89
33. Xu K, Fang J, Fang Y, Sun Q, Wu C, Liu M (2021) The importance of digital elevation model selection in flood simulation and a proposed method to reduce DEM errors: a case study in Shanghai. Int J Disaster Risk Sci 12(6):890–902
34. Prachansri S (2007) Analysis of soil and land cover parameters for flood hazard assessment. International institute for geo-information science and earth observation, Enschde, Netherlands
35. Kikuchi R (2003) Flood hazard map manual for technology transfer. International training program on total disaster risk management

Enhancing Blue-Green Infrastructures for Flood and Water Stress Management: A Case Study of Chennai

Nadeem Ahmad and Quamrul Hassan

Abstract The urban water system has been severely affected across the globe in the recent decades due to rampant urbanisation, industrialisation and climate change. Many cities in India have witnessed a rise in the frequency of urban flooding as well as water scarcity. Chennai, the fourth largest metropolitan city lying on the southeast coast of India and the capital of the state of Tamil Nadu, is severely facing both flooding and water scarcity. In 2015, the city suffered the most disastrous flood in a century. More than 400 human casualties were reported; about USD 80,000 million loss were estimated and about 2 million people were very badly affected. While four years later in June 2019, the city was surprisingly hit by 'Day Zero' and all of its major reservoirs ran dry. With the rapid urbanisation, the blue and green spaces of the city have been drastically decreased. This paper focuses on the roots of flooding and water scarcity issues of the city. The paper further explores 'Blue-Green Infrastructure' (BGI) approach to integrate flood management along with water crisis management as an innovative, sustainable and nature-based solution. The paper also explores the emerging concept of BGI and analyses the existing plans and research projects in some major global cities and further, the possibility of their implementation in India. It is observed that adaptation of BGI measures (wetlands, lakes, ponds, rivers, swales, rain gardens, parks, green roofs etc.) minimises the flood risks as well as water stress including other urban ecosystem services (UES) to derive multiple benefits regarding ecological, socio-economic and overall urban well-being.

Keywords Urban flooding in Chennai · Flood management · Day zero · Water crisis management · Blue-Green infrastructure · Nature-based solutions · Urban ecosystem services

N. Ahmad · Q. Hassan (✉)
Department of Civil Engineering, Jamia Millia Islamia, New Delhi 110025, India
e-mail: qhassan@jmi.ac.in

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1 Introduction

Cities across the globe are facing the challenges in mitigating the flood risk, improving access to potable water, treating urban water effluents or improving the groundwater level. Climate related extremes (floods and droughts) have become an accepted component of coupled human–environment systems [1]. The frequency of droughts (or water scarcity) followed by extreme precipitation causing urban flooding has increased in the recent decades. Such extreme events cause disruption of food production and water supply, alterations to ecosystem, huge damage to the properties and even loss of lives. With increasing urbanisation, the blue and green spaces of the city have been drastically decreased. An uncontrolled and environmentally unplanned urbanisation is primarily responsible for urban floods as well as increased water scarcity issues across the world. The global urban population increased by five times during 1950 to 2014. Currently, more than 50% of the world's population resides in the cities and it has been projected that by 2050, 68% of the world's population will be urban [2]. By 2050, one in every two Indians is expected to live in urban areas [3]. The environmentally unplanned urbanisation has created many problems in urban spaces: increased pressure on essential resources and services; increased urban flood risk; increased water, air and noise pollution; loss of biodiversity; urban heat island; and increased risk of ill health [4]. Rapid urbanisation and extreme weather condition have made urban water management one of the most severe problems in the cities across the globe. When a natural landscape is altered by human interventions for socio-economic development, its outflow pattern gets disrupted. The change in LULC pattern in the urban spaces from natural surfaces to impervious surface due to urbanisation has reduced the natural seepage and increased the surface runoff. Furthermore, the unprecedented extremes of rainfall (i.e., too high or too low rainfall scenario) due to climate change are aggravating the flooding or water scarcity problem [5]. Every year these floods or droughts adversely affect billions of people, cause damage to properties worth billions of dollars, and cripple the economic infrastructure of the cities all over the world. In India, the city of Chennai is a typical example of the cities suffering from both urban flooding as well as water crisis. In the last decade, Chennai has witnessed the most devasting flood of the century in 2015 and 'Day Zero' in 2019. The 'Day Zero' condition of a city refers to the day when the city's taps dry out and people have to stand in line to collect a daily quota of water.

As the vulnerability and risks of urban flooding and other urban water-related problems are rising, several global cities have shifted their urban water management approach from conventional methods to innovative and integrated solutions 'Blue-Green Infrastructure' (BGI) measures such as wetlands, lakes, ponds, rivers, swales, rain gardens, parks etc. BGI includes interventions making use of natural processes and ecosystem services for functional purposes. BGI is a sustainable and nature-based solution with multiple benefits. In the present study, the concept of BGI and other similar terms have been discussed with many successful implementations in different parts of the world and explore the possibilities of BGI in Chennai region as well.

2 Urban Flooding and Water Crisis in Chennai

2.1 A Brief Description About Chennai

Chennai, the capital City of Tamil Nadu is the fourth largest Metropolitan City in India. The city of Chennai is situated within the latitude range 12°50′4″N–13°17′24″N and longitude range 79°58′53″E and 80°20′12″E, lying on the south-eastern coast of India (Fig. 1). The Chennai Metropolitan Area (CMA) comprises Chennai District, part of Thiruvallur District, and part of Kancheepuram District; with a total extent of 1189 km^2 [6]. The municipal area of the city has been expanded from 174 426 km^2. The average elevation of this low-lying flat coastal plain area is about 6.7 m above mean sea level. The city has a tropical climate and experiences most of its rainfall during the northeast monsoon (October-December) with an average annual of nearly 1300 mm [7, 8]. The natural ecosystem of Chennai comprises three rivers namely Kosasthalaiyar, Cooum and Adyar. A man-made canal known as Buckingham Canal also flows through the city plays an equally important role. The city depends on the northeast monsoon and its four major reservoirs (Chembarambakkam lake, Poondi lake, Puzhal lake and Cholavaram lake) for its water demand. The role of historic 'temple tanks' has been very crucial in the rainwater management in Chennai. It is a network of connected ponds, lakes, marshlands, small water bodies or reservoirs at temples as a rainwater harvesting system.

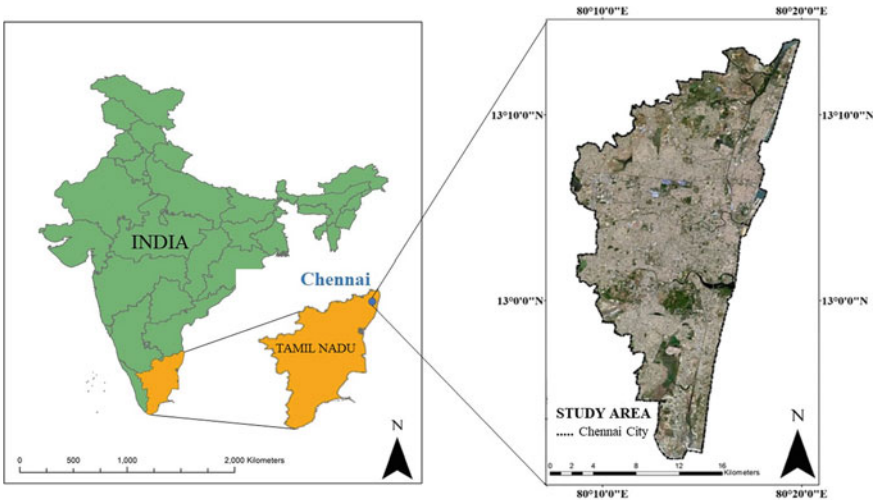

Fig. 1 Location map of Chennai [7]

2.2 Root Causes and Impacts of Urban Water Issues in Chennai

Chennai has been suffering from recurrent floods and droughts, struggling to meet its escalating water demand. An extremely high water stress is experienced by the city i.e., on average more than 80% of the available water supply is used up every year [9]. High water stress causes deterioration of fresh water resources and poses serious threats to human lives and livelihoods. The city is also prone to tropical storms and cyclones due to its location. Problems like urban flooding; overflowing of the lakes or rivers; and choking of available sewer system (mostly combined sewerage system) and natural drainage networks are quite common during extreme rainfall events [10, 11]. The catastrophic floods of the city (1943, 1978, 1985, 2002, 2005, 2015) raised the alarm against its drainage system [7, 12, 13]. Flood and water scarcity have the same roots: Unplanned rampant urbanisation; rainfall extremes attributed to Climate Change; Inadequate and poor urban drainage; and Lack of sustainable framework [14–16].

Human intervention in the natural environment disturbs the hydrological cycle and natural urban drainage pattern which ultimately increases the flood risk and other urban water crisis [17]. Although Chennai city has a population of about 4.6 million but its metropolitan population is nearly 8.6 million; and it is forecasted to exceed 14 million by 2031 [18]. Prior to urbanisation, Chennai had a very effective natural drainage system. In the last three decades, the city has witnessed a very rapid development but most of these developments seem to be environmentally and ecologically unplanned—the Adyar river basin once characterised by swamps, marshlands, low-lying areas, and temple tanks are encroached and converted into special economic zones and housing complexes [15]. Encroachments along the Cooum river have narrowed the river [19]. At present, developments have taken over 90 per cent of wetlands of the city. In urban spaces, wetlands exist in the form of ponds, lakes, swamps and marshlands. These wetlands are quite efficient in absorbing excess water during floods and in contributing adequate surface and groundwater during droughts. Increased impervious area and the loss of wetlands in the city have jeopardised its resilience to floods and droughts [20, 21]. Disposing untreated sewage into waterbodies is common practise in Chennai. Consequently, groundwater and surface water quality get deteriorated, further worsening water security of the city. Due to drastic decrease in natural land-use land-cover (LULC) and rampant urbanisation, all the three major rivers (Kosasthalaiyar, Adyar and Cooum) have significant issues, such as reduced discharge carrying capacity due to encroached floodplains; heavily polluted due to the continuous liquid and solid waste dumping [7, 9, 20, 22]. Overall, the urbanisation trend of Chennai has worsened the urban water problems. In the 2015 Chennai floods, more than 400 human lives were lost, over 2 million people were affected and properties worth nearly USD 80,000 million were damaged [23]. Chennai floods in 2015 is also associated with the unprecedented heavy rainfall in the months of November and December. More than 1200 mm rainfall occurred in the month of November and nearly 490 mm of single day rainfall was recorded on

December 1, 2015 [20, 23]. Despite the 2015 deluge, all the reservoirs of the city ran completely dry merely four years later, pushing the city into a severe water crisis mayhem. The city depends for water supply on the varying rainfall of NE monsoon and four reservoirs. But during scanty rainfall periods, these lakes and reservoirs get dry. Due to frequent dry spells of rainfall attributed to climate change and increasing urban population, the groundwater resources of the city have been also over-exploited to fulfil its water demand.

3 Need of Sustainable Approach of Urban Water Management in Chennai

The natural drainage systems in most of the city is in peril due to encroachment, poor maintenance, improper solid waste management and unavailability of properly designed stormwater drainage infrastructures. The city experiences recurring weather extremes (droughts and floods) almost every other year. The extreme climate change caused severe setbacks during the events of incessant rainfall and exiguous rainfall; with associated economic, socio-economic and environmental problems. Since Chennai is a coastal city, the increasing groundwater exploitation does not only deplete the groundwater level but also leads to seawater intrusion [7, 24]. Even with the advent of urban planning and development measures, the urban water issues of the city continue to aggravate. The city has a minimum of 108 L per capita per day (LPCD) of water supply, much less than the WHO minimum criteria of 150 LPCD [25]. Chennai lacks a sustainable and holistic approach to manage the floods, droughts, and other water-related infrastructure system inefficacies. The major causes and impacts of urban flooding or drought in the city make it fundamentally a man-made disaster.

With the changing paradigm of urban water management across the globe, the urban planners and policy makers in Indian cities should also adopt sustainable practises, taking into account the climate change mitigation and adaptation. Urban sustainability needs to be considered at the policy formulation stage, incorporating current and future scenarios. Adaptation of sustainable practises like ‘blue-green infrastructure’ measures has become very crucial because these strategies optimise the flood risk reduction with other objectives to achieve multiple benefits regarding ecological, socio-economic and overall urban well-being [26, 27]. The concept of ‘blue-green infrastructures’ has been discussed in detail in the next section.

4 Blue-Green Infrastructure (BGI): A Way Forward

4.1 Overview of BGI

Blue-Green Infrastructure (BGI) is a new term but not an absolutely new concept. It is deeply enrooted within the planning and conservation efforts that started more than a century ago in the early 1900s. The concept evolved back then from two major antecedents: the linking of parks and other green spaces for the benefit of humans; and the linking of natural areas to benefit biodiversity [28]. In twenty-first century, the 'blue-green infrastructure' has been re-evolved as a set of nature-based solutions for urban flood management as well as riverine flood management with overarching ecological, environmental and socio-economic benefits. However, there is no typical definition of the concept of BGI. But with the growing interest in sustainable approaches for flood management, numerous terminologies with similar concepts have been developed in different parts of the world. Broadly used terms which are almost similar in the urban spaces in the context of flood management are 'green infrastructure' (GI), 'green blue infrastructure' (GBI/BGI), 'nature-based solution' (NBS), 'low impact development' (LID), 'sustainable drainage system' (SuDS), and 'ecosystem-based adaptation' (EBA). The European Commission explicates GI solutions as a strategically planned network of high quality natural and semi-natural areas with other environmental features (vegetation, forests, waterbodies), which is designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings [29]. Many organisations or researchers isolate the 'blue' measures (like different waterbodies) from 'green' measures (vegetation and forests). In most of the western countries, 'green infrastructure' and 'blue-green infrastructure' are synonymously used. Nature Based Solutions (NBS), a relatively new concept which is defined as solutions supported by nature offering multiple benefits to society, ecology and climate change mitigation [26, 27, 30, 31]. But even having several similarities between the concepts of NBS and GI or BGI, a wide range of artificial interventions are included in nature-based solutions [32]. Figure 2 depicts the historical development of BGI or Blue-Green Solutions (BG-S) for urban spaces via Sustainable Urban Drainage System (SUDS) and Water Sensitive Urban Design (WSUD). Under WSUD, the most natural technological solutions (green roofs, bioretention system, rainforest and hydrophyte systems) are considered [33]. In the present study, the terms BGI, NBS, SuDS and non-traditional measures are interchangeably used, referring to the measures supported by nature.

4.2 Salient Features of BGI Implementation and Associated Urban Ecosystem Services

BGI is the most common way to implement nature-based solutions. BGI measures are significant components in the holistic planning of sustainable urban regions in

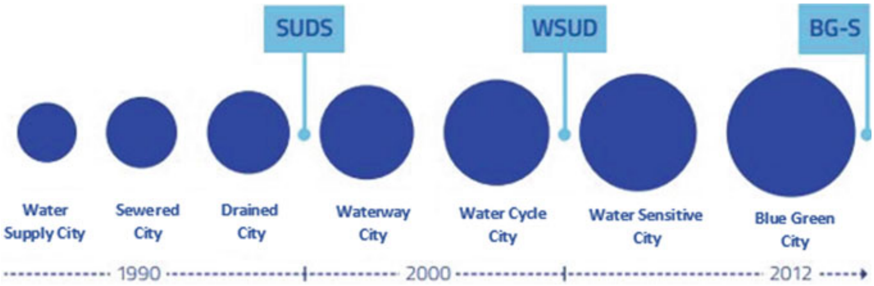

Fig. 2 Historical development of BGI for urban spaces [34]

future [35]. BGI helps in creating natural circumstances and ecosystem services in urban regions to alleviate urban pressures and to achieve climate change resilience [36]. There are numerous BGI measures (rain garden, blue-green roofs, green streets, wetlands and urban lakes, bioswales, permeable pavements etc.) being implemented for urban flood mitigation and other urban ecosystem services in different parts of the world. 'Urban ecosystem services' (UES) refers to the benefits which are derived from the ecosystem by urban population [37]. Figure 3 depicts the various urban pressures including water problems and UES related to nature-based solutions [34]. Apart from stormwater management and urban flood mitigation, some other common examples of UES are aesthetics, urban water supply, urban heat island (UHI) mitigation, improved water quality, improved air quality, resource efficiency, biodiversity, Recreation and well-being. Initially, NBS components (rain gardens, swales, green roofs and walls etc.) were contrived as a means of both managing surface runoff (stormwater) and improving amenities at local level. Later, BGI has enhanced and established various blue-green spaces in combination with the macro-scale concepts such as WSUD to strengthen urban sustainable development. BGI measures play a crucial role in creating a healthy microclimate in cities. Such as, green covers mitigate the effect of UHI and flood risks; while urban parks (and lakes) aesthetically attract inhabitants and provide space for relieving mental stresses and well-being [36]. Further, green roofs have multiple benefits (like urban agriculture and rainwater harvesting) within BGI territory. Many of the BGI measures such as 'green roof' and 'wetland'; are considered to contribute to the local water cycle through evapotranspiration. According to Environmental Protection Agency (EPA), the impervious surface would have 55% runoff with 30% evapotranspiration and 15% infiltration while the natural ground cover would only have 10% runoff with 40% via evapotranspiration and 50% through infiltration [33]. Due to increasing impervious surfaces and frequency of meteorological extremes attributed to climate change, cities can adopt nature-based solutions which could manage all the water resources within a city. Figure 4 illustrates how the retention and infiltration through BGI approach affects the water drainage [38]. Similarly, Fig. 5 depicts the increased infiltration and reduced runoff levels through increased provision of blue-green components in urban space; a BGI based plan of Nagoya city in Japan [1, 39]. BGI concept

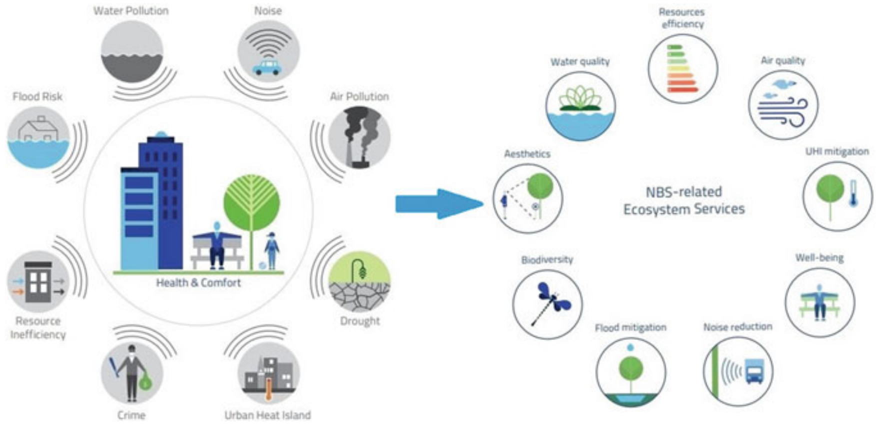

Fig. 3 Various urban pressures including water problems and urban ecosystem services (UES) related to nature-based solutions [33, 34]

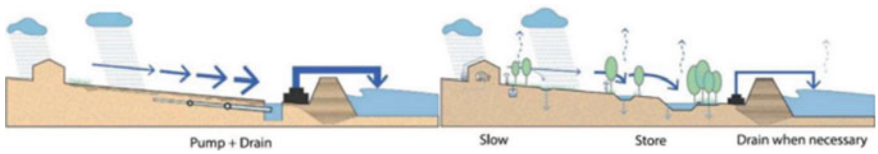

Fig. 4 Retention and infiltration obtained by BGI approach [38]

provides a sustainable infrastructure for cities which can replace grey infrastructure [40]. Many successful implementations of associated aspects of the NBS concept exist worldwide; such as the Gardens by the Bay, Singapore; the High Line Park, New York; the Blue-Green Wave, Paris; City Park, Budapest and so on. Table 1 represents some of the major global BGI measures and their multiple benefits in the urban ecosystem with some regional implementations [34, 41–44].

4.3 *Some of the Major BGI Projects for Cities Across the Globe*

In the last two decades, the adaptation of nature-based solutions has been increased for sustainable and integrated water management. The Netherlands has achieved great success in the riverine and coastal flood management in its territory by implementing the ‘Room for the River’ project (not primarily a UFM project) based on sustainable and innovative practises [68]. With the increasing research based on sustainable solution with the intervention of NBS, several BGI projects have been initiated in

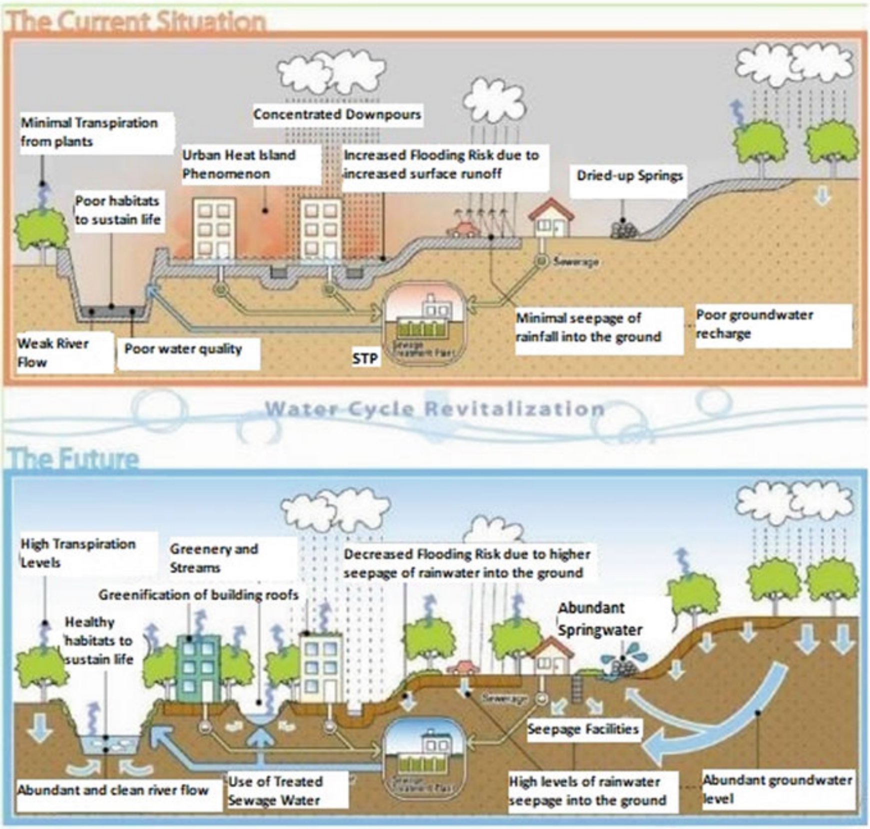

Fig. 5 BGI based Nagoya city strategy [39]

many cities all over the world. Six major urban projects related to NBS or BGI are briefly discussed as follows.

Rain City Strategy

It is a sustainable and pragmatic roadmap for the city of Vancouver in Canada; approved in 2019 to become a water sensitive city by evolving the rainwater management practises and UES. The primary goals of 'Rain city Strategy' are: to increase Vancouver's resilience through sustainable water management (SWM); to improve and protect Vancouver's water quality; and to enhance Vancouver's liveability by improving natural and urban ecosystems. Similar to GI or BGI measures, the 'Rain City Strategy' has defined the term 'green rainwater infrastructures' (GRI) which consists the measures such as rain gardens, bioswales, rainwater tree trenches, blue & green roofs, parks and absorbent landscape, permeable pavements, wetlands, downspout disconnection and some modular systems. To reinforce the strategy goals, six measurable objectives were recognised: removal of pollutants from water and air;

Table 1 BGI measures for urban flood mitigation and other urban ecosystem services

BGI measures	Benefits/urban ecosystem services	Some regional implementations and studies	References
Street trees (green roads)	Stormwater management and urban flood mitigation, UHI mitigation, improved air quality, recreation and well-being, aesthetics	Many implementations in Australia, US, UK, Taiwan, China, Vietnam	Depietri and McPhearson [41], Brown and Mijic [43], Hamel and Tan [45], Eva and Christoph [46], Schuch et al. [47]
Permeable pavements	Stormwater management and urban flood mitigation, improved water quality, aesthetics	Taichung city (Taiwan); many cities of US, UK Australia, Indonesia	Depietri and McPhearson [41], Puchol-Salort et al. [44], Schuch et al. [47], Lin et al. [48]
Engineered stormwater controls (rain gardens, bioswales and retention ponds)	Stormwater management and urban flood mitigation, urban water supply, UHI mitigation, improved water quality, improved air quality, urban agriculture, biodiversity, Recreation and well-being, aesthetics	Increased implementations in Southeast Asian cities and European cities	Natural Resources Defence Council (NRDC) [42], Kato et al. [49], Sidek et al. [50], Wang et al. [51]
Green roofs and blue roofs	Stormwater management and urban flood mitigation, UHI mitigation, improved air quality, biodiversity, aesthetics	Paris (France), London (UK), Brussels (Germany), Seoul (South Korea), Victoria (Australia), many cities of Thailand, Singapore and Malaysia	Oral et al. [34], Brown and Mijic [43], Hermawan et al. [52], Mentens et al. [53], Shafique et al. [54], Lim and Lu [55], Maryati and Humaira [56]
Green facades	UHI mitigation, improved air quality, biodiversity, aesthetics	Thamesmead Waterfront development plan in London (UK), Melbourne (Australia), many cities of Europe and North America	Brown and Mijic [43], Victoria State Government [57], Norton et al. [58]
Urban parks and gardens	Stormwater management and urban flood mitigation, urban agriculture, UHI mitigation, improved water quality, improved air quality, biodiversity, recreation and well-being, aesthetics	The centenary park at Chulalongkorn University in Bangkok (Thailand); 'pocket parks' in Kuala Lumpur (Malaysia); New York (US) and London (UK)	Depietri and McPhearson [41], Natural Resource Defence Council (NRDC) [42], Puchol-Salort et al. [44], Liberalesso et al. [59]

(continued)

Table 1 (continued)

BGI measures	Benefits/urban ecosystem services	Some regional implementations and studies	References
Wetlands and urban lakes	Stormwater management and urban flood mitigation, biodiversity, urban water supply, Recreation and well-being, aesthetics	Can Tho (Vietnam), Thamesmead Waterfront development plan in London (UK), Newcastle (England), Phnom Penh (Cambodia), Mississippi (US)	Depietri and McPhearson [41], Brown and Mijic [43], Holmes [60], U.S.Army Corps of Engineers (USACE) [61], Irvine et al. [62], Institute for Social and Environmental Transition ISET)-International [63]
Rainwater harvesting system	Stormwater management and urban flood mitigation, urban water supply	London (UK), Portland (US), Northern Taiwan, Dhaka (Bangladesh) and many other cities of across the globe	Depietri and McPhearson [41], Brown and Mijic [43], O'Donnell [64], Li et al. [65]
Green parking lots	Stormwater management and urban flood mitigation, UHI mitigation, improved air quality	'Green Street Program' of Portland (US); Montgomery in Maryland (US)	Depietri and McPhearson [41], Ahammad [66], Environmental Protection Agency (EPA) [67]

increase in managed impermeable area; increase in total green area; UHI mitigation; rainwater harvesting; and reduction of rainwater volume entering the drainage pipes. Therefore, the implementation of GRI ensures multiple UES such as improved air and water quality; reduced overland flooding; enhanced biodiversity; improved microclimate through shading and green spaces; and replenished groundwater. This is a paradigm shift in 'how to manage water' in the city having the potential to protect the health and well-being of communities and urban ecosystems [69, 70].

Sponge City Programme

The concept of the Sponge City Programme (SCP) was proposed in 2013 to deal with the urban water management challenges in the rapidly urbanising cities of China and ultimately to achieve a sustainable urban development. Based on the application of six technical measures (infiltration, retention, storage, purification, utilisation and discharge); SCP develops solutions to manage urban floods, improve water quality, enhance water storage and discharge capacity, and mitigate UHI through the integration of NBS. The SCP targets 20% and 80% of the city area to meet the sponge city standards by 2020 and 2030 respectively; absorbing 60–85% of annual rainfall. The primary focus for sponge city construction should be the conservation, restoration and rehabilitation of natural ecosystems to build "resilience" for cities. Wuhan is one of the cities out of 30 sponge pilot cities in China and the implementation of SCP was initiated in the city in 2015. The infrastructures applied in Wuhan consist of rain gardens, grass swales, bioretention facilities, porous pavements, infiltration trenches, and rainwater harvesting components. Wuhan City experienced multiple extreme and unprecedented precipitation events during the rainy season of 2020, but no severe waterlogging occurred in any region of the city. The Wuhan Sponge City Programme has showcased the potential of NBS and successfully managed the flood risk in the city and achieved other social, ecological and environmental benefits [71–73].

Grey to Green (G2G) Initiative

Portland, one of the most populous cities in the United States is a torchbearer in nature-based sustainable practises in stormwater management. The City of Portland started the Grey to Green (G2G) initiative in 2008 to expand the City's green infrastructure (GI) and to implement sustainable practises in stormwater management with multiple goals such as protecting and restoring natural areas and their ecosystems. The green infrastructure (GI) measures under the G2G Initiative include green streets, blue-green roofs (eco-roofs), raingardens, removing invasive vegetation and restoring the natural areas. During its implementation period from 2008 to 2013, the public and private partners of the initiative expanded GI in the city and supported jobs through the installation of 398 eco-roofs; the plantation of more than 32,200 street and yard trees capable of capturing over 18 million gallons of stormwater each year; the construction of 867 new green street planters (rain gardens); treatment of over 7,400 acres of lands for invasive vegetation; the plantation of more than 500,000 new native vegetation on about 4,100 acres of lands; and the acquisition of 406 acres of natural areas in the city for natural stormwater management functions and clean water sources. The investment in green infrastructures through the Portland Bureau of Environmental Services (BES) has been increased. The green infrastructures provide a range of ecosystem services such as reduced stormwater runoff, urban flood resilience, UHI mitigation, climate change adaptation, improved water and air quality, urban agriculture, biodiversity, aesthetics, Recreation and well-being [70, 74, 75].

New York City (NYC) Green Infrastructure Plan

The NYC Green Infrastructure (GI) Plan was introduced in 2010 with a 20 year plan to reduce combined sewer overflow (CSO) with sustainable stormwater management practises incorporating green infrastructure measures. The NYC Department of Environmental Protection (DEP) is the governing agency for the implementation of the city's GI Plan. "By preventing one inch of precipitation from becoming runoff that surges into the sewers over 10% of each combined sewer watershed's impervious area, DEP estimates that CSOs will be reduced by approximately 1.5 billion gallons per year" [76]. This translates to installing GI on about 8,000 acres by 2030. The types of GI in the programme consist of rain gardens, infiltration basins, permeable pavements, green roofs, detention basins etc. The implementation of the NYC plan does not only reduce the CSO volume in the city but also provides substantial co-benefits such as UHI mitigation, energy use reduction, air quality improvement, groundwater recharge, habitable environment and increasing property values [75, 76].

Green Living Spaces Plan

The Green Living Spaces Plan was approved in 2013 for the city of Birmingham (United Kingdom). The plan introduces seven key principles considering the issues of climate change and other multiple social, economic and environmental needs of the city. Incorporating BGI measures, the major intended outcomes of the plan are: to adopt the measures of WSUD for Integrated SuDS, flood and water management solutions; to embrace urban forestry and urban food production; to adopt Natural Health Improvement Zones (NHIZ); and to ensure the adaptation of future growth [77].

Blue-Green Cities Research Project

The Blue-Green Cities Research Project was initiated in 2013 at the University of Nottingham in United Kingdom (UK) to devise novel strategies for urban flood risk management and integrated urban planning to accomplish environmental enhancement in which multiple benefits of Blue-Green Cities are thoroughly analysed and evaluated. In this three-year duration project from 2013 to 2016, eight other universities in UK also participated in addition to several academic, industrial and local government partners. The major objectives of the project were: to identify the uncertainties and barriers to BGI; to develop a 'flood footprint' tool to quantify the economic impact of flooding; to remodel the existing urban drainage system; to create hybrid strategies combining hard and soft flood adaptation; and to identify knowledge gaps in urban drainage network. Flood inundation simulations have proven that the inclusion of BGI (such as green roofs, permeable pavements, swales, green spaces and detention ponds) reduced flood risk with additional benefits such as carbon sequestration, reduce air and noise pollution and many other ecosystem services [63, 78, 79].

BGI provides various urban ecosystem services (Fig. 3) and multiple economic advantages are associated with these UES [75]. Table 2 summarises the description of the metropolises and BGI adoption plans considered in the present study.

5 Challenges in the Intervention of BGI for Urban Water Management

Although existing BGI based projects in the world may differ from region to region on the basis of the nature of problem and desired results. In India, every city has some unique set of problems due to the vast diversity in socio-economic culture, demography and hydro-meteorology. But the lessons learnt from the global initiatives would be proven to be a constructive step towards developing BGI frameworks to address the regional challenges in flood and stormwater management in Indian cities. Despite the importance of the blue and green spaces to the community and environment, these natural spaces are declining and impervious surfaces are increasing in urban areas of

Table 2 Summary of BGI adoption plans in the major global cities analysed in the present study

Name of BGI projects and implementation years	Metropolis	Population	Area (km^2)	Major objectives	References
Rain city strategy (approved in 2019)	Vancouver (Canada)	6,31,486	114	• To increase Vancouver's resilience through SWM through GRI implementation • To improve Vancouver's water quality • To enhance Vancouver's liveability	European Environment Agency (EEA) [69], Rain City strategy [70]
Sponge city programme (2013-present)	Wuhan (China)	1,06,00,000	8494	• To manage urban floods, improve water quality, enhance water storage and discharge capacity, and mitigate UHI through integration of NBS • Targets 80% of the city area to meet the sponge city standards by 2030; absorbing 60–85% of annual rainfall	Udas Mankikar and Driver [71], Qi et al. [72], Peng and Reilly [73], Fenner [80]
Grey to green initiative (2008–2013)	Portland (USA)	22,26,009	17,310	• To implement GI measures for urban flood resilience, UHI mitigation, and climate change adaptation, with other environmental and socio-economic benefits	Rain city strategy [70], [74], Li and Zhang [75]
NYC green infrastructure plan (2010–2030)	New York (USA)	1,95,67,410	34,490	• To reduce CSO through sustainable stormwater management practises incorporating GI measures; with additional UES	Li and Zhang [75], [76, 81]

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Table 2 (continued)

Name of BGI projects and implementation years	Metropolis	Population	Area (km^2)	Major objectives	References
Green Living Spaces plan (approved in 2013)	Birmingham (UK)	37,01,107		• To adopt integrated SuDS, flood and water management solutions; • To embrace urban forestry and food production; • To ensure the adaptation of future growth	Li and Zhang [75], Shakya and Ahiablame [77]
Blue-green cities research project (2013–2016) (Collaborative BGI research project in the university of Nottingham, UK)	–	–	–	• To characterise the challenges and barriers to BGI; • To develop a 'flood footprint' tool to quantify economic impact of flooding; • To remodel the existing urban drainage system; • To create adaptive strategies through BGI integration	Institute for Social and Environmental Transition (ISET)-International [63], NYC green infrastructure plan [78], Green living spaces plan [79]

India. Analysing the factors causing urban water issues in Chennai, some of major challenges in BGI intervention which need to be addressed are as follows.

- **Availability of natural landscapes**: Due to rampant urbanisation, the proportion of blue and green spaces has declined over time in Chennai. The available natural spaces limit the implementation of many BGI measures (e.g., urban parks, gardens, lakes, retention ponds and wetlands) in the city.
- **Demographic features of city**: Chennai is one of the oldest Indian cities and exhibits very high population density; making the existing combined sewer system inadequate. In such cases, designing and remodelling separate sewer systems with SuDS measures will be quite challenging.
- **Lack of appreciation of overarching benefits of BGI**: Due to the lack of quantification of the multiple benefits and the knowledge gaps, BGI may not be initially treated as an important dimension for urban planners and some local authorities.
- **Limitation of BGI research and funds**: The traditional approach of flood management is still practised in India. There has been a lack of research for the nature–based solutions in India. Implementations of BGI projects are quite expensive. In a developing nation like India, investing million of dollars on BGI projects will not be easy; that too in the lack of extensive researches.

- **Lack of enforceable standards at the policy making and planning level**: However, the Government of India initiated the major urban transformation programme 'Atal Mission for Rejuvenation and Urban Transformation' (AMRUT) focussing on the provision of stormwater drains, water supply, sewerage, green spaces and public transport in 500 cities of India [82]. At planning and policy making stage, there is a lack of enforceable standards for a certain quality and quantity of BGI in new or existing developments.

6 Conclusion

Climate across the globe has been changing for the past few decades, and it seems unavoidable in the foreseeable future. The impacts of climate change will be further exacerbated if the trend of urbanisation and economic development keeps increasing without incorporating environmental aspects. In India, Chennai has witnessed a sharp growth in urban population and an uncontrolled expansion of urban settlement in the recent decades. The unplanned rapid expansions of the city are leading to the loss of natural LULC (i.e., blue and green spaces) thereby increase in impermeable surfaces. Associated problems with urban agglomeration and climate change further aggravate the flood and drought vulnerability of the city. The root causes which are making the city more vulnerable to climatic extremes (floods and droughts) and their impacts have been discussed in the present study. The extreme precipitation events have been intensified in last few decades due to climate change. Even subsequent to a short-term heavy precipitation event, the urban drainage system (generally, combined sewer system) result in overflow and waterlogging of nearby areas. Inappropriate solid and liquid waste management have also severely deteriorated the water management system of the city. Therefore, a need of innovative research for sustainable solutions to manage urban flooding and water scarcity issues in the city is inevitable.

Chennai needs to consider the urban water issues on a priority basis, exploring a systematic nature-based sustainable model for effective urban flood and water stress management. This paper also explores the emerging, innovative and sustainable concept of BGI and the various related terminologies (such as GI, SuDS, NBS, LID and EBA). The overarching benefits of BGI in terms of UES have been highlighted in the present study with some of the regional implementations in the world. Many cities of Europe and other developed countries have successfully implemented the BGI measures to manage their floods with other ecosystem services (such as aesthetics, urban water supply, UHI mitigation, improved water quality, improved air quality, urban agriculture, biodiversity, Recreation and well-being). Hardly any comprehensive literature on BGI concept with the additional UES for Indian cities was found. The insightful use of BGI will be one of the most promising actions for adaptation to rapidly changing urban spaces; which needs to be recognised at the planning stage, starting from regional level to city level. The analysis of the six major BGI projects in some of the major cities of the world has been presented to understand the potential of BGI intervention for urban water management. The findings emphasised on the need of a paradigm shift from traditional approaches to BGI based approaches for the urban flood and water stress management in Chennai. Considering the extent of flood damages and the expected impact of climate change in future; it can be concluded that resilient, sustainable and rational solutions are no longer a choice but rather a compulsion. Developing a BGI based integrated and sustainable approach for urban flood and water stress management is essential to derive multiple ecosystem benefits regarding urban well-being and to maintain the natural hydrologic regime, in addition to the stormwater and water supply management.

References

1. Ghofrani Z, Sposito V, Faggian R (2017) A comprehensive review of blue-green infrastructure concepts. Int J Environ Sustain [IJES] **6**(1): 15–36. ISSN 1927-9566
2. UN (2018) World Urbanisation Prospects: The 2018 Revision [Key Facts]. https://esa.un.org/unpd/wup/Publications/Files/WUP2018-KeyFacts.pdf
3. Tewari M, Godfrey N, et al (2016) Better cities, better growth: India's urban opportunity. New climate economy, world resources institute, and Indian council for research on international economic relations. London, Washington, DC, and New Delhi. http://newclimateeconomy.report/workingpapers
4. Bozovic R, Maksimovic Č, Mijic A, Smith KM, Suter I, Van Reeuwijk M (2017) Blue green solutions. A systems approach to sustainable, resilient and cost-efficient urban development. https://doi.org/10.13140/RG.2.2.30628.07046
5. IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781139177245
6. Chennai Metropolitan Development Area (CMDA). http://www.cmdachennai.gov.in/
7. Kaaviya R, Devadas V (2021) Water resilience mapping of Chennai, India using analytical hierarchy process. Ecol Process 10:71. https://doi.org/10.1186/s13717-021-00341-1
8. Lavanya AK (2012) Urban flood management—a case study of Chennai city. Architecture Res 2(6): 115–121. https://doi.org/10.5923/j.arch.20120206.01
9. World Resources Institute (WRI) (2015) Aqueduct water risk atlas. https://www.wri.org/data/aqueduct-global-maps-21-data
10. Boyaj A, Ashok K, Ghosh S, Devanand A (2018) The Chennai extreme rainfall event in 2015: the Bay of Bengal connection. Clim Dyn 50(7):2867–2879. https://doi.org/10.1007/s00382-017-3778-7
11. MoHUA (2019) Manual on storm water drainage systems, vol I & II, 1st Edn. Central public health and environment engineering organisation, ministry of housing and urban affairs (MoHUA). Government of India
12. Mujumdar M, Bhaskar P, Ramarao MVS, Uppara U, Goswami M, Borgaonkar H, Chakraborty S, Ram S, Mishra V, Rajeevan M, Niyogi D (2020) Droughts and floods. In: Krishnan R, Sanjay J, Gnanaseelan C, Mujumdar M, Kulkarni A, Chakraborty S (eds) Assessment of climate change over the Indian region. Springer, Singapore, pp 117–141. https://doi.org/10.1007/978-981-15-4327-2_6
13. Bremner L (2020) Planning the 2015 Chennai foods. Environ Plan E Nat Space 3(3):732–760. https://doi.org/10.1177/2514848619880130
14. National disaster management guidelines: management of urban flooding. national disaster management authority (NDMA). Government of India. ISBN: 978-93-80440-09-5, September 2010, New Delhi
15. Sharif M, Dhillon MS, Chandra S, Kumar M, Vasanthakumar V (2020) Urban flooding—a case study of Chennai floods of 2015. In: Ahmed S, Abbas S, Zia H (eds) Smart cities—opportunities

and challenges. Lecture notes in civil engineering, vol 58. Springer, Singapore. https://doi.org/10.1007/978-981-15-2545-2_64
16. Vazhuthi N, Kumar A (2020) Causes and impacts of urban floods in Indian cities: a review. Int J Emerging Technol 11(4):140–147
17. O'Donnell EC, Thorne CR (2020) Drivers of future urban flood risk. Phil Trans R Soc A 378:20190216. https://doi.org/10.1098/rsta.2019.0216
18. Census (2011) Census of India 2011. https://www.census2011.co.in/
19. Gupta AK, Nair S (2011) Urban floods in Bangalore and Chennai: risk management challenges and lessons for sustainable urban ecology. Curr Sci 100(11)
20. Esther S, Devadas MD (2016) A calamity of a severe nature: case study- Chennai, India. Urban water system and floods. WIT Trans Built Environ 165: 227–236. https://doi.org/10.2495/UW160201
21. The Nature Conservancy (2021) "Restoring Chennai's wetlands". Care Earth Trust. IIT Madras. https://www.nature.org/content/dam/tnc/nature/en/documents/india/restoring-chennai-wetlands.pdf
22. Narasimhan B, Bhallamudi M, Mondal A, Ghosh S, Mujumdar P (2016) Chennai floods 2015: a rapid assessment report. Interdisciplinary centre for water research, Indian Institute of Science, Bangalore. May 2016
23. http://www.icwar.iisc.ac.in/wp-content/uploads/2016/06/Chennai-Floods-Rapid-Assessment-Report.pdf
24. Ramasamy SM, Vijay A, Dhinesh S (2018) Geo-anthropogenic aberrations and Chennai floods: 2015. India. Nat Hazards 92(1):443–477
25. Rajaveni SP, Nair IS, Elango L (2016) Evaluation of impact of climate change on seawater intrusion in a coastal aquifer by finite element modelling. J Clim Change 2:111–118. https://doi.org/10.3233/JCC-160022
26. Roumeau S, Seifelislam A, Jameson S, Kennedy L (2015) Water governance and climate change issues in Chennai, pp 1–34
27. Vojinovic Z (2015) Floor risk: the holistic perspective—from integrated to interactive planning for flood resilience. The International Water Association (IWA) Publishing
28. Alves A (2020) Combining green-blue-grey infrastructure for flood mitigation and enhancement of co-benefits. CRC Press/Balkema—Taylor & Francis Group
29. Benedict M, MacMahon E (2002) Green infrastructure: smart conservation for the 21st century. Renew Resour J 20(3): 12–17. ISSN 0738-6532
30. European Commission (EC) (2017) Green infrastructure and flood management: promoting cost-efficient flood risk reduction via green infrastructure solutions. EEA Report No 14/2017, European Environment Agency, Denmark
31. Raymond CM, Frantzeskaki N, Kabisch N, Berry P, Breil M, Nita MR, Geneletti D, Calfapietra C (2017) A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. Environ Sci Policy 77(June):15–24. https://doi.org/10.1016/j.envsci.2017.07.008
32. Nesshöver C, Assmuth T, Irvine KN, Rusch GM, Waylen KA, Delbaere B, Haase D, Jones-Walters L, Keune H, Kovacs E, et al (2017) The science, policy and practice of nature-based solutions: an interdisciplinary perspective. Sci Total Environ 579: 1215–1227. ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2016.11.106
33. Dorst H, van der Jagt S, Raven R, Runhaar H (2019) Urban greening through nature-based solutions—key characteristics of an emerging concept. Sustain Cities Soc. https://doi.org/10.1016/j.scs.2019.101620
34. Oral HV, Carvalho P, Gajewska M, Ursino N, Masi F, Hullebusch ED, Kazak JK, Exposito A, Cipolletta G, Andersen TR, Finger DC, Simperler L, Regelsberger M, Rous V, Radinja M, Buttiglieri G, Krzeminski P, Rizzo A, Dehghanian K, Nikolova M, Zimmermann M (2020) A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature. Blue-Green Syst 1 2(1): 112–136. https://doi.org/10.2166/bgs.2020.932

35. Blue Green Solutions (BGS) (2017) A systems approach to sustainable, resilient and cost-efficient urban development, March 2017. Technical Report. Climate-KIC, European Union. https://doi.org/10.13140/RG.2.2.30628.07046
36. Winker M, Gehrmann S, Schramm E, Zimmermann M, Rudolph-Cleff A (2019) Greening and cooling the city using novel urban water systems: a European perspective. In: Sharma AK, Begbie D, Gardner T (eds) Approaches to water sensitive urban design. Potential, design, ecological health, urban greening, economics, policies, and community perceptions. Elsevier, Duxford, UK, pp 431–455
37. Maksimovic C, Mijic A, Smith KM, Suter I, van Reeuwijk M (2017) Blue green solutions. a systems approach to sustainable, resilient and cost-efficient urban development. Technical report. https://doi.org/10.13140/RG.2.2.30628.07046
38. Bolund P, Hunhammar S (1999) Ecosystem services in urban areas. Ecol Econ 29(2): 293–301. ISSN 0921-8009. https://doi.org/10.1016/S0921-8009(99)00013-0
39. Cruijsen A (2015) Design opportunities for flash flood reduction by improving the quality of the living environment: a Hoboken City case study of environmental driven urban water management, PhD thesis, TU Delft, Delft University of Technology
40. Kazmierczak A, Carter JG (2010) Adaptation to climate change using green infrastructure, a database of case studies. The Town and Country Planning Association, London
41. Depietri Y, McPhearson T (2017) Integrating the grey, green, and blue in cities: nature-based solutions for climate change adaptation and risk reduction. In: Kabisch N, Korn H, Stadler J, Bonn A (eds) Nature-based solutions to climate change adaptation in urban areas. Springer, pp 91–109. https://doi.org/10.1007/978-3-319-56091-5
42. Natural Resource Defence Council (NRDC) (2019) Green infrastructure: how to manage water in a sustainable way. https://www.nrdc.org/stories/green-infrastructure-how-manage-water-sustainable-way
43. Brown K, Mijic A (2019) Integrating green and blue spaces into our cities: making it happen. Grantham Institute Briefing Paper, No 30. Imperial College London
44. Puchol-Salort P, O'Keeffe J, Reeuwijk M, Mijic A (2021) An urban planning sustainability framework: systems approach to blue green urban design. Sustain Cities Soc 66: 102677. ISSN 2210-6707. https://doi.org/10.1016/j.scs.2020.102677
45. Hamel P, Tan L (2021) Blue-green infrastructure for flood and water quality management in southeast Asia: evidence and knowledge gaps. Environ Manage. https://doi.org/10.1007/s00267-021-01467-w
46. Eva N, Christoph W (2008) Green lines—red dots: combining waste water infrastructure, nutrient recycling and urban landscape development in Le Binh, Can Tho Vietnam, faculty of architecture and landscape science, institute for open space planning and design, Studio Urbane LandSchaften, Leibniz University Hanover
47. Schuch G, Serrao-Neumann S, Morgan E, Choy DL (2017) Water in the city: green open spaces, land use planning and flood management—an Australian case study. Land Use Policy 63:539–550
48. Lin J-Y, Chen C-F, Ho C-C (2018) Evaluating the effectiveness of green roads for runoff control. J Sustain Water in the Built Environ 4(2):04018001. https://doi.org/10.1061/JSWBAY.0000847
49. Kato S, Hishiyama K, Agung Ketut Darmadi A, Ngurah Suprapta D (2017) Changing roles of traditional small urban green spaces (Telajakan) in Bali, Indonesia. Open J Ecol 7: 1–11. https://doi.org/10.4236/oje.2017.71001
50. Sidek LM, Muha NE, Noor NAM, Basri H (2013) Constructed rain garden systems for stormwater quality control under tropical climates. IOP Conf Ser: Earth Environ Sci 16: 012020
51. Wang J, Chua LHC, Shanahan P (2019) Hydrological modeling and field validation of a bioretention basin. J Environ Manage 240:149–159
52. Hermawan AA, Talei A, Salamatinia B, Chua LHC (2020) Seasonal performance of stormwater biofiltration system under tropical conditions. Ecol Eng 143:105676. https://doi.org/10.1016/j.ecoleng.2019.105676

53. Mentens J, Raes D, Hermy M (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landsc Urban Plan 77:217–226. https://doi.org/10.1016/j.landurbplan.2005.02.010
54. Shafique M, Reeho Kim R, Lee D (2016) The potential of green-blue roof to manage storm water in urban areas. Nat Environ Pollution Technol 15(2). ISSN: 0972-6268
55. Lim HS, Lu XX (2016) Sustainable urban stormwater management in the tropics: an evaluation of Singapore's ABC waters program. J Hydrol. https://doi.org/10.1016/j.jhydrol.2016.04.063
56. Maryati S, Humaira ANS (2017) Implementation of green infrastructure concept in citarum watershed. In: Proceedings of the AIP conference proceedings. American institute of physics inc., p 020031. https://doi.org/10.1063/1.4976895
57. Victoria State Government (VSG) (2017) Planning a green-blue city: a how-to guide for planning urban greening and enhanced stormwater management in Victoria, February 2017, Department of environment, land, water and planning, Victoria, Australia
58. Norton BA, Coutts AM, Livesley SJ, Harris RJ, Hunter AM, Williams NSG (2015) Planning for cooler cities: a framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. Landsc Urban Plan 134:127–138. https://doi.org/10.1016/j.landurbplan.2014.10.018
59. Liberalesso T, Cruz CO, Silva CM, Manso M (2020) Green infrastructure and public policies: an international review of green roofs and green walls incentives. Land Use Policy 96: 104693. ISSN 0264-8377. https://doi.org/10.1016/j.landusepol.2020.104693
60. Holmes D (2019) Chulalongkorn University Centenary Park—green infrastructure for the city of Bangkok [WWW document]. World Landscape Architecture. https://worldlandscapearchitect.com/chulalongkorn-centenary-park-green-infrastructure-for-the-city-of-bangkok/#.Yg3IpThBzIU
61. U.S. Army Corps of Engineers (USACE) (2012) ROOM FOR THE RIVER: preparedness, response, recovery and mitigation—summary report of the 2011 Mississippi river flood and successful operation of the Mississippi river and tributaries system
62. Irvine K, Sovann C, Suthipong S, Kok S, Chea E (2015) Application of PCSWMM to assess wastewater treatment and urban flooding scenarios in Phnom Penh, Cambodia: a tool to support eco-city planning. J Water Manag Model. https://doi.org/10.14796/jwmm.c389
63. Institute for Social and Environmental Transition (ISET)-International (2018) Policy brief: the role of green infrastructure in managing urban floods. December, 2018. https://www.preventionweb.net/publication/policy-brief-role-green-infrastructure-managing-urban-flood
64. O'Donnell EC, Thorne C, Yeakley JA (2018) Managing urban flood risk in blue-green cities: the clean water for all initiative. J Flood Risk Manage. https://doi.org/10.1111/jfr3.12513
65. Li YH, Tung CP, Chen PY (2017) Stormwater management toward water supply at the community scale—a case study in Northern Taiwan. Sustainability 9: 1206. https://doi.org/10.3390/su9071206
66. Ahammad M (2018) Analysis of stormwater runoff for a selected catchment of eastern Dhaka using hydrologic model, M.Sc. engineering thesis, Department of water resources engineering, Bangladesh university of engineering and technology, March, 2018
67. Environmental Protection Agency (EPA) (2008) Green parking lot resource guide—February 2008, National service center for environmental publications (NSCEP), United States
68. Montgomery County Planning Commission (MCPC) (2011) Planning by design: green parking lots. Montgomery County, Maryland, US. https://www.montcopa.org/DocumentCenter/View/3017/Green_Parking_08_29_2011
69. European Environment Agency (EEA) (2021) Interview—The Dutch make room for the river. https://www.eea.europa.eu/signals/signals-2018-content-list/articles/interview-2014-the-dutch-make
70. Rain city strategy: a green rainwater infrastructure and rainwater management initiative, November 2019. City of Vancouver, Canada. https://vancouver.ca/files/cov/rain-city-strategy.pdf
71. Udas Mankikar S, Driver B (2021) Blue-green infrastructure: an opportunity for Indian cities. ORF Occasional Paper No. 317, May 2021, Observer Research Foundation

72. Qi Y, Chan FKS, O'Donnell EC, Feng M, Sang Y, Thorne CR, Griffiths J, Liu L, Liu S, Zhang C, Li L, Thadani D (2021) Exploring the development of the sponge city programme (SCP): the case of Gui'an new district, Southwest China. Front. Water 3:676965. https://doi.org/10.3389/frwa.2021.676965
73. Peng Y, Reilly K (2021) Grow green - using nature to reshape cities and live with water: an overview of the Chinese sponge city programme and its implementation in Wuhan. IUCN European Regional Office
74. http://growgreenproject.eu/wp-content/uploads/2021/01/Sponge-City-Programme-in-Wuhan-China.pdf
75. Li F, Zhang J (2022) A review of the progress in Chinese Sponge City programme: challenges and opportunities for urban stormwater management. Water Supply 22(2): 1638–1651. https://doi.org/10.2166/ws.2021.327
76. Grey to green accomplishments, environmental services - working for clean rivers, bureaus & offices of the city of Portland, Oregon, United States. https://www.portlandoregon.gov/bes/article/321331
77. Shakya R, Ahiablame L (2021) A synthesis of social and economic benefits linked to green infrastructure. Water 2021(13):3651. https://doi.org/10.3390/w13243651
78. NYC green infrastructure plan (2010) A sustainable strategy for clean waterways. https://www1.nyc.gov/assets/dep/downloads/pdf/water/stormwater/green-infrastructure/nyc-green-infrastructure-plan-2010.pdf
79. Green living spaces plan (2013) Development directorate—birmingham city council, city of Birmingham, United Kingdom. https://www.birmingham.gov.uk/greenlivingspaces
80. Fenner R (2020) Urban flood resilience—philosophical transactions of the royal society A., The Royal Society Publishing, London, United Kingdom. https://royalsocietypublishing.org/toc/rsta/2020/378/2168
81. Blue green cities: delivering and evaluating multiple flood risk benefits in blue-green cities; a research project. University of Nottingham, UK. http://www.bluegreencities.ac.uk/
82. Zhou Y, Sharma A, Masud M, Gaba GS, Dhiman G, Ghafoor KZ, AlZain MA (2021) Urban rain flood ecosystem design planning and feasibility study for the enrichment of smart cities. Sustainability 13:5205. https://doi.org/10.3390/su13095205
83. McPhearson T, Hamstead Z, Kremer P (2014) Urban ecosystem services for resilience planning and management in New York city. AMBIO 43.https://doi.org/10.1007/s13280-014-0509-8
84. Gupta K (2020) Challenges in developing urban flood resilience in India. Phil Trans R Soc A 378:20190211. https://doi.org/10.1098/rsta.2019.0211

Issues and Challenges of Small-Town Water Supply and Distribution: A Case Study of Leh Town in UT Ladakh

Anub Tsetan Paljor and Kamal Kumar Murari

Abstract Leh-Ladakh is one of the most sought-after tourist destinations in the country. The annual tourist arrivals have ever increased in Leh town without appropriate and necessary urban infrastructure evolving such as water supply and sewage system. This paper aims to highlight certain water issues such as availability, accessibility, and vulnerabilities in Leh town. The town depends on two sources for all its freshwater requirements, glacial melt water and groundwater. Glacier-melt water comes in the form of springs and surface runoff such as streams. Both Public and Private borewells are dug across the town so that the extraction of groundwater becomes easier and over the years it has become economically more viable for the locals. Leh Town has three spring sources and several major tube wells operated by the Public Health and Engineering Department (PHE), which oversees providing drinking water to the town. These sources and their Service Reservoirs (SR), where water is stored before releasing it into the distribution pipes, presently have the capacity of supplying 6.07 MLD in Leh Town, assuming all service reservoirs are functioning at maximum capacity (PHE, 2018). This maximum capacity of water supply is, however, less than the total water demand which stands at 7.5 MLD according to calculations done using population projection data of Leh Town of the year 2018. Further, this demand fluctuates when you consider the large amount of floating population which consists of tourists, service sector employees, migrant labourers, local migrants from other parts of Ladakh, and the defense forces. With regards to the quality of water, groundwater is getting more polluted due to anthropogenic reasons, mainly due to seepage from soak pits. This issue is especially highlighted in the wards of the town where clusters of hotels and guesthouses are close together and hence causes greater pollution of the groundwater. According to the PHE department, a private piped connection of water is presently being given at

A. T. Paljor (✉)
Water and Sanitation Team, Ladakh Ecological Developmental Group (LEDeG), Liveable Leh Project, Leh, UT Ladakh, India
e-mail: anubpaljor@gmail.com

K. K. Murari
School of Habitat Studies, Tata Institute of Social, Mumbai, India
e-mail: kamal.murari@tiss.edu

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a flat rate of INR 2400 per annum for both commercial and household use. However, a very small percentage of these customers pay their tariffs (as per PHE) making the PHE supply water almost free of cost. This practice has led to the department having a poor CAPEX. Thus, an appropriate water pricing mechanism needs to be introduced to control water consumption and pollution.

Keywords Ladakh · Leh Town · Developmental challenges · Water · Sanitation · Groundwater · Glaciers · Tourism · Unplanned rapid urbanization

1 Introduction

Nestled in the high ranges of the Himalayas, at an altitude of above 3,500 m, the Himalayan region of Ladakh was recently declared as a separate Union Territory (UT) of India, bifurcating it from the erstwhile state of Jammu and Kashmir. UT Ladakh has two districts, Leh and Kargil. Leh town in Leh district is also the capital of the UT. The entire region is sparsely populated due to its harsh terrain and semi-arid climatic conditions and is often termed a 'cold desert.' There are no monsoons as the district is in the rain shadow region between the Karakoram and upper Himalayas and barely receives rainfall of 60–100 mm per annum. Traditionally precipitation takes place mostly in the form of snowfall in winters; however, changes in precipitation patterns can be observed where the number of rainy days in a year is increasing and snowfall in winters is decreasing.

Ladakh has traditionally been an agro-pastoral community. Subsistence food farming is still largely prevalent in the villages. Sustainable toilet practices such as the use of dry toilets in a 'cold desert' have helped negate the scarcity of water for centuries and the use of dry manure from these dry toilets has led to the traditional food being completely organic. Today, things have changed. Leh-Ladakh is one of the most sought-after tourist destinations in India and as such, the footfall of tourist in the region has increased at a great pace, especially in the last decade, bringing in unprecedented levels of economic development along with developmental challenges. Most of the residents of Leh town no longer practice agriculture and subsistence farming and instead have shifted to tourism-related businesses. Leh has become a service sector economy. This has led to many changes in the lives of the people, traditions, and systems. Agricultural fields have given way to big hotels, guest houses, commercial buildings, restaurants and cafes, etc. The age-old tradition of managing water through the 'Churpon System' (Chu = water, Spon = manager) where individuals/families were given charge of distributing water among all residents has completely vanished from the town.

The increasing number of tourists every year along with migration from other parts of India for work and local migration within Ladakh have rendered Leh town fall short of appropriate urban infrastructure including water supply and a proper wastewater disposal system. Leh Town has been dependent on glacier-melt water and groundwater for all its freshwater needs. Glacial-melt water in the form of streams and springs has been the major source of fresh water for all domestic and agricultural purposes [1]. Today, however, groundwater is being extracted to meet the water demand of the town, which has increased over the years mainly due to tourism-related activities.

The quality of potable water in Leh has also come up as a major concern in the past decade as people are realizing that without proper wastewater disposal, their groundwater is getting polluted. Historically, water from springs and streams in Leh town was safe for consumption, as it still is in far remote villages and valleys of Ladakh. Within Leh town, however, these sources are now contaminated to drink directly from.

Hundreds of hotels and guest houses now provide western flush toilets and bathrooms which consume large amounts of water. It is to be noted that not all hotels or guest houses in Leh town have sceptic tanks; on the contrary, most of the hotels and guesthouses, especially the old ones, do not have sceptic tanks but rather soak pits. There seems to exist a confusion among the locals as to what exactly is the difference between a septic tank and a soak pit. They may think that they have a septic tank in use, but it often turns out to be a soak pit further complicating the issue of quality of water due to seepage of black and grey wastewater.

At present, there is no formal record of the exact number of private borewells in Leh and the exact volume of groundwater extracted. Without this information, any groundwater research of the town would be incomplete. The PHE department along with the Municipal Committee Leh is yet to collect data to quantify all existing private borewells in the town and develop a registration and permit system to control the number of borewells and groundwater extraction. The Municipal Committee has tried getting the official numbers from all different boring companies, and as of now, they have a record of around 700–800 new borewells in Leh. This is not the complete list as some of the old boring companies that have been digging over the last two decades are no longer operational and as such this data does not exist. Ladakh Ecological Development Group (LEDeG), which is one of the oldest NGOs in Ladakh, puts this number at around 1500–2500 borewells in Leh town.

This paper seeks to shed light on the drinking water issues of Leh town, water availability, accessibility, vulnerabilities, and appropriate policy approaches towards sustainable management of drinking water. The paper first outlines the research methods employed in this research. It then estimates water supply and demand in Leh Town. The paper also investigates the current water pricing policy in Leh Town as per PHE and suggests improved water pricing techniques to enhance PHE departments CAPEX.

2 Research Methods

Being a local of Leh town, the author conducted a preliminary round of household surveys in April 2018, after a detailed literature review. The household survey questionnaire was designed to gather information and views on potable water in Leh town, issues including the source of water for domestic uses, and their perception of water quality and water pricing. In addition, semi-structured interviews were conducted in February 2019 with key stakeholders from various organizations. These include engineers from the PHE department Leh, The President of All Ladakh Tour Operators Association (ALTOA), and representatives from Ladakh Ecological Development Group (LEDeG). Semi-structured interviews were also conducted with residents in three wards of Leh Town namely Tukcha, Changspa, and Skampari.

Tukcha and Changspa are considered among the 'green' wards of the town with agricultural fields, trees, hotels, and cafes, whereas Skampari is an upcoming residential area on the side of a hill within the town with virtually no green fields, trees, etc. due to its elevation.

This research also makes use of survey data collected by LEDeG. In October–November 2017, LEDeG in partnership with the Technical University of Munich, Germany (TUM), conducted a survey in the town entitled '*Keeping natural water sources safe and available in Leh: Urban nexus project for water reclamation and reuse pilot project development*'. This study was designed to get an understanding of water supply, demand, quality, and issues in Leh Town under their larger study [2].

Leh Town encompasses a surface area of about 19 km^2 with an estimated local population of 30,870 (Census, 2011). Thus, the population density of Leh Town is about 1,625 persons per km^2 whereas the population density of Leh District is around 3 persons per km^2 [3]. Further, *Leh Town receives a massive floating population, especially in the five summer months (May-Sept) which consists of tourists, service sector employees, and migrant labourers from different states of India, as well as local migrants from other parts of Ladakh who come to Leh town in search of better livelihood opportunities, education,* etc. *as well as the Indian Army* [4].

There are only two sources of freshwater that cater to all the agricultural, industrial, commercial, and domestic needs of the town: that is glacier-melt water and groundwater. There is a lack of data and literature when it comes to Leh's glacier study. The information available is mainly on large glaciers or as a collective study of all the glaciers in the region but nothing specific to the Khardungla glacier that directly feeds the town. '*Despite the hydrological importance of glaciers for the adjoining lowlands, data on the glaciers of the Himalaya, Karakorum, and Hindu Kush ranges are sparse and inconsistent. There is a lack of long-term series and field investigations, especially for glaciers at higher altitudes*' [5, 6].

However, local NGOs such as *Ladakh Environment and Health Organisation* (LEHO) claim that the *Khadungla glacier has presently become a small version of its former past use to be a permanent glacier several decades ago* [7]. Similarly, locals are of the opinion that water shortages are becoming more common than ever before, especially during the spring season when water is needed most.

The PHE has three spring sources from which they provide water to the town, namely Gyalung Spring, Gyamtsa Spring, and T-Trench (PHE, 2019). Approximately 0.8 L of water from these springs are delivered to the residents through piped private connections and public stand posts (PSPs) [8]. The second source of freshwater is groundwater. The PHE department operates 6 tube wells distributed across the town;

out of these, the Indus Bank Lift station is the major source accounting for almost 33% of the water supplied to the town. About 1.3 million litres of water are extracted from these tube wells and distributed in Leh Town.

In order to meet their water demands, locals who can afford to do so have dug private borewells for both domestic and commercial usage. These private borewells extract groundwater from the shallow aquifer underlying Leh town, which is fed by glacial melt water and precipitation. *It was estimated that about 1 million litres of groundwater per day is being extracted in the tourist season* [8].

LEDeG estimates over 50% of all hotels and guest houses in Leh town use private borewells as their main source of water and are extracting more than 1.5 million litres of groundwater daily. *Even though the construction of a borewell actually requires permission, the groundwater extraction itself is not regulated and the total number of borewells, rates of extraction, and groundwater aquifer levels are currently not known* [9]. *Inhabitants of Leh believe that the drying of many springs might be related to the severe exploitation of the shallow groundwater and so far, no strategy exists to tackle the water demand issues in Leh Town* [9].

Presently, there are no regulations or policies that govern the usage and management of groundwater in the town.

3 Results and Discussion

3.1 Estimation of Water Supply and Demand in Leh Town

In order to calculate the total supply of water in Leh, the capacities of the service reservoirs were calculated based on the information provided by engineers of the PHE department. Assuming that the service reservoirs are functioning at maximum capacity, the total supply of water in Leh stands at 6.1 Million Litres Per Day (MLD) in summer and 2.3 MLD in winter, as presented in Table 1.

The total demand for water in Leh Town can be estimated against its projected population and water consumption per capita per day. The population fluctuates in Leh town by season because of tourist numbers and seasonal local migrants. According to the recommendations provided by the Central Public Health and Environmental Engineering Organization (CPHEEO) under the Ministry of Housing and Urban Affairs, if a town has piped water supply but no sewerage system then the max water supply should be considered at 70 L per capita per day (LPCD). Similarly in a town/city which has piped water supply as well as an existing sewerage system

Table 1 Estimate of water supply based on the seasonal operation of service reservoirs

Season	No. of service reservoirs in operation	Total capacity
Summer	14	6,137,100
Winter	6	2,273,000

Table 2 Estimation of water demand for local population in Leh Town as per CPHEEO norms

Season	Population scenario	Water demand scenario (litre per capita per day)	Total demand (litre)
Summer	60,000	70	4,200,000
Winter	40,000	70	2,800,000
Summer	60,000	135	7,800,000
Winter	40,000	135	5,200,000

or contemplating to get one, then the recommended water supply is 135 LPCD with 15% unaccounted for water. Leh presently has partial coverage of the newly built sewerage system. Therefore, calculations of water demand under both 70 LPCD and 135 LPCD are presented in Table 2.

On the other hand, water demand estimates of the town by LEDeG (Liveable Leh Project) are given in a different manner. According to the Livable Leh Project, water demand is calculated for the town based on different LPCD requirements among the locals (summer = 75l pcd, winters = 60l pcd), tourists (summers = 100l pcd, winters = 80l pcd), and the migrant workers (summers = 30l pcd and winters = 0, as there are no migrant labourers in winters.) This results in the summer demand of the town to be at 5.1MLD and the winter demand at 1.9 MLD.

3.2 *Water Demand Estimates with Tourist Population Data for 2018 for All months*

Month wise tourist data for the year 2018 was taken from the Department of Tourism, Leh, and is given in Table 3 below and the water demand for each month of 2018 was calculated. It is widely acknowledged that the summer months in Leh span from May to September hence for these 5 months, the local population was assumed at 42,680 which is the population as calculated by the PHE for the base year 2012 for their *water supply reorganisation project*. Similarly, for the winter months October–March, local population of 37,282 was assumed as per PHE estimations.

Assuming consumption at 135 LPCD + 15% unaccounted for water, and adding the tourist population given in Table 3, to the local population according to PHE (Summer at 42,680 and winter at 37,282), the following are the water demand estimates in Leh for all the months of 2018:

Months	Demand (in MLD)
January	6.6
February	5.9
March	5.9

(continued)

(continued)

Months	Demand (in MLD)
April	7.5
May	13.5
June	18.5
July	17.5
August	14.9
September	12.5
October	9.0
November	6.1
December	5.9

As we can see from the table above, these figures present a picture of the actual water demand in Leh when we consider real tourist figures. It must be noted here that the present total supply assuming that all the S/Rs work on maximum capacity in Leh is **6.1 MLD.** This is enough to meet the water demand of only three months, i.e. February, March, and December when the demand is **5.9 MLD.** For all the other months, the demand is estimated to be way higher than supply, especially for the summer months where the demand reaches as high as **18.5 MLD** in June. Thus, there is a clear gap between supply and demand of water in the town. The widest being in the month of June where there is a gap of **12.4 MLD.** However, these calculations are simply an approximation where demand is calculated at 135 LPCD consumption as well as assuming SRs working at maximum capacity; however, some of the SRs are not operational, especially in the winter months. Likewise, not all residents of the town consume water at 135 LPCD; as mentioned earlier, the literature points to the practice of less water use on the part of the locals. This lifestyle, however, is changing with new trends, increased sense of hygiene, and an overall shift towards modern/western water consuming lifestyle, thanks to the growth in the tourism industry.

Therefore, it is safe to assume here that the remaining water demand is being met through the extensive use of borewells and through informal water markets/suppliers.

3.3 Quality of Water in Leh Town

Traditionally Ladakhi toilets are dry toilets, but as tourism took up pace since 1974 people started building western/Indian styled toilets. Today, almost all houses/hotels/guest houses in the town have either only western toilet or a combination of both western and Ladakhi dry toilets. The problem here lies in the fact that people only used soak pits (dug in the grounds) for their toilet discharge and sceptic tanks are relatively new. In a survey carried out by the Ladakh Ecological Developmental Group (LEDeG) on the quality of groundwater in the town, about 64% of the specimen

Table 3 Month wise tourist influx 2018). (*Source* Tourism Department, UT Ladakh

Month	Tourists
January	5665
February	1136
March	1298
April	11,277
May	44,583
June	77,041
July	70,139
August	53,621
September	38,049
October	20,784
November	2416
December	1357
Total	3,27,366

collected from different areas of the town were found to have high levels of nitrate and E. Coli [10] (LEDeG, 2018).

In 2020, water samples from different reservoirs operated by PHE were sent for laboratory analysis to New Delhi and it confirmed the presence of E. Coli and Nitrate in some of them. This report has been submitted to PHE department and is available at LEDeG office library in Leh. (Water Audit Report, Liveable Leh-BORDA, Indian Institute of Sustainable Development, 2020).

3.4 Water Pricing in Leh Town

Currently, PHE provides water connection at a flat rate of Rs. 2400 per annum for both commercial and household use. This clearly is a major issue as a small household in the town does not consume water anywhere as much as a big hotel or guesthouse. Various public stand posts (taps) across the town provide free water. The PHE dept. also operates water tankers and provides this service to residents living in areas where piped connections haven't reached (due to geographical reasons or freezing of pipes in winters). Hence, compared to other residents of the town, such wards of the town (Skampari for example) face extra difficulties, especially during winters when even storing water becomes a challenge. Due to the shortcomings in water supply, especially during winters, there is a thriving informal market of water in the town. There are no water meters in Leh for households or for commercial establishments and as such people often consume more water than needed. According to PHE representatives, most households with PHE piped connection don't even pay their annual charge and therefore operation and maintenance becomes difficult for the department.

For religious places, schools, hospitals and other public institutions, etc., the PHE provides water for free.

Price of water provided by PHE		
Private connection domestic and commercial	PSPs	Water tanker service
Rs. 2400/annum	Free	Free
In reality as claimed by the PHE, 90% of the people don't pay and thus water to the town is being supplied for free	Only 150 PSPs work in winters and depending on where you live in the town the degree of dependence would change	The frequency of water tanker service has been brought down as the new connections are being laid. Having a new connection however does not guarantee water supply

Regarding the 'informal sources of water', the following is the analysis of the information provided by one of the persons that runs the informal Van Water service. They charge Rs. 450 per trip where they fit 13 cans of 15 L each, i.e. 195 L for Rs. 450. As claimed by the person, usually commercial establishments order three such trips, whereas households tend to order just one trip. Their customers include hotels, guest houses, restaurants as well as households. Even though their business tends to become more visible during winters, they are most busy during summers running water services at night to avoid traffic. At the time of this interaction, the person claimed he had 10 hotels/guest houses that he provides water to and that this number shoots up in summers.

4 Concluding Remarks

- PHE department is still in process of covering all households of the town with functional household tap connections. Providing water meters for each of these households would prove to be a good measure to reduce demand and recover water tariffs based on usage, as have been proven in many cities across India.
- The same is true of the centralized sewerage system which does not cover the entire town and is a major challenge for Leh where different wards of the town have different geographical challenges. India's first PPP model Faecal Sludge Treatment Plant (FSTP) has been built in Leh since 2018 to aid the STP. Decentralized sewerage treatment facilities can provide better service in Leh compared to one centralized unit.
- Under the Liveable Leh Project, multiple reports have been prepared (by the author) after extensive research and collaborative efforts between PHE Dept., LEDeG, LAHDC, BORDA, Technical University of Munich, Indian Institute of Sustainable Development, etc. These are Water Audit reports, Water Strategy reports, Water Safety Plan as per International Water Association standards, Integrated Urban Water Management Plans, Water-Energy-Food nexus reports, etc.

and have been submitted to the PHE department as actionable policies with short-term, mid-term, and long-term focus. It is now up to the Administration of UT Ladakh and PHE department to consider them seriously and implement the ones that they agree as feasible.

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Both senior and junior engineers from PHE Leh have been extremely helpful in providing information as well as implementing pilots under the Liveable Leh project.

Bremen Overseas Research and Developmental Authority (BORDA):

BORDA is one of the funding agencies for the Liveable Leh project and is also revolutionizing wastewater management in Leh town by building India's first PPP model Faecal Sludge Treatment Plant and piloting other innovative solutions in the town.

Dr. Daphne Gondhalekar, Technical University of Munich (TUM):

Dr. Gondhalekar has been working on water and wastewater management in Leh for more than a decade and has numerous publications on the said topic. She has been extremely helpful in providing knowledge and information to the author not only for this paper but numerous other studies that were done in collaboration with the Technical University of Munich under the Liveable Leh Project.

Liveable Leh Project (LEDeG-BORDA-LAHDC)

Ladakh Autonomous Hill Development Council (LAHDC).

References

1. Dolma K, Rishi MS, Lata R (2013) An appraisal of centralized waste water treatment plant with respect to Leh Town 4
2. Gondhalekar D, Drewes JE, Grambow M (2018) Risk and water management under climate change: towards the Nexus City. In: Wilderer PA, Renn O, Grambow M, Molls M, Mainzer K (eds) Sustainable risk management. Springer International Publishing, Cham, pp 85–101
3. District at a Glance | District Leh, Union Territory of Ladakh | India, https://leh.nic.in/about-district/ataglance/
4. Akhtar A (2010) Tourism and water resources in Leh Town (NW-India): aAnalysis from a political ecology perspective. University Heidelberg. Heidelb Ger
5. Armstrong RL (2010) The glaciers of the Hindu Kush-Himalayan region: a summary of the science regarding glacier melt/retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain ranges. Glaciers Hindu Kush-Himal. Reg. Summ. Sci. Glacier Meltretreat Himal. Hindu Kush Karakoram Pamir Tien Shan Mt. Ranges
6. Schmidt S, Nüsser M (2012) Changes of high altitude glaciers from 1969 to 2010 in the trans-Himalayan Kang Yatze Massif, Ladakh. Northwest India. Arct Antarct Alp Res 44:107–121. https://doi.org/10.1657/1938-4246-44.1.107
7. Deen M (2009) Role of LEHO in managing water resources of LehAmruta Sudhalkar
8. Gondhalekar D, Nussbaum S, Akhtar A, Kebschull J (2015) Planning under uncertainty: climate change, water scarcity and health issues in Leh Town, Ladakh, India. In: Leal Filho W, Sümer V (eds) Sustainable Water Use and Management: Examples of New Approaches and Perspectives. Springer International Publishing, Cham, pp 293–312
9. Gondhalekar DD, Kebschull J, To centralize or not to centralize
10. Schwaller C (2018) Assessment of the impact of on-site sanitation systems on groundwater quality in Leh Town, India

Real-Time Smart Water Management System (SWMS) for Smart Home

Anupriya Verma, Amrendra Kumar Singh, Ashutosh Kumar Pathak, and Gaurav Saini

Abstract Water plays a vital role in ensuring a healthy human life. Many water-related issues have been faced by developing countries like poor infrastructure for water, scarcity of drinking water, water pollution, falling water table, and low levels of water security. Over-pumping of groundwater leads to the depletion of the groundwater table. Unfortunately, this situation is worsening. Recently, the trend toward smart and sustainable housing is gaining traction. IoT-based sensors and system automation are a key to such smart constructions. This paper gives a general framework for a Real-time Smart Water Management system (SWMS) for smart homes with the help of sensors added to the water distribution system in a home/villa. Sensors are broadly categorized into three classes, namely Quality Sensors (SQ), Quantity Sensors (QS), and Overflow Sensors (SO). Installation of sensors in the system can be done to prevent overflowing by measuring the water level in terms of capacity. The quality of water can be maintained in terms of certain parameters namely Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Turbidity, pH, Conductivity/Salinity, suspended solids, and oil. The sensors will classify the water emanating from various domestic fixtures as poor or better quality and cause their disposal or reuse accordingly and automatically. Application of the proposed system to smart homes would enable the monitoring of overflowing and quality of water, thereby providing measures for its conservation and reuse. Moreover, it provides an awareness highlight to users about water management in their smart homes.

Keywords Sensors · Sustainable · Water conservation · Water quality · Reuse · Decision system

A. Verma (✉) · A. K. Singh · G. Saini
Department of Civil Engineering, Netaji Subhas University of Technology, New Delhi, India
e-mail: anupriya.verma.phd21@nsut.ac.in

A. K. Pathak
Department of Chemistry, Netaji Subhas University of Technology, New Delhi, India

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1 Introduction

Water is a key necessity for our survival and well-being, due to its multifarious applications in daily activities. Unfortunately, the amount of fresh water available to humankind is very limited and is reducing drastically due to the rampant exploitation of available water resources. This is resulting in water scarcity around the world, with a large number of metropolitan cities in danger of running out of it [1]. This calls for immediate, strong, and concerted efforts at conserving this key resource. The other aspect, apart from the quantity, is the quality of water. It has been known for millennia that consumption of impure (or low-quality) water can result in adverse health effects. Water-borne diseases, such as cholera, dysentery, typhoid, diarrhea, and giardiasis, have killed millions of people since the advent of human civilization [2]. Unfortunately, and disastrously, the demand for better quality and higher quantity has been rising by leaps and bounds since the inception of the industrial age. Population explosion and climate change have further exacerbated these issues and increased the pressure on already stressed (and limited) water resources. Despite several steps by governments around the world, the situation is worsening continuously. This is especially true for developing and underdeveloped countries where resource limitation forces the governments to prioritize other areas (such as defense, energy industrial growth, and employment creation) over water conservation. This calls for a greater role of individuals and households in the efforts to save better-quality water and increase efforts at reclaiming decent quality water, that will otherwise be discarded. A sustainable water management system is the need of the hour. Unfortunately, the common households lack the knowledge and initiative to work toward water conservation and reuse. An appropriate water management system will need to cover the aspects of providing quality water at low cost and low energy while minimizing wastage and increasing the reuse of lower-quality water for appropriate applications.

One of the main areas of water wastage in modern homes is the water purification system installed in the kitchen. These are generally based on reverse osmosis technology, which unfortunately wastes 5–7 L of water for every liter of water it generates as the final product. It has been estimated that for every 1 L of water purification about 3 L of water are wasted [3]. Similarly, there are other areas of a home where a relatively better quality of water is wasted at different times due to the wasteful habits of human beings. This may include wash basins, kitchens, showers, taps, etc. About 27% of the water supplied to a home is generally used for toilet and bathing applications. As much as 20 gallons of water per day can be wasted by one single leaky faucet in a household. The EPA estimates that leaky faucets are estimated to waste almost 1 trillion gallons of water annually in the United States [4]. It has been estimated that almost 45 L of water are wasted daily by each Indian [6]. Furthermore, as much as 50% of the water is wasted of what it received by the city of Kolkata, 26% by New Delhi, and 49% by Bangalore [5]. Unfortunately, a large fraction of this wastewater is of better quality and can be safely reused. Thus, there is a strong need to manage the water based on its quality before finally discarding it, which can be preceded by its storage and reuse in various applications such as gardening, water spraying, cleaning, and aquifer recharge.

As per the Census report in 2011, 63% of India's GDP comes from the urban areas and only 31% of India's population is residing there. The population residing in rural areas started shifting to urban areas for a better lifestyle. By 2030, the country is expecting 40% of the population will be there in cities and that will contribute to 75% of India's GDP. To accommodate this urbanization, developments in infrastructures in terms of physical, economic, and social are mandatory [1]. In recent times, smart housing has gained a significant amount of attention due to its focus on the comfort, safety, and health of the inhabitants, while preserving the environment and minimizing resource wastage. The Government of India launched a smart cities mission on 25 June 2015 with a focus to develop 100 smart cities between 2019 to 2023 [6].

The incorporation of Internet of Things (IoT)-based sensors in smart homes enhances the performance and quality of services [7]. IoT combines physical objects with the Internet which includes various domains like environmental monitoring, human security, health, home automation, etc. [8]. Sensors play a crucial role in the system because they gather all the relevant information and transfer the information in real time to citizens, cities, and communication networks. Although the usage of sensors is diverse, their application can be categorized into six different groups: energy, health, mobility, security, water, and waste management [9]. Sensors for measuring water quality and quantity in real time are available and can be suitably used in water conservation efforts. To measure the depth of water level in soil, a water depth sensor can be used which is helpful in the irrigation process. This will ultimately help in monitoring the amount of water delivered to the fields during the irrigation process and result in appropriate amount of water delivery to the plants, thus conserving it [10]. The Aguardio G2 is a sensor for showers that measures usage and alerts users to the amount of water wasted, helping to nudge individuals into shorter shower times, and sensor named Aguardio Leak attaches to the toilet's water inlet and detects leaky valves, notifying homeowners of this difficult-to-detect problem [11]. Here a smart water management system (SWMS) is proposed for a smart home or villa, which uses water quality and quantity sensors and makes smart decisions about water conservation and reuse. The same can also be used at a larger scale for a residential or commercial installation or even at the level of the smart city. Water conservation at the household level is expected to significantly complement the efforts of the governing bodies and will help in the preservation of this key resource.

Alam et al. [12] described the collective information related to sensors, communication protocols, multimedia devices, and widely used systems in the implementation of the smart home. The paper presented an overview of smart home research previously done along with their associated technologies [12].

Raad and Yang [2] explained a user-friendly cost-effective telemedicine system to serve the disabled and elderly [2]. It consists of general-purpose sensors (weight sensors, motion detectors, and light sensors) and physiological sensors (pulse oximeter sensor and blood pressure sensor). The physiological sensors are attached to a wheelchair, which can communicate to a database server through a personal digital assistant. The doctor can analyze the patient's health condition from the database remotely. Other sensors are used to track the location and detect the activities of the residents.

Water quality sensors namely Proteus Multiparameter BOD sensor, TOC-300 COD Analysis, ZS-406 Online turbidity sensor, ORP/Redox sensors, DDM-406 Online Conductivity sensor, TPS-206A Online Transparency sensor, and OIL-206A Online water oil sensor are available in the market which test parameters like BOD, COD, Turbidity, pH, Conductivity/Salinity, suspended solids, and oil in water, respectively [12]. One of the drawbacks to the effective implementation of sensors is the poor linkage between water quality regulation and sensor technologies [11]. The linkage between water quality regulation and sensor technologies can be improved by regular monitoring.

Manoharan and Rathinasabapathy [13] made use of sensors along with LoRa mote that was placed in Smart villages of Tamil Nadu, India, in water tanks at 200 locations within corporation limit and monitored the quality of water during its distribution and detected the chemical leakage in rivers located nearby. Water levels and water quality were continuously monitored in specified tanks and were displayed in the controlling room. It was concluded that LoRaWAN is suitable where the cellular network is unavailable like in mountains and forest areas as well as where the cellular network is available like in cities [13]. This proposed system will not only save water but will also provide good quality water to people.

Chen and Han [14] made use of wireless sensors in a pilot study in Bristol city, the UK, for the smart management of water at the city level. This study represented a system for the management of water quality that checked the quality of multiple parameters through a multi-parameter monitoring system for water quality [14]. Dissolved oxygen (DO), conductivity, phosphates, salinity, pH, temperature, *Escherichia coli*, Fecal *streptococci*, and presumptive *Enterococci* were the parameters that were monitored for water quality. This system showed that the environmental quality data can be successfully collected in real time and can be effectively used for decision-making.

Mohapatra and Rath [15] proposed an ICT-based water distribution network that helps in preventing water loss and monitoring excessive water supply. The work also highlighted the failure in managing the water distribution system due to poor management [15]. An ICT-based water distribution network was used in Odisha, India. A smart tap and heterogeneous wireless sensor was used in the distribution system to detect the water loss and thus it will prevent the unnecessary wastage of water.

Chary et al. [16] made use of rejected water from domestic water purifying systems which have a high TDS value of about 1800 ppm. A complete plant care unit was set up where rejected water was sent to water harvesting pits. This utilized the rejected water from the purification system. A device was developed which utilized the wastewater generated from R.O. to grow phytoremediating plants [16]. The purifier brands normally recommend that the runoff water can be reused in activities, such as gardening, cleaning floors, and washing clothes/vehicles [17].

Fishman et al. [7] discussed groundwater depletion and evidence was taken from Gujarat, India. Certain evidence like rural to urban migration, rural employment shifts, and exogenous variation in environmental stress was discussed as responsible for the depletion of the groundwater table [7]. All this requires proper management of water starting from the lower scale to the higher scale, i.e. from an individual level up to the city level.

Ramos et al. [9] made use of smart pipe and sensor, smart water metering designed as a module unit with a monitoring capacity expandable for future available sensors. With several smart pipes installed in critical sections of a public water system, real-time monitoring automatically detects the flow, pressure, leaks, and water quality, without changing the operating conditions of the hydraulic circuit. Briefly, the smart wireless sensor network is a viable solution for monitoring the state of pressure and loss of water control in the system [9]. The use of smart pipes and sensors helps in water management. The main objective of this was to disclose the technological breakthroughs associated with water and energy use.

A significant amount of research has been conducted in the last couple of decades related to the use of sensors in automating various systems related to water supply, health, etc. The same can be used in water conservation in single homes/villas as well, thereby helping in achieving the smart cities target, while saving perhaps the most valuable resource known to mankind: the water.

2 Methodology

The proposed smart water management system (SWMS) at the level of smart homes/villas is shown in Fig. 1. The supply of usable water is through centralized water supply tanks. The entire water distribution system is automated with three types of sensors: quality sensors, quantity sensors, and overflow sensors. Firstly, water passes through one of the sensors named overflow sensor (SO). Sensor for overflow checks whether the centralized water tank is sufficiently filled or not and if that tank is overflowing then the water supply to the tank will be switched off automatically. There are various overflow check sensors available in the market, such as LCS and Ijinus CSC [18]. These sensors detect overflow by measuring the capacity of water overflowing in the tank. An overflow sensor can also be provided in a separate tank that stores recycled water as shown in Fig. 1. Installation of overflow sensor at recycled water tank will lead to two cases:

- **Case A**: In case of overflowing, there will be a quantity check with the help of a quantity sensor (QS) and then that water will pass to the rainwater harvesting pits.
- **Case B**: In case of no overflowing, water can be used for domestic purposes and also, miscellaneous purposes like gardening, or spraying to control dust particles, after a due quality check at the various domestic fixtures. Along with water management, this will also improve the air quality in and around the smart home/villa.

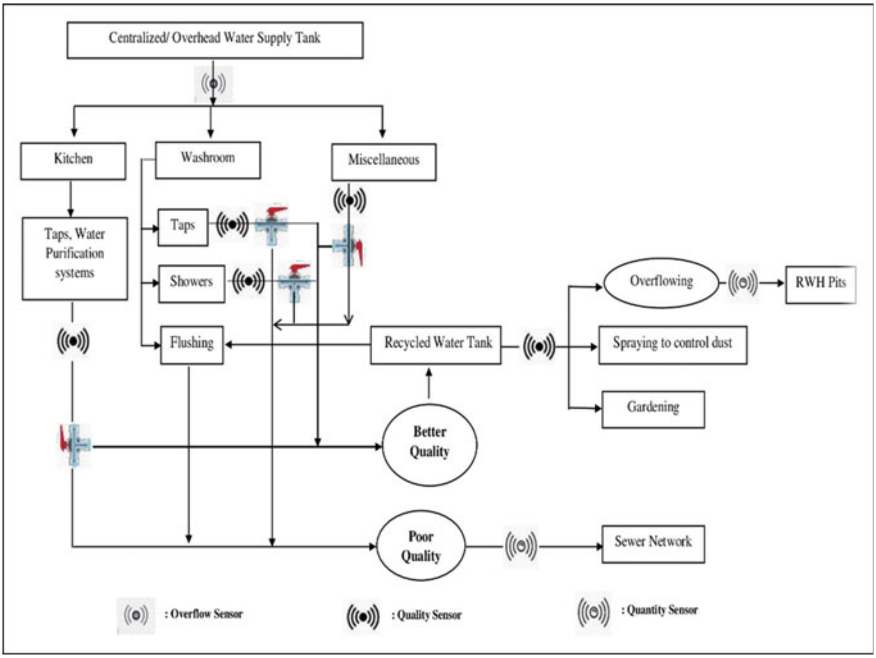

Fig. 1 Real-time smart water management system for smart home

Checks for water quantity are done to assess the amount of water being passed to harvesting pits. Installation of a water quantity sensor before the sewer network is done to monitor the amount of wastewater generated by the smart home. Usable water crosses from the storage water tank for various uses like the kitchen, washroom, and miscellaneous purposes. Miscellaneous includes all the taps provided at other places in the house, excluding the kitchen and washrooms. Taps and water purification system of the kitchen are installed with a quality sensor. The sensor is further connected to a three-way ball valve which will bifurcate the water into two categories namely Poor quality water and better-quality water. Similar bifurcation will be done by the quality sensor provided at the taps and shower of the washroom, and taps provided for miscellaneous purposes. There are various quality sensors available in the market like RDO-206A Dissolved Oxygen Sensor, TOC-300 COD Analysis, ZS-406 Online Turbidity Sensor, PHG-406 Online pH sensor, DDM-206A-S Online Salinity sensor, TPS-206A Online Transparency Sensor, and self-cleaning oil in water sensor which can be installed within the pipeline system [19]. The water distribution system can be automated with these sensors to prevent water wastage. Quality sensors test multiple water quality parameters when installed in the distribution system. Various parameters considered for the water quality check are listed below along with their respective suggested sensors in Table 1.

BOD, COD, turbidity, pH, Conductivity/Salinity, suspended solids, and oil in water are the quality parameters that sensors will monitor. These parameters will

Table 1 Water quality sensors along with their parameters [19]

S. no	Parameter	Sensors	Description
1	Biochemical Oxygen Demand (BOD)	RDO-206A dissolved oxygen sensor	Measures the amount of organic matter present in water in terms of oxygen
2	Chemical Oxygen Demand (COD)	TOC-300 COD analysis	Measures the total organic and inorganic matter present in water
3	Turbidity	ZS-406 Online turbidity sensor	It measures the clarity of the Water
4	pH	PHG-406 online PH sensor	It tells how acidic or basic the water is
5	Conductivity/ salinity	DDM-406 online conductivity sensor, DDM-206A-S online salinity sensor	Measure the dissolved substances, chemicals, and minerals present in water
6	Suspended solids	TPS-206A Online Transparency Sensor	Measures the small solid particles which remain in suspension in water as a colloid or due to the motion of the water
7	Oil in water	Self-cleaning oil in water sensor	Measures Oil released from the kitchen

decide whether the water is of better quality or poor quality. The general standards given under the Environmental Protection Act, 1986, India, for disposal of wastewater in inland water surface bodies (such as rivers, lakes, and ponds) suggest BOD (3 days at 27 ºC) $\leq$ 20 mg/L ($\leq$ 10 mg/L for the Yamuna stretch in Delhi NCR); COD $\leq$ 250 mg/L; Turbidity $\leq$ 5 NTU; pH: 5.5–9.0; Conductivity: 456.4 to 982.7 µS/cm; Suspended Solids $\leq$ 100 mg/L; Oil in water $\leq$ 10 mg/L. For sewer disposal, the effluent should conform to these standards: BOD (3 days at 27ºC) $\leq$ 350 mg/L; Turbidity $\leq$ 5; pH: 5.5- 9.0; Conductivity: 456.4 to 982.7 µS/cm; Suspended Solids $\leq$ 600 mg/L; and oil in water $\leq$ 20 mg/L [20]. The water that conforms to these criteria will be termed as better-quality water and will be stored for reuse, while the poor quality water would be passed on to the municipal sewer network.

Better-quality water will move to the recycle tank so that it can be used for flushing. As specified when water is within the permissible limit then it will fall in the category of better quality otherwise the water will pass to the poor quality which is further connected to the sewer network. Figure 1 shows three types of sensors with different sensor icons. All quality sensors are further connected with a three-way ball valve which distributes the water into better and poor quality. A Three-way ball valve is provided with a closing, when the closing is open then it will lead to two cases:

- **Case A**—Better-quality water will be passed to the recycled water tank.
- **Case B**—Poor quality will be passed to the sewer network, and the sewer pipeline network used to collect the wastewater from human connection.

Further, wastewater generated from the air conditioner can be collected in the recycled water tank and then used for gardening purposes and/or in spraying to control the dust. Thus, the system will provide an opportunity for the reuse of relatively better-quality water, while quantifying wasteful water usage, which can be used to motivate the users to pursue conservation efforts more seriously and sincerely.

3 Conclusion

Many Indian cities like Delhi, Mumbai, Lucknow, and Nagpur are facing the water scarcity problem due to which there is an urgent need for the management of water. The use of sensors to check the quality, quantity, and overflow of water not only helps in managing the water but also helps in minimizing water wastage. Installation of quantity sensors in the water distribution system will assess the quantity of water that can be passed to the rain harvesting pits and/or the sewer network. Quantity sensors will do the measurement in terms of capacity. Overflow sensors will prevent the water from overflowing, thus preventing the unnecessary wastage of water. Quality sensors will monitor the water in terms of various parameters like BOD, COD, conductivity, dissolved solids, oil and grease, pH, and turbidity. Bifurcating the used water into better and poor quality helps in reusing the better-quality water. This Real-time Smart Water Management (SWMS) for the smart home can be applied on a larger scale.

Application of the proposed system to smart homes would enable the monitoring of overflowing and quality of water, thereby providing measures for its conservation and reuse. Moreover, it provides an awareness highlight to users about water management in their smart homes.

References

1. Mohammed Shahanas K, Bagavathi Sivakumar P (2016) Framework for a smart water management system in the context of smart city initiatives in India. Procedia Comput Sci 92:142–147. https://doi.org/10.1016/j.procs.2016.07.337
2. Raad MW, Yang LT (2009) A ubiquitous smart home for elderly. Inf Syst Front 11(5):529–536. https://doi.org/10.1007/s10796-008-9119-y
3. Kovner DS, Ushakov YP (1973) Analysis of the characteristics of conduction-type magnetohydrodynamic pumps in similarity *criteria* 9(3). https://doi.org/10.2788/35499
4. https://simplygreenplumbing.com/stop-wasting-water-with-leaky-faucets/
5. https://indiaeducationdiary.in/every-indian-wastes-45-litres-water-per-day/
6. Rathore I (2017) Smart cities mission in India. Int J Technol 7(1):79. https://doi.org/10.5958/2231-3915.2017.00013.x
7. Fishman R, Jain M, Kishore A (2013) Groundwater depletion, adaptation and migration: evidence from Gujarat, India. Int Growth Cent Work Pap

8. Ajala JA, Saini G, Pooja (2020) CLOUD-IOT based smart villa intrusion alert system. ICRITO 2020 - IEEE 8th international conference reliabliation infocom technology optimization (Trends Futur. Dir., pp 1326–1329, https://doi.org/10.1109/ICRITO48877.2020.9198022
9. Helena AMPAL-J, Ramos M, Pérez-Sánchez M (2019) Smart water management towards future water. Water, pp 1–13
10. Mitra A, Pooja, Saini G (2019) Automated smart irrigation system (Asis). Proceedings 2019 international conference computer communication intelligent system ICCCIS 2019, pp 327–330. https://doi.org/10.1109/ICCCIS48478.2019.8974466
11. A novel pair of sensors help users to save water in the bathroom, by detecting toilet leaks and encouraging shorter showers
12. Alam MR, Reaz MBI, Ali MAM (2012) A review of smart homes—past, present, and future. IEEE Trans Syst Man Cybern Part C Appl Rev 42(6):1190–1203. https://doi.org/10.1109/TSMCC.2012.2189204
13. Manoharan AM, Rathinasabapathy V (2018) Smart water quality monitoring and metering using Lora for smart villages. 2nd international conference smart grid smart cities, ICSGSC 2018, pp 57–61. https://doi.org/10.1109/ICSGSC.2018.8541336
14. Chen Y, Han D (2018) Water quality monitoring in smart city: a pilot project. Autom Constr 89:307–316. https://doi.org/10.1016/j.autcon.2018.02.008
15. Mohapatra H, Rath AK, Detection and avoidance of water loss through municipality taps in India by using smart taps and ICT. IET Wirel Sens Syst 9(6):447–457. https://doi.org/10.1049/iet-wss.2019.0081
16. Chary NSK, Kumar RU, Kalyan P, Ajay T (2021) Automatic phyto-remediating plant care unitusing RO purifier rejected water. Mater. Today Proc 45:3264–3267. https://doi.org/10.1016/j.matpr.2020.12.389
17. Onoja SB, Enokela JA, Ebute GO (2014) A digital soil moisture meter using the 555 timer. ARPN J. Eng. Appl. Sci. 9(10):1994–1998
18. https://elscolab.com/en-be/products/overflow-detector
19. https://en.chemins-tech.com/sz1.html.
20. Sawal M (1986) General standards for discharge of environmental pollutants. Environ Rules 2(174):545–560

An Assessment of Vulnerability to Extreme Rainfall and Livelihood Resilience in Hillslope Geography: A Case Study of Malappuram, Kerala, India

Haani and Kamal Kumar Murari

Abstract Extreme rainfall events and hazards may rise as a result of climate change, which is already known to intensify the global water cycle. Disasters like floods and landslides are also becoming more common in India. Located in the state of Kerala, the district of Malappuram is prone to both landslides and floods. People become vulnerable as a result of disasters because they are initially deprived of their support systems and have few options for recovery. Rural poor communities lose jobs and their income is reduced as a result of such events, limiting their capacity to prepare for, respond to, and recover from future floods. In order to retain livelihood resilience, livelihoods must respond to global and local changes. For this research study, 127 quantitative household surveys were carried out throughout the Chaliyar Panchayat of the Nilambur block in the Malappuram District. Respondents were categorized into different groups based on their caste category (General/OBC (Other Backward Classes) and SC(Scheduled Caste)/ST(Scheduled Tribes)) to compare their overall household livelihood resilience by index method. The results show that the overall livelihood resilience of general/OBC (0.619) household is higher than SC/ST household (0.330). Better access to five livelihood capitals (Natural, Physical, Human, Financial, and Social) by General/OBC households helped them to build better livelihood resilience compared to SC/ST households. The study additionally looks at how extreme rainfall events affect people's livelihood, including losses and damages.

Keywords Extreme rainfall events · Livelihood resilience · Loss and damages · Adaptation · Vulnerability

Haani (✉) · K. K. Murari
Centre for Climate Change and Sustainability Studies, School of Habitat Studies, Tata Institute of Social Sciences, Mumbai, India
e-mail: haanit007@gmail.com

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1 Introduction

Climate change has affected the social and ecological systems on the earth with changes in weather patterns which result in increased magnitude and number of extreme events like floods, drought, and cyclones [1]. This can bring a significant risk to the livelihood, health, and culture of communities as more frequent climatic disasters have a huge impact on the poor section of society who are forced to live in a vulnerable environment [2, 3]. [4] expressed vulnerability as "a function of exposure, sensitivity, and adaptive capacity" to such hazards. Therefore, the degree to which people are dependent on natural resources and ecosystems, as well as how sensitive those resources are to changing climate and how well they are able to adapt to it, determines how vulnerable they are to disaster [5].

Vulnerabilities of many communities, especially poor communities, are enhanced by the effects of disasters caused by extreme events [6]. Poor communities experience a disproportionate share of loss during a disaster since they are typically less resilient to loss and rarely have access to social protection or insurance [7]. Their welfare is negatively affected over the long term as the impacts of disasters lead to income and consumption shortfalls. Low-income groups always struggle for a better livelihood due to lack of access to resources [8]. When a disaster strikes, they are the ones that suffer the biggest loss of their livelihood resources, which makes it challenging to mitigate the effects that make many people sensitive to better livelihoods due to disasters [9].

Between 2003 and 2013, more than 1.3 billion people were affected by natural hazards and disasters in developing countries and caused an estimated damage of over US $494 billion [10]. Disasters cause loss in crop production and livestock and destroy agricultural assets [11]. Millions of small-scale farmers and people in developing countries that depend on forests are directly impacted by disasters in terms of their livelihood and food security [12]. Livelihood security of developing countries is concerned with the effort to cope with climate change at community level as it is always poor and marginalized communities that are susceptible to the negative effects of climate change due to their habitat and livelihood activities [5].

Resilience is the process to tackle shocks and vulnerability [13] and livelihood resilience is the capacity of a person or community to rebound after facing challenges with their livelihood to reduce susceptibility, recover from the past and present impacts of vulnerabilities, and may endure in a challenging livelihood environment [14]. There is a need to focus on the assessment and identification of vulnerability instead of only focusing on hazards or extreme events in order to promote resilience and adaptive capacities of communities [15]. A community's livelihood system is solely dependent on the socio-ecological system, as livelihood consists of financial, natural, human, physical, and social capital and is dependent on the community's complex system of financial, biophysical, political, and institutional conditions [14].

The livelihood of individuals who have few resources is impacted by natural disasters, and environmental conditions are responsible for impeding their support system [16]. Access to and control over resources are crucial factors in determining a household's capacity, and that household's vulnerability to disaster is determined by its ability to handle, absorb, and manage with a disaster. Due to differences in how different households respond to shock or stress caused on by disasters and how they adjust and sustain their way of life through their adaptive capacity, households with differential potential are relatively more often at risks and vulnerable to disasters. This can worsen the livelihood conditions of households with poor capacity [17].

Extreme rainfall events like floods and landslides are the most frequent natural disasters that can have an impact on livelihoods, and India has seen some of the most extreme rainfall events that have resulted in flooding and loss of lives [18]. Anthropogenic activities including deforestation, the cultivation of plants incapable of adding root cohesiveness to steep slopes, mining, and quarrying all contribute to the increasing occurrence of several forms of landslides on hill slopes in Kerala's western ghats [19]. Exposure to landslide hazard and preparedness to face the hazard are essential to assessing the vulnerability to landslides [20]. It is very important to learn about such impacts on the livelihood and to understand their coping mechanism for effective adaptation that can build the resilience of the communities. It will help them to enhance the ability of the community or people to sustain livelihood opportunities [21]. Thus, there is a need to reduce the adverse impacts on the livelihood and to find proper coping mechanisms that will reduce the vulnerability.

This research is an attempt to understand the resilience of the rural livelihood of households in Chaliyar Panchayat of Nilambur, Kerala, to extreme rainfall events like floods and landslides. The major focus of the research project is to find out changes in the livelihood resilience among different social groups such as General, Other Backward Class (OBC), and Scheduled Caste/Scheduled Tribes (SC/ST), along with a focus on the impacts and losses incurred by them. In this context, this study has put forth the following research questions:

1. What are the differences in level of livelihood resilience between General/OBC and SC/ST households?
2. What are the losses and damages that households have suffered?

2 Study Area

Chaliyar is a panchayat in Nilambur Taluk of the Malappuram district of Kerala, India. Chaliyar panchayat covers a total of 14 wards in an area of 125 km^2 with a population of 20,834 people and 4614 households with a population density of 166.67 people per sq.km. Nilambur taluk has a total of 6 grama panchayats. Western Ghats hills surround Chaliyar Panchayat on one side, and the Chaliyar River on the other. Chaliyar is the fourth largest river in Kerala at 169 km in length, also known as the Chulika River or Beypore River [22]. Malappuram is one of the four major districts, including Idukki, Palakkad, and Wayanad, that experienced heavy rainfall from August 8 to 9, 2018, and was severely affected in the form of numerous landslides. However, in 2019, another heavy rain resulted in catastrophic landslides and floods and made a devastating impact across 14 districts of Kerala. Malappuram

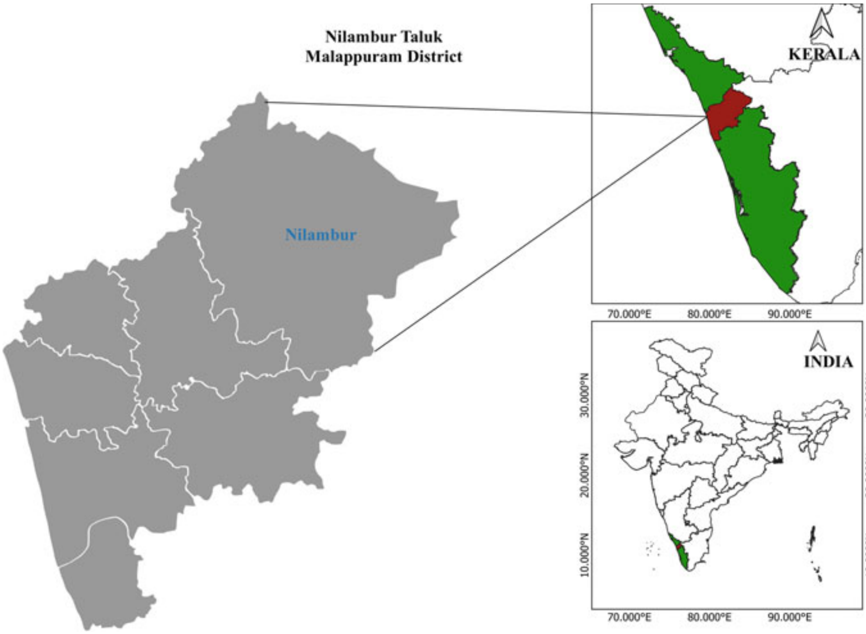

Fig.1 Map of study area

district, with the Chaliyar river region, is one of the worst hit regions in Kerala due to massive landslides.

Due to its steep slopes and frequent flooding caused by the presence of the river Chaliyar, Nilambur Taluk is among the most vulnerable places in the region. Chaliyar panchayat has three villages: Akampadam, Kurumbilangode, and Pullipadam. The study was conducted in Akampadam and Kurumbilangode villages of Chaliyar Panchayat (Fig. 1). The households of these villages fall into various social categories, including general, OBC (Other Backward Class), SC (Scheduled Caste), and ST (Scheduled Tribe). The general and OBC respondents were located mainly along the Chaliyar River, whereas the SC/ST respondents were located on the hillsides. Most of the ST communities live in the settlement near to the forest.

3 Methodology

3.1 Data Collection

The study has adopted a mixed method approach that includes both qualitative and quantitative methods of collecting primary as well as secondary sets. Quantitative data was collected to get baseline information about the village, various forms of losses and damage, and the impact on the livelihoods of people living in flood and landslide-prone areas. Secondary data was collected from the panchayat on loss and damage. A household survey was conducted at the village level with the help of panchayat officials, to select the wards and areas that were worst affected. A random sampling technique was adopted and the surveyed households were spread all throughout the panchayat, based on the extent of extreme events and damage incurred. 127 households in the panchayat (Akampadam and Kurumbilangode villages) were surveyed. Households were selected with the help of local ward members so that the researcher would be able to survey respondents to meet the research objectives. Within this sampling, variation sampling was undertaken to make sure that the surveyed samples include households belonging to different social categories, such as general/OBC/SC/ST. A structured questionnaire was used to conduct household surveys, and the data was analysed statistically based on their basic demographic details such as occupation, gender, education, income, and age.

3.2 Livelihood Resilience Index

A household livelihood resilience index was developed in order to compare and evaluate the households' livelihood resilience, as outlined by [23]. A two-sample mean z-test was used to compare the differences in livelihood resilience between different social groups. A p value of <0.05 was used as a statistically significant cutoff point. Indicators of livelihood resilience were developed based on the livelihood capitals of the sustainable livelihood framework. Household surveys with quantitative questions based on the indicators presented in Table 1 were conducted with 127 respondents. To create the composite index for each household, survey results were converted in such a way that answers to questions were on a scale of 0 to 1 for each indicator. The most desirable response was assigned as 1 and the least desirable response as 0. For example, a question about any household member with a salaried job is assigned a result of 1 if the answer is yes, and 0 for a response of no. Any question with more than one choice was given values within the range of 0 to 1 (for example, 0, 0.25, 0.5, 0.75, 1). It was assumed that a higher level of livelihood capital should be indicated by higher scores and thus greater livelihood resilience. The main reason for converting responses from 0 to 1 is that it enables us to average them all together and simplifies analysis. Equal weightage was given for each indicator.

The composite asset index for each livelihood asset was created by taking an average of the individual indicator scores for all selected households. This is done by calculating the average of all the results for each livelihood asset for each household. For instance, the total financial capital score for that a household was calculated by averaging all the responses to the financial capital questions for that household. This process is done at the household level, and now these scores are aggregated to represent general/OBC and SC/ST households. For each survey respondent, the average scores for five capitals were used to create an overall livelihood composite asset index. From this overall index, the livelihood resilience between general/OBC

Table 1 Household survey livelihood resilience indicators

Capitals	Indicators
Financial capital	• Main source of fuel (Firewood, LPG, Both) • Own vehicle (Yes or No) • Own TV, radio, or smartphone (Yes or No) • Remittances (Yes or No) • Salaried job (Yes or No) • Own farm equipment (Yes or No)
Human capital	• Highest level of education (Below 5, 5 to 10, 10 to 12, above 12) • Health issues impact on capacity to practice livelihoods (Scale of no to very much) • Chronic ailments in family (Yes or No) • Health problem as a result of flood (Yes or No) • Labour availability (number of household members between 18 and 60) • Skilled work (Yes or No) • Education of head of household
Natural capital	• Size of land (in acres) • Own farmland (Yes or No) • Collect forest produce or bee hives (Yes or No) • Livestock (Yes or No) • Face soil erosion (Yes or No)
Social capital	• Participation in self-help groups (Yes or No) • Participation in local politics (Yes or No) • Family living nearby (Yes or No) • Seek advice from Krishi Bhavan (Yes or No) • Received financial help from government (Yes or No) • Social/Insurance schemes (Yes or No)
Physical capital	• Distance from market • Source of water (well or Springwater) • Distance from hospital • Distance from school • Condition of road • Condition of road during rainy season

and SC/ST households can be compared and analysed. The overall composite asset index and the composite asset index were used to compare general, OBC, and SC/ST respondents. The intention of this process is to determine which groups are more resilient and the reason for the same (which group's capital is higher for a particular group). This is done using a spider chart, which helps to compare the five capital assets between general/OBC and SC/ST households.

4 Results and Discussion

4.1 Livelihood Asset Analysis

Financial Capital

The livelihoods of surveyed respondents largely depend on the daily wage. Majority of them (around 62%) depend on wage earnings as their primary occupation. Only a small percentage of them are farmers, and a few of them had salaried jobs or had their own businesses. But all these account for only 27% of the total households. Disasters like floods and landslides had a significant impact on their livelihoods, especially on their financial capital, because these areas were completely affected by flooding and destroyed their properties, which affected their work and, thereby, their income. Most people were compelled to spend many days in shelter camps as a result of loss, damage, and destruction of their homes. This had a severe impact on their economic condition as people were unemployed for several weeks.

Physical Capital

Natural disasters and climate change can cause extensive damage to physical commodities and infrastructure, as well as a significant number of casualties. Compared to other communities, the physical environment surrounding ST households is relatively poor because of the remoteness of their place. ST settlements do not have access to proper metalled roads, and the condition of their roads is more worse during the monsoon season. This can have an impact on their accessibility to markets, schools, and hospitals. During the monsoon, the roads near the river flood, forcing many people to relocate to shelter camps. In a few settlements, the electricity connection was destroyed in the 2018 flood and landslide. Most of the households in ST communities did not have access to electricity and had to walk 2–3 km to charge their phones. Villagers emphasized how severely the devastating landslides and floods affected physical capital, including infrastructures such as roads and houses. Community roads are easily affected by flooding and landslides if such climate risks occur. Of the total economic loss, 59.7% of the loss and damage are houses and related infrastructure loss (Table 3).

Natural Capital

Agriculture was not their primary occupation, and just eight of them are farmers; nonetheless, those with land holdings of more than 30 cents practiced farming for their household requirements. Animals pose a threat to agriculture in this area and many of them experience crop raiding. The main crops cultivated in these areas are vegetables and fruits which include bananas, pineapples, and coconuts. These crops are attacked and destroyed by animals such as elephants, wild boar, and monkeys. So, in order to prevent such a situation, people have shifted their land to rubber plantation. Farmers lose their crops every year due to heavy rain and high winds during the monsoon season. Coconut and areca nut trees have been damaged in recent years by certain diseases that destroy the trees and render them unproductive, making it difficult for farmers to improve their production. During the 2018 and 2019 floods and landslides, many households lost farmland and crops. Some of their lands had become sand-filled or barren, rendering them uncultivable. People in this region also have extremely limited livestock holdings. They raise hens and cows for eggs and milk, primarily for their own consumption. Data on livestock loss can be seen in the section loss and damage.

Human Capital

Climate change may endanger health conditions. Extreme floods, for example, can cause epidemics in the aftermath. Extreme events can also result in the death or injury of humans. Access to health-care facilities is critical for those living in disaster-prone and vulnerable areas. The health of the head of the household and any earning members of the household has a significant impact on the household's livelihood. Because of their remote location and limited financial resources, ST communities have reduced access to medical care, which may jeopardize their ability to sustain their livelihoods. While comparing the ST households to others, we can observe the impact of properly metalled roads on the day-to-day life of a household. People from ST settlements had difficulties travelling to the hospital and schools, and transport services are severely constrained. Education is another crucial component influencing the human capital. Lower education among ST communities limits them from alternative jobs except for manual labour. All general/OBC households have wells for drinking water and domestic purpose whereas ST households depended on spring water and river stream for water supply. These sources of drinking water have been depleted throughout the summer and muddied during the winter. On the other side, ST communities lack decent sanitary facilities.

Social Capital

There are distinctions between general/OBC households and SC/ST households in terms of the perception of social cohesion within communities. This was because the ST communities live in a place that is secluded and remote from the other households. Moreover, the lack of a better or more convenient mode of transportation and appropriate roads to their places makes their accessibility to towns or cities more difficult. Kudumbashree's (an initiative by State Poverty Eradication Mission (SPEM) of the Government of Kerala to eradicate poverty and empower women.) advocacy of self-help groups (SHGs) was not active in these areas. However, until 2019, either region's social cohesion is adequate for disaster preparedness. During flooding occurrences in their areas, the people hardly ever prepare to put their belongings and important documents in a secure place. Thus, the communities may experience a loss of livelihood as a result of the lack of mutual support and disaster awareness. Based on the experiences of the 2018 and 2019 floods in the area, different political parties, NGOs, and government agencies reportedly offered support to respondents in order to facilitate their coping mechanisms and to make their lives amid flooding easier.

4.2 Livelihood Resilience

A livelihood resilience index was calculated to compare the livelihood capitals between SC/ST and General/OBC households. For assessing each livelihood capital, different indicators and factors were selected. From Table 2, we can see and compare each livelihood capital between General/OBC and SC/ST households. Z-tests (two samples for mean) found that all livelihoods were statistically different between the two groups. The Z-test for all five livelihood capitals showed a significant difference between both social groups. The resilience index for each livelihood capital was calculated for both general/OBC and SC/ST households. It has been observed that there is a significant difference between all capitals with only a very slight difference in natural capital (Table 2). However, the resilience index for each livelihood capital is explained below.

Financial Capital

From Table 2, it has been observed that the value for General/OBC is 0.63 and the value for SC/ST is 0.30. The reason for the lower value among SC/ST households is mostly due to their lesser asset holding. Majority of SC/ST households primarily depended on fuelwood as a source of energy and had no Liquified Petroleum Gas (LPG) connection. They rely on manual labour as a primary source of income and none of them had a salaried job. Also, the proportion of people who possess any kind of vehicle is larger in general/OBC families compared to others, while most SC/ST households do not own any kind of vehicle.

Physical Capital

A significant difference in physical capital was observed, with a value of 0.27 for SC/ST households and 0.76 for general/OBC households (Table 2). ST communities do not have access to decent roads since they dwell in hilly places where the topography makes road construction difficult. Furthermore, due to their remoteness, these regions receive comparatively less development, limiting their access to government programmes and developmental activities. The road's condition makes it difficult to commute to many locations, such as markets, schools, and hospitals. The issue worsens during the monsoon, when most roads become muddy and inundated.

Table 2 Livelihood resilience index for each capital asset

Livelihood capitals	General/OBC	SC/ST
Social capital	0.544	0.351
Financial capital	0.633	0.301
Human capital	0.608	0.455
Natural capital	0.463	0.402
Physical capital	0.760	0.273
Overall	0.619	0.330

Natural Capital

The value of natural capital does not significantly differ between both social groups (Table 2). This is due to the fact that there's not much of a difference between the two in terms of land holding. The ST communities had a large amount of land, which they also used for farming. Some ST households collect forest produce, and the distribution of livestock holdings is nearly identical among these households.

Human Capital

A significant difference in the resilience of human capital between both social groups can be noticed in this category (Table 2). However, there is a gap between these groups in their education, health, and skills. In particular, there are many uneducated members in SC/ST households compared to other groups. ST households also have very poor health conditions. The primary reason for these groups' poor education and health is the remoteness of their region and lack of access to schools and hospitals.

Social Capital

The main indicators used to measure the social capital among the households were their involvement in SHGs and politics, the number of family members living nearby, social insurance schemes, and financial support from the government. The value of general/OBC is 0.54 and that of SC/ST is 0.35 (Table 2). ST communities have very little interaction with the outside world, and this restricts them from active participation in politics and weak SHG formation.

Overall Livelihood Resilience

An overall household livelihood resilience index was calculated for all respondents. A spider diagram is constructed (Fig. 2) to compare the individual livelihood capital between both social groups. While calculating overall livelihood resilience, weightage was given to each livelihood capital. In order to give weights to capital, key informants were asked to rank different livelihood capitals. Based on their response, 50% of the weight is given to financial capital, 15% to social capital, 15% to physical capital, 10% to human capital, and 10% to natural capital. After calculating the livelihood resilience index value for each household, a weighted average was calculated as described above for all livelihood capitals to find the overall resilience at the household level. In order to compare the overall livelihood resilience between General/OBC and SC/ST households, an average of both groups was calculated. A value of 0.619 was obtained for the general/OBC household, and a value of 0.330 was obtained for the SC/ST household.

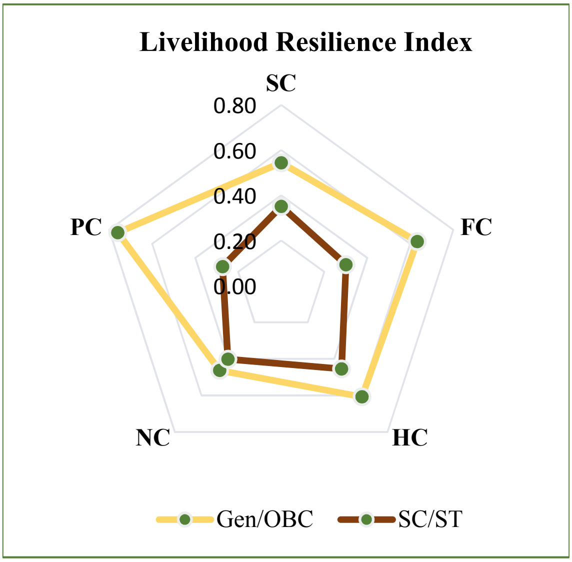

Fig. 2 Spider diagram comparing the five livelihood capitals between General/OBC and SC/ST households

4.3 Loss and Damages

The villages of Akampadam and Kurumbilangode were damaged by the floods of 2018 and 2019. However, the floods' effects were not evenly dispersed among the settlements. In 2018, ST communities were the most affected group compared to low-lying places along the river. This was mostly due to a number of landslides that happened in various regions. Riverside locations are the most impacted in 2019 due to river overflow induced by heavy rains and debris flow at several sites throughout the Nilambur taluk, notably at Kavalappara in the Pothukal panchayat. However, each of these catastrophes resulted in significant loss and damage across the settlements.

Table 3 shows data from the 2018 and 2019 floods on overall agricultural losses, house losses, vehicle damage, medical losses, lost wages, and livestock losses. The total economic losses of respondents due to the flood and landslides amounted to Rs. 2,99,77,500 and the average economic loss to be borne by each household is Rs. 2,36,043.31. We can observe that the average economic loss of general/OBC households (Rs. 4,04,306.45) is more than the total average economic loss (Rs. 2,36,043.31) and that of SC/ST households (Rs. 75,546.15) is lower than the total average economic loss (Fig. 3).

In comparison to 2018, agriculture losses are predicted to increase in 2019. This is because floods in 2019 impacted low-lying areas where many people practiced agriculture. During the 2018 and 2019 floods, we can see that floods damaged several houses and caused significant damage. Floods have had a significant influence on many people's sources of income and livelihoods. People have been unable to work for several days since cleaning their homes from the mud, stones, and sand dumped inside took several days. For some households, it took a few months for them to

Table 3 Total loss and damages incurred by households (in Rs)

Types of lose	Household		
	Gen/OBC (n = 62)	SC/ST (n = 65)	Total (n = 127)
Agriculture	23,96,500	6,35,000	30,31,500
Vehicle damage	71,88,500	33,000	72,21,500
Medical cost	48,000	6,500	54,500
Earnings lost	16,77,000	2,72,500	19,49,500
House and other infrastructure	1,35,30,000	38,40,000	1,73,70,000
Livestock	2,27,000	1,23,500	3,50,500
Total economic loss	**2,50,67,000**	**49,10,500**	**2,99,77,500**

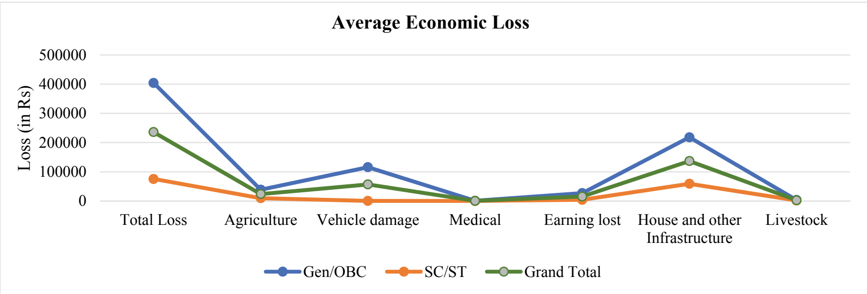

Fig. 3 Average value of different types of loss incurred by households

return to normal. Farmers were unable to cultivate their land since all crops had been destroyed and the land had been deposited with mud and sand.

Only around 30% of the total surveyed households (41 households) owned livestock. Most of them owned livestock for domestic use solely, not as a source of income. Only a very small percentage of the surveyed households relied on agriculture as their primary source of income, but many of them continued to do small-scale farming on their land. The major agricultural products in these areas include rubber, pepper, bananas, coconut, Areca nuts, nutmeg, and turmeric. In comparison to 2018, the 2019 floods had a higher impact on agriculture in these locations. The majority of the land that was impacted was in low-lying areas near the river.

5 Conclusion

The study attempted to capture general livelihood resilience between general/OBC and SC/ST households to a variety of shocks, including climate change-related shocks including floods and landslides. General/OBC households had 29 percent higher average scores for all five livelihood capitals, as well as 33 percent higher scores for financial capital, 19 percent for social capital, 15 percent for human capital, 6 percent for natural capital, and 49 percent for physical capital than SC/ST households. Flood resistance is more likely to be found in households with more stable sources of income (higher livelihood capital scores) [23]. The major livelihood shocks studied in this study contribute to localized economic instability by reducing agricultural yields, disrupting people's daily lives and livelihood activities, and affecting access to local markets [24]. As a result, the findings directly and implicitly explore how different livelihood capitals contribute to livelihood resilience in the face of economic uncertainty. The findings of this study emphasize the value of each livelihood capital during periods of economic uncertainty caused by severe events in the study area.

A balance of these five capitals is thought to be essential for a household to maintain overall well-being and sustain their adaptive capacity [25]. The development of various types of livelihood assets can be facilitated by the accumulation of one type of livelihood asset. A better financial capital can reduce the vulnerability and enhance resilience in the time of shock [26]. Dealing with economic insecurity by a household depends on the balanced accumulation of their livelihood capital assets [27]. The findings of this study show that there is a difference in livelihood resilience between SC/ST and general/OBC households, as well as an increase in livelihood resilience among general/OBC households. There were also substantial differences between SC/ST and General/OBC households in terms of overall livelihood resilience. Casual labour was the most common source of income for SC/ST households, while some General/OBC households had businesses, salaried employment, and other stable sources of income. The availability of livelihood opportunities may differ greatly among various communities due to the ecological, social, and political conditions of each community.

This study adds to our understanding of the impact of floods and landslides on household livelihood in addition to presenting empirical evidence on livelihood resilience. This was primarily determined by examining the losses and damages suffered by the households surveyed. Since some of the households affected in 2019 were not affected in the 2018 floods, the data on loss and losses was focused on both 2018 and 2019 flood events. Floods cause havoc on agriculture, food distribution networks [28], infrastructure, and employment, as well as other aspects of daily life [29]. Since 2018, residents have had to contend with floods and landslides in their daily lives.

This study only offers a "snapshot" of livelihood resilience rather than a complex indicator of how resilience is evolving. The same questions about resilience measures would need to be asked of households twice if the goal was to determine how resilience has changed over time. Furthermore, the methodology used here does not prioritize measures of resilience. This method might not take some indicators into account, even though those indicators might be more crucial than others in developing resilience. Various surrogates could be given different weights during the analysis using the same techniques. It is possible to weigh various surrogates; however, this study will not do so.

Another drawback is that large-scale variables such as macroeconomics, national politics, and international trade, which can directly impact livelihoods and their adaptation practices, can be challenging to integrate into resilience calculation. This is a criticism of sustainable livelihoods in general [30], but it also applies to the approaches discussed in this article. In addition, resilience measurement is frequently highly contextualized, which makes it difficult to incorporate into policy [31].

6 Future Scope of the Study

Despite studies and theories that focus on the implication of extreme events on the resilience of local livelihood and their day-to-day activities, there is still a lack of literature on livelihood resilience mainly focusing on their five livelihood capitals. Most of the existing studies are on the concept of vulnerability, adaptation, and resilience with respect to climate change and extreme events. These studies, however, lack in analysing the direct implication of climate change and related extreme events and disasters on livelihood of local people at household level. Also, most of the studies are only region specific and not focusing on socioeconomic and cultural background of the region especially the various social groups. This study is an attempt to unravel the impact of extreme events on livelihood of local people and to measure their livelihood resilience. This study tries to address certain gaps in existing literature as only a few studies have been conducted at household level on livelihood resilience in India.

The findings of this study are intended to be beneficial to both development organizations and policymakers. These findings can be applied to development programmes as well as wider policies aimed at increasing livelihood resilience. A wide range of international development and humanitarian organizations use the concept of resilience. At a number of scales, resilience has also gained popularity in policy-making. This study has the possibility to provide policy recommendations on how to increase livelihood resilience to losses and damage brought on by climate change.

The research's second future path is to broaden the scope of the analysis to include more locations. To further understand livelihood resilience to extreme rainfall events, conducting a study similar to this in a few different locations with various social, economic, and environmental settings would be beneficial. Many of the findings in this study were context-dependent, and changing the context may influence the main types of disturbances or their characteristics. Additionally, the capacity of households in diverse locations to absorb shocks and respond to disturbances may vary. The availability of livelihood options and a household's capacity to withstand shocks may be influenced by local politics, educational options, land tenure policies, and climate patterns.

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References

1. Field CB, Barros V, Stocker TF, Dahe Q, Dokken DJ, Ebi KL, Mastrandrea MD, Pauline KJM, Plattner G-K, Allen SK, Tignor M, Midgley PM (2011) Special report of the intergovernmental panel on climate change edited. In: Managing the risks of extreme events and disasters to advance climate change adaptation special
2. Bauer T, Ingram V, De Jong WD, Arts B (2018) The socio-economic impact of extreme precipitation and flooding on forest livelihoods: evidence from the Bolivian amazon. Int For Rev 20(3):314–331. https://doi.org/10.1505/146554818824063050
3. Kundzewicz ZW, Kanae S, Seneviratne SI, Handmer J, Nicholls N, Peduzzi P, Mechler R, Bouwer LM, Arnell N, Mach K, Muir-Wood R, Brakenridge GR, Kron W, Benito G, Honda Y, Takahashi K, Sherstyukov B (2014) Le risque d'inondation et les perspectives de changement climatique mondial et régional. Hydrol Sci J 59(1):1–28. https://doi.org/10.1080/02626667.2013.857411
4. IPCC (2001) TAR AR3 third assesment report-workgroup ii: impacts, adaptation & vulnerability. In Ipcc. http://www.ipcc.ch/ipccreports/tar/wg2/index.htm
5. Iwasaki S, Razafindrabe BHN, Shaw R (2009) Fishery livelihoods and adaptation to climate change: a case study of Chilika lagoon, India. Mitig Adapt Strat Glob Change 14(4):339–355. https://doi.org/10.1007/s11027-009-9167-8
6. Shepherd J (2013) Impacts of urbanization on precipitation and storms: physical insights and vulnerabilities. In: Climate vulnerability: understanding and addressing threats to essential resources, Vol 5, pp 109–125. https://doi.org/10.1016/B978-0-12-384703-4.00503-7
7. Coirolo C, Commins S, Haque I, Pierce,G.(2013) Climate change and social protection in bangladesh: Are existing programmes able to address the impacts of climate change? Dev Policy Rev 31(Suppl. 2):o74–o90. https://doi.org/10.1111/dpr.12040
8. Banks N (2016) Livelihoods limitations: the political economy of urban poverty in Dhaka. Bangladesh. Dev Change 47(2):266–292. https://doi.org/10.1111/dech.12219
9. Sadeka S, Reza MIH, Mohamad MS, Sarkar MSK (2013) Livelihood vulnerability due to disaster : strategies for building disaster resilient livelihood. 2nd international conference on agricultural, environment and biological sciences (ICAEBS'2013), 95–100
10. FAO (2015) The impact of natural hazards and disasters on agriculture and food security and nutrition: A call for action to build resilient livelihoods. FAO Report, May, 16. http://www.fao.org/3/a-i4434e.pdf
11. FAO (2017) The impact of disasters and crises on agriculture and food security. In: Food and agriculture organization
12. Aggarwal PK (2011) Climate change and food security in South Asia. Climate Change Food Secur South Asia. https://doi.org/10.1007/978-90-481-9516-9
13. Adger WN, Hughes TP, Folke C, Carpenter SR, Rockström J (2005) Social-ecological resilience to coastal disasters. Science 309(5737):1036–1039. https://doi.org/10.1126/science.1112122

14. Sarker MNI, Cao Q, Wu M, Hossin MA, Alam GMM, Shouse RC (2019) Vulnerability and livelihood resilience in the face of natural disaster: A critical conceptual review. Appl Ecol Environ Res 17(6):12769–12785. https://doi.org/10.15666/aeer/1706_1276912785
15. Cardona OD, Van Aalst MK, Birkmann J, Fordham M, Mc Gregor G, Rosa P, Pulwarty RS, Schipper ELF, Sinh BT, Décamps H, Keim M, Davis I, Ebi KL, Lavell A, Mechler R, Murray V, Pelling M, Pohl J, Smith AO, Thomalla F (2012) Determinants of risk: Exposure and vulnerability. In: Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change (Vol 9781107025). https://doi.org/10.1017/CBO9781139177245.005
16. Ibarrarán ME, Ruth M, Ahmad S, London M (2009) Climate change and natural disasters: macroeconomic performance and distributional impacts. Environ Dev Sustain 11(3):549–569. https://doi.org/10.1007/s10668-007-9129-9
17. Madhuri, Tewari HR, Bhowmick PK (2015) Livelihood vulnerability index analysis: an approach to study vulnerability in the context of Bihar. Jamba J Disaster Risk Stud 6(1):1–13. https://doi.org/10.4102/jamba.v6i1.127
18. De U, Dube RK, Rao GSP (2005) Extreme weather events over India in the last 100 years. J Ind Geophys Union 9(3):173–187. https://doi.org/10.16818/j.issn1001-5868.2017.05.004
19. Kuriakose SL, Sankar G, Muraleedharan C (2009) History of landslide susceptibility and a chorology of landslide-prone areas in the Western Ghats of Kerala. India. Environ Geol 57(7):1553–1568. https://doi.org/10.1007/s00254-008-1431-9
20. Sharma VK (2020) Landslides in India: issues and perspective. J Geol Soc India 95(1):110–110. https://doi.org/10.1007/s12594-020-1393-4
21. Uy N, Takeuchi Y, Shaw R (2011) Local adaptation for livelihood resilience in Albay. Philippines. Environ Hazards 10(2):139–153. https://doi.org/10.1080/17477891.2011.579338
22. Ambili V, Narayana AC (2014) Tectonic effects on the longitudinal profiles of the Chaliyar River and its tributaries, southwest India. Geomorphology 217:37–47. https://doi.org/10.1016/j.geomorph.2014.04.013
23. Quandt A (2018) Measuring livelihood resilience: the household livelihood resilience approach (HLRA). World Dev 107:253–263. https://doi.org/10.1016/j.worlddev.2018.02.024
24. Uddin MS, Haque CE, Khan MN, Doberstein B, Cox RS (2021) "Disasters threaten livelihoods, and people cope, adapt and make transformational changes": Community resilience and livelihoods reconstruction in coastal communities of Bangladesh. Int J Disaster Risk Reduct 63:102444. https://doi.org/10.1016/j.ijdrr.2021.102444
25. Jacobs B, Nelson R, Kuruppu N, Leith P (2015) An adaptive capacity guide book, 27
26. Mayunga JS (2007) Understanding and applying the concept of community disaster resilience: a capital-based approach. Summer academy for social vulnerability and resilience building, July, 1–16. http://www.ehs.unu.edu/file/get/3761.pdf
27. Rakodi C (1999) A capital assets framework for analysing household livelihood strategies: implications for policy. Dev Policy Rev 17(3):315–342. https://doi.org/10.1111/1467-7679.00090
28. Kumssa A, Jones JF (2010) Climate change and human security in Africa. Int J Sust Dev World 17(6):453–461. https://doi.org/10.1080/13504509.2010.520453
29. Ramakrishna G, Solomon RG, Daisy I (2014) Impact of floods on food security and livelihoods of IDP tribal households: the case of Khammam region of India. Int Ournal Dev Econ Sustain 2(1):11–24
30. Serrat O (2017) The sustainable livelihoods approach. Knowl Solut, https://doi.org/10.1007/978-981-10-0983-9_5
31. Cooper SJ, Wheeler T (2015) Adaptive governance: livelihood innovation for climate resilience in Uganda. Geoforum 65:96–107. https://doi.org/10.1016/j.geoforum.2015.07.015

Dynamics of the Aquacultural Intensification in the Godavari-Krishna Inter Delta Region in India and Its Impact on Ecological Balance

T. V. Nagaraju, T. Rambabu, Sireesha Mantena, and B. M. Sunil

Abstract One of India's mega deltas, the Godavari-Krishna inter delta, has abundant natural resources that are good for the growth of agriculture. However, regional limitations are also rapidly giving way to aquaculture. In the coastal districts of Andhra Pradesh, particularly in the West Godavari and Krishna districts, aquaculture is one of the land feature classes that is expanding quickly. The other land cover elements, including vegetation and built-up areas, will be negatively impacted by aquaculture's unrestrained and indiscriminate expansion. Geographic information system (GIS) software was used to evaluate the dynamic changes in land use and land cover between 2013 and 2019. With the loss of about 650 square kilometers in both deltas, agricultural practices are changing to intensive aquaculture with an emphasis on increasing yields rather than lowering environmental quality. In the short period between 2013 and 2019, 16.5% of the agricultural land in the Godavari-Krishna delta was cleared to make way for infrastructure improvements and aquaculture. The essential components of the Godavari-Krishna delta aquaculture scenario are also highlighted in this research. The Godavari-Krishna delta is changing coastal ecology and is vividly depicted in this study.

Keywords Aquaculture · Coastal management · Environment · Remote sensing

T. V. Nagaraju (✉)
Department of Civil Engineering, S.R.K.R Engineering College, Bhimavaram, India
e-mail: varshith.varma@gmail.com

T. Rambabu
Water and Environment Technology (WET) Center, S.R.K.R Engineering College, Bhimavaram, India

S. Mantena
Department of Geo-Engineering, Andhra University, Visakhapatnam, India

B. M. Sunil
Department of Civil Engineering, National Institute of Technology Karnataka, Mangalore, India

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1 Introduction

One of the agricultural and livestock industries with the most significant growth rate is aquaculture, which offers a potential means of enhancing livelihoods and food security and generating export income in Asian nations, including China, India, Bangladesh, and Vietnam [1]. India is one of the leading countries in producing and exporting aquatic products. The West Godavari district produces the most aquaculture in India and contributes considerably to export earnings [1, 2]. This area, which serves as the primary hub for aquaculture production in the state, makes a substantial contribution to the whole country's economy and regional and global food security. One-fourth of the state's aquaculture production in 2018 was produced by the West Godavari district alone [1]. The western Godavari delta region contributes significantly to the state's overall shrimp output, primarily raised in small, intense farming operations along significant waterways including Kolleru Lake, Yarracalava, Tammileru, and Ramileru. In 2019, the West Godavari district produced 11,52,201 tons of vannamei shrimp and fish across a total farming area of about 67,518 acres. Additionally, the new administration wants to make shrimp aquaculture, a significant business in the Godavari-Krishna inter delta, a vital economic sector. More specialized inputs and economies of scale are driving the development trend toward growing large-scale intensification. Diseconomies of scale, however, can also happen if a company becomes too big to operate effectively or through overcapitalization. Furthermore, farmers who lack sufficient capital are unable to access sources of livelihood capital or lack managerial skills would be unable to take advantage of such productivity advances because they face difficulties accessing capital or are being dominated by big input suppliers. Since shrimp output depends on a stable environment, expanding the production size also raises the chances for adverse environmental effects [3, 4]. Aquaculture development carries risks of adverse environmental effects, such as landform change, ecological degradation, loss of habitat, and nutrient enrichment, which can result in significant epidemics of shrimp disease [5, 6]. Despite the potential for high profits, employment opportunities, and increased exports to ensure better profits and food security, these benefits come at a cost. Rural households in the Godavari and Krishna delta do most small-scale shrimp farming [7].

There is already numerous research on land cover dynamics in river deltas, estuaries, and coastal areas utilizing remote sensing data. According to numerous studies of coastal areas and deltas, urban growth and human impacts caused agriculture and mangrove areas to shrink rapidly through time [8]. In contrast, urban surfaces, vegetated prawn fields, lakes, and ponds grew rapidly. Agricultural acreage declined dramatically in certain areas while growing in others. Because of the rapid developments in inland aquaculture cultivation, the Godavari delta in India and the Mekong delta in Vietnam have recently attracted the scientific community's interest [9, 10].

This study's primary objective is to list the most appealing characteristics of the Godavari-Krishna inter delta following the interconnection of the rivers Godavari and Krishna with the Pattiseema lift irrigation project. After the new state of Andhra

Pradesh was formed in 2014, geographical and temporal patterns of land use and land cover were observed in the Godavari-Krishna inter delta. The research was created to particularly accomplish the following goals: identify and map the main land cover/ land use classifications in the study area; (ii) collate the geographic and temporal distribution of the land cover/land use developments, and (iii) determine the scope and purpose of these modifications that occurred over these years. These results will be the foundation for assessing how the region's land use and cover have changed over time. In addition to providing a solid foundation for creating economic, social, and environmental policies to ensure sustainable development in the study region, this research will enhance the long-term knowledge about the causes and impacts of land cover/land use changes.

2 Godavari-Krishna Inter Delta

The study area, with a shoreline of about 88 km, Krishna District, was further separated into Krishna and West Godavari Districts in 1925. The study region included the Andhra Pradesh districts along the western and eastern deltas of the Godavari and Krishna rivers. About 6426.78 square kilometers are occupied by the West Godavari and Krishna inter delta, which is located between the latitudes of 16°56′15.63″ and 15°59′25.53″ N and the longitudes of 80°36′8.37″ and 81°52′31.35″ E. It is made up of 24 mandals in West Godavari and 31 mandals in Krishna District. The research area is situated between the Krishna and Godavari River deltas. Figure 1 displays the location of the present study's map. The climate is humid and hot, with summertime highs of up to 42 degrees Celsius. In summer, the mean daytime temperature is between 35 °C and 40 °C, whereas in winter, it ranges between 25 °C and 30 °C.

The western delta region of Andhra Pradesh is referred to as the "rice bowl" of the state since it produced most of the state's agricultural output overall and more than 50% of the export yields of rice during the early 1980s. It is one of the Andhra Pradesh coastal regions with the highest number of homes and agricultural fields; between 1970 and 1990, major natural disasters were experienced and resulted in severe damage. Due to its low elevation (between −1 and 5 m above sea level) and the significant tidal fluctuations caused by the Bay of Bengal, the Godavari and Krishna delta is a low-lying, flat area that is readily inundated. Since the 1990s, improvements in water resource management have decreased flood levels and created a favorable environment for aquaculture techniques.

Before the white spot syndrome virus (WSSV) epidemic hit the aquaculture industry in 1994, Penaeus monodon had been raised on farms since 1990 with stocking numbers of 20,000 shrimp/acre. As a result, the area used for aquaculture production shrunk dramatically, and the sector nearly died. With a maximum legal stocking density of 1 lakh shrimp/acre, the Government of India permitted the specialized pathogen-free Penaeus vannamei culture to restart the sector in 2009. Aquaculture exports from Andhra Pradesh were worth Rs. 2,100 crores in 2009–10; this amount rose to Rs. 14,000 crores in 2014–15. Andhra Pradesh had the most

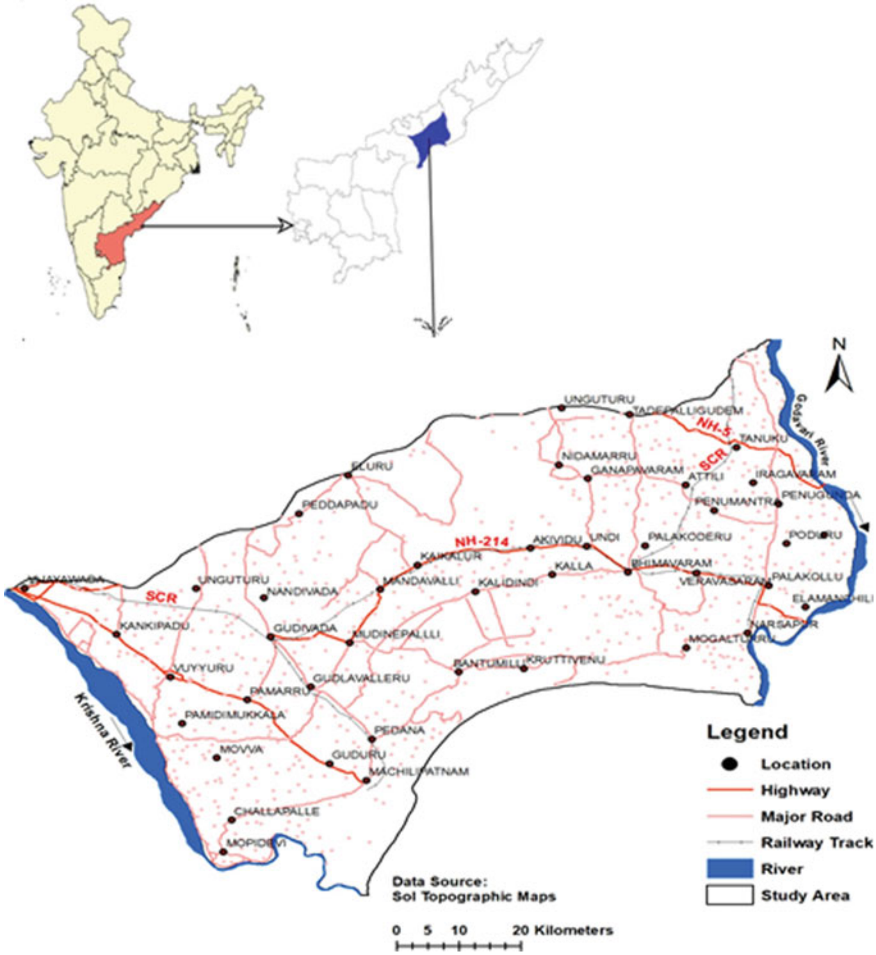

Fig. 1 Godavari-Krishna inter delta

outstanding production value in 2019 with 44,856 crores, of which 11,519 crores were attributable to exports from the Godavari delta alone [1]. With 1.323 lakh ha, the Godavari-Krishna inter delta is the state's largest aquaculture production area.

3 Methodology

A land use and land cover categorization feature goal are to make it possible to arrange/group the variety of information that is readily available into a helpful framework. Along with systematic inventory and mapping, land use information from satellites and other sources is also included. The created framework for classifying land use and land cover lends itself to remote sensing-based mapping. The National Remote Sensing (NRSC) Agency's classification scheme is used in this study [11]. Level-I, Level-II, and level-II classifications of land use and land cover are described in the classification. Level-II provides a semi-detailed breakdown of information for the catch-wide class, whereas Level-l provides a broad categorization of several land use classes. Some Level-I classes still have a more acceptable level separation of units in the third-level groups. We fulfill the minimal data requirements for the 1:20,000 scale mapping. Visual interpretation techniques have been used to map the study area's land use and cover. Visual interpretation techniques have been used to map the study area's land use and cover. Using satellite data from the Kharif and Rabi seasons, the land use/land cover features have been identified and mapped based on image attributes. Additionally, various reports and maps pertaining to land use and land cover were used in creating the land use and land cover maps. Field observations about cropping patterns, changes in land use and land cover, and sample images are also acquired in order to physically verify the doubtful areas or hotspots caused by similar spectral responses and spectral fingerprints.

4 Land Use and Land Cover Results

4.1 Land Use and Land Cover Classification and Detection

In 2014, before and after state bifurcation, Figs. 2 and 3 display the surface distribution (in km^2) and evolution of the fraction of each land cover/land use class. Over the past 50 years, cultivated lands have remained the dominant land cover in the area. In the research area, aquaculture ponds made up the second-highest land cover. Trends can be seen in the land cover classes changing the most between 2013 and 2019, mainly cropland and aquaculture ponds. Due to the active involvement of the Patiseema lift irrigation project connecting the rivers Godavari and Krishna, bare lands have significantly diminished in recent years. Throughout the study period, built-up areas and aquaculture ponds developed dramatically and steadily. In the inter delta region, agricultural lands altered during all the studied years, primarily due to the increase of aquaculture ponds. During the study period, it was particularly evident in the east and west catchments of the Upputeru and Undi canals that agricultural lands were being drastically converted into aquaculture grounds.

Table 1 displays the specific dynamics of the changing land use and covers the research area. The table displays the conversion of one class to another because of the cross-tabulation matrix of the land cover/land use change. For instance, while considering the entire study period of 2013–2019, the agricultural land covering area varied from 4601.74 km^2 in 2013 to 3948.77 km^2 in 2019, when it eventually began to decline. Figure 4 makes it easy to see how agriculture is dynamic. Aquaculture is the most prevalent land use class in the region after agriculture. Aquaculture is

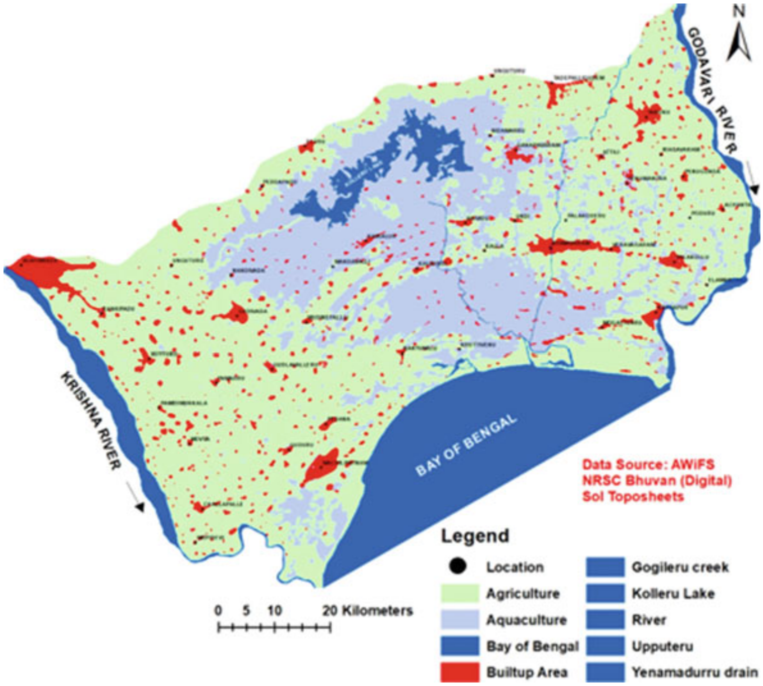

Fig. 2 Land use and land cover in 2013

not very advanced in the research region. Most of the area's significant drainage systems are covered by it. Figure 4 displays the variances in the aquaculture land coverage area. Initially covering 1279.18 km^2 in 2013, the aquaculture coverage area continued to grow till it ultimately covered 1892.80 km^2 by the end of 2019.

4.2 Potential Drivers of Aquaculture Land Cover in the Godavari-Krishna Inter Delta

The study region's principal water resources are the Godavari River, Krishna River, Kolleru Lake, Upputeru River, Yanamaduru Drain, and Gogilleru Creek (see Fig. 5). One of the most significant fresh waters in the country is Kolleru Lake, which is situated between the Krishna and Godavari Rivers deltas. The two most significant streams that flow into the lake are Guvaleru and Tammileru. In addition, irrigation channels and drains feed the lake. The river Upputeru is the lake's only exit. The remote sensing-based analysis shows that aquaculture pond development and converting productive agricultural land to aquaculture disturb Kolleru Lake and its surroundings.

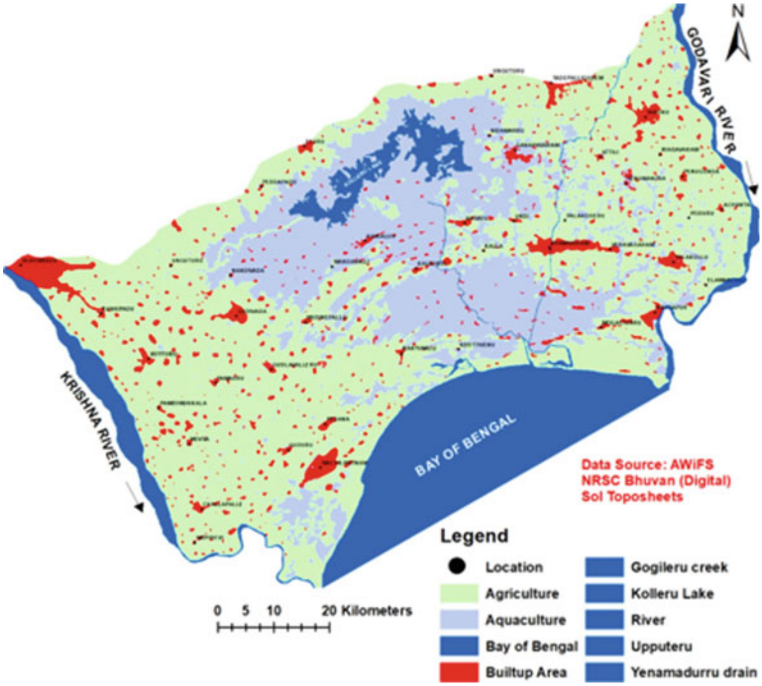

Fig. 3 Land use and land cover in 2019

Table 1 Land use and land cover classes in the study area

Class	Area (km^2) in the year				
	2013	2015	2016	2018	2019
Aquaculture	1279.18	1325.65	1432.75	1797.09	1892.80
Built-up area	293.86	311.61	347.04	395.09	396.18
Agriculture	4601.74	4539.57	4424.69	4042.26	3948.77
Others	251.99	249.95	222.30	192.34	189.04
Total	6426.77	6426.78	6426.77	6426.77	6426.78

The favorable government policies, the salt encroachment issue, and the commercial dimension are the leading causes of this transformation. The presence of a higher concentration of saline waters in the study area is due to the plain, low-lying area's extensive network of rivers and canals, the Bay of Bengal's strong tides, the pumping of saline waters from deep aquifers for shrimp culture, and the rising sea levels. Additionally, paddy farming revenue 14 times less per crop than shrimp culture (four months). Moreover, in the current intensive inland aquaculture context, engineered aquaculture components are crucial to reducing pollution load. Rich in

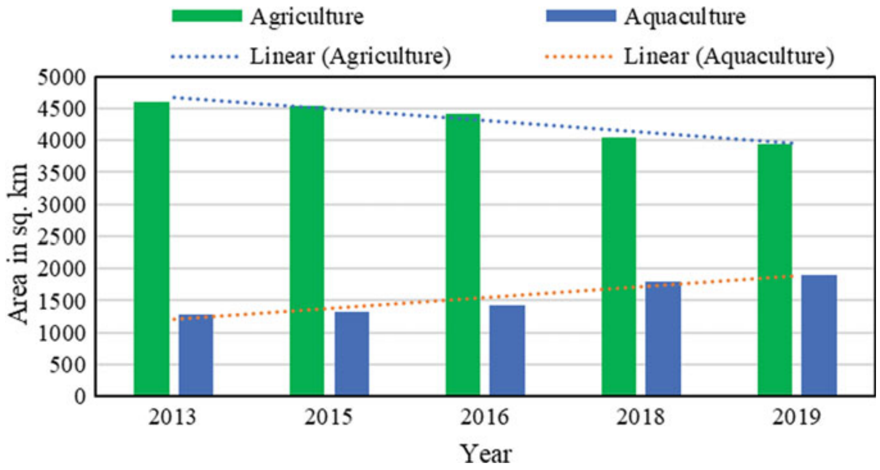

Fig. 4 Land use and land cover trend of agriculture and aquaculture

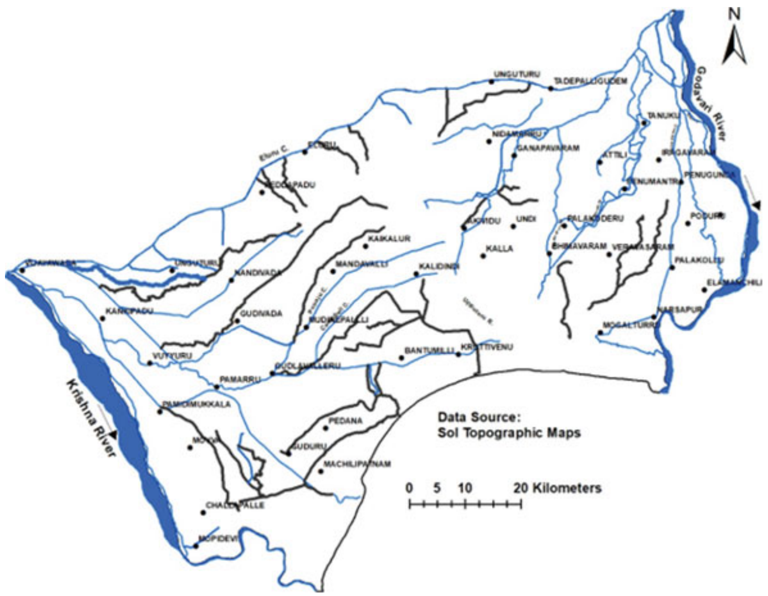

Fig. 5 Water resource map of Godavari-Krishna delta

nutrients, treated effluent can be used to crops as fertilizer and promote sustainable environment and energy nexus.

The Godavari-Krishna inter delta has suffered significant harm due to climate change, environmental degradation, economic growth, and rapid population growth. The implications on biodiversity and ecological changes include rising sea levels, severe storms, and typhoons, flooding during the wet seasons, salinity intrusion during the dry seasons, a lack of fresh water for home and agricultural use, an alkaline environment, and contaminated water. The dynamics of intensive aquaculture have been noticed and analyzed in this research study and are presumed to be a result of all the variables.

5 Conclusions

This study aims to fill a critical gap to assess the dynamics of LULC in South Asia's massive Godavari-Krishna inter delta. Findings from the current study showed that between 2013 and 2019, Andhra Pradesh's inter delta experienced significant land changes. In comparison to the Krishna delta, the Godavari delta has seen more haphazard growth in human settlements, increasing by 100 km^2 between 2013 and 2019. It may result in the depletion of natural resources and lower-than-average living standards.

The significant growth of intensive aquaculture ponds, particularly along the catchments of Kolleru Lake, Upputeru River, Yanamaduru Drain, and Gogilleru Creek, is most noteworthy. The aquaculture area exhibits tremendous expansion, with 32.4% from 2013 to 2019. The unique expansion of aquaculture can be seen in lake Kolleru's periphery and in the fertile deltaic soils that support prawn farming. In addition to the salinization of soils, this causes a considerable loss of water quality in the deltaic environment. It might affect soil production and result in food-based drought situations.

References

1. Nagaraju TV, Malegole S, Chaudhary B, Ravindran G (2022) Assessment of environmental impact of aquaculture ponds in the western delta region of Andhra Pradesh, India, Sustainability 14(20):13035
2. Jayanthi M, Ravisankar T, Nagaraj G, Thirumurthy S, Muralidhar M, Saraswathy R (2019) Is aquaculture abandonment a threat to sustainable coastal resource use?–a case study of Andhra Pradesh, India, with options for reuse. Land Use Policy 86:54–66
3. Kautsky N, Rönnbäck P, Tedengren M, Troell M (2000) Ecosystem perspectives on management of disease in shrimp pond farming. Aquaculture 191(1–3):145–161
4. Ahmed N, Thompson S, Glaser M (2019) Global aquaculture productivity, environmental sustainability, and climate change adaptability. Environ Manage 63(2):159–172
5. Yang P, Zhao G, Tong C, Tang KW, Lai DY, Li L, Tang C (2021) Assessing nutrient budgets and environmental impacts of coastal land-based aquaculture system in southeastern China. Agr Ecosyst Environ 322:107662
6. Do HL, Thuy TD (2022) Productivity response and production risk: a study of mangrove forest effects in aquaculture in the Mekong River Delta. Ecol Econ 194:107326
7. Muralidhar M, Kumaran M, Jayanthi M, Syama Dayal J, Ashok Kumar J, Saraswathy R, Nagavel A (2021) Impacts of climate change and adaptations in shrimp aquaculture: a study in coastal Andhra Pradesh. India. Aquatic Ecosyst Health Manag 24(3):28–38

8. Giri S, Daw TM, Hazra S, Troell M, Samanta S, Basu O, ... Chanda A (2022) Economic incentives drive the conversion of agriculture to aquaculture in the Indian sundarbans: livelihood and environmental implications of different aquaculture types. Ambio, 1–15
9. Latha PS, Rao KN, Kumar PV (2022) Hydrochemical evaluation of subsurface water in the aquaculture region of coastal India using multivariate statistics, GWQI and GIS. Int J Energy Water Resour, 1–21
10. Trang NTT, Loc HH (2021) Livelihood sustainability of rural households in adapting to environmental changes: an empirical analysis of ecological shrimp aquaculture model in the Vietnamese Mekong Delta. Environ Dev 39:100653
11. Nagaraja R, Kumar R, Kesava Rao P, Ravishankar G, Saxena M, Tejaswini V (2021) IRS-1C applications in land use/land cover studies: indian experience. J Indian Soc Remote Sens 49(1):97–109

A Comparative Assessment of the Water Footprint of Agricultural, Industrial and Domestic Practices in India

Deepali Goyal, A. K. Haritash, and S. K. Singh

Abstract Water footprint assessment is done to quantify direct and indirect water consumption by categorizing it into blue, green and grey categories. The present study has analysed water footprint of India in contrast to global consumption using the national water footprint data as available online on WaterStat. For the years 1996 to 2005, India has the 2nd largest water footprint value of 1182 Gm^3/year and 1144 Gm^3/year for both production and consumption, respectively. This value accounts for 13% and 13.4% of global total. In terms of blue water footprint, India has the largest share of 243 Gm^3/year, which is 24% of global aggregate blue WF of national production. India too has a very small external water footprint of consumption, i.e., 2.5% of its total value. High footprint values can be attributed to the high population of the country and partly to the consumption patterns and the inefficient production processes.

Keywords Water footprint · National consumption · Virtual water flow

1 Introduction

In the world of increasing water demands where it has become difficult to constrain different drivers of change such as economic growth, population growth, technological development, changing consumption pattern and production/trade pattern, the inevitable consequence of degrading water supplies and increasing scarcity has become more explicit [1]. To understand the linkages between the growing pressure on the limited world water resources and human consumption, researchers worldwide are making use of water footprint (WF) assessment. This method was introduced by Hoekstra [2], in 2002, to provide a structured way of measuring water use throughout the regional scale. Water footprint assessment refers to the quantification of direct and

D. Goyal (✉) · A. K. Haritash · S. K. Singh
Department of Environmental Engineering, Delhi Technological University, New Delhi 110042, India
e-mail: deepali.goyal16@gmail.com

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indirect water consumption volumes by source (blue, green) and by type of pollution (grey) of a process, product, producer, consumer, or a specific geographic area [3]. It consists of three components—blue, green and grey water footprint. The blue water footprint refers to the consumption of surface and groundwater resources whereas the green water footprint in turn refers to the consumption of rainwater when it is stored as soil moisture, i.e., before it contributes to runoff and groundwater recharge. However, unlike blue and green water footprint, grey water footprint is not actually consumed during the production or supply process. It represents the amount of water that is required to dilute the pollution caused by different processes by taking into account the existing ambient water quality standards and natural concentrations of the substance under consideration [4, 5]. It, therefore, represents a probable use.

Internal or International trade acts as a mechanism of water redistribution through the transfer of commodities across different regions. Water footprint analysis can be used to study the water footprint of the existing trade patterns and suggest a strategic solution to alleviate regional water deficits. This is because this method can help us realize water savings through virtual water import to meet increasing water demands [1, 3, 5, 6]. Studies at the global level have suggested that if products were produced in regions with low water footprint and exported to places where they would be otherwise produced with high water footprint, an absolute advantage in water savings can be realized [3, 5, 6].

India like other countries is facing a hovering situation of severe water scarcity. A study by Hoekstra et al. [7], that analysed 405 river basins for global water scarcity for the period 1996–2005, pointed out that in India, the states of Punjab, Rajasthan and Haryana, each of which lies completely or partially in the Indus River Basin, face acute water scarcity for eight months yearly. Also, the Pennar River basin in southern India, a catchment with a population of 10.9 million people faces nine months of severe water scarcity. Therefore, it has become extremely important to look for alternative options to sustain the potable water supply and food self-sufficiency goals of the national government by understanding the present water consumption and pollution patterns.

Recently, many attempts have been made to assess the global water footprint for consumption and production in agriculture, industry and domestic water use. Likewise, this study also aims to understand the water footprint of India in comparison to global consumption using the National water footprint data as available online on WaterStat [8]. This will help us to understand the variations of water availability, consumptive uses and distribution of scarcity so that the results can form a basis for integrated water resources management at the national level. Such an attempt will ensure that the regional differences find adequate representations in the aggregate national water management plan.

2 Materials and Method

The online source for national water footprint data has been used to estimate the national water footprint of production (National WF_{prod}) for agricultural, industrial and domestic sectors by summing up the volume of freshwater consumed and polluted from different economic activities happening within the nation. The footprint associated with the products that will be exported is also included in this assessment. Also, the data has been used to estimate the water footprint of national consumption (National WF_{cons}) in which the water footprint of the exported product (known as direct component) has been removed from the previous estimate and the water footprint associated with goods and services produced in other nations but imported to the country under consideration for local consumption has been added (known as indirect component) (Eq. 1). Different sources of online database include estimates from Mekonnen and Hoekstra [8–11], AQUASTAT database [12], EUROSTAT (2011) [13] and SITA database [14].

$$\text{National}\,WF_{\text{production}} - WF_{\text{Export}} + WF_{\text{Import consumed}} = \text{National}\,WF_{\text{consumption}} \quad (1)$$

The indirect component in the above equation is also called as the external water footprint of an area.

3 Results and Discussion

3.1 *Water Footprint of Production (WF_{prod})*

For the years 1996 to 2005, India has the 2nd largest value of the water footprint of production globally, i.e., 1182 Gm^3/year. This alone accounts for 13% of global total of water footprint of production. China is the topmost consumer of national WF_{prod} with the value of 1207 Gm^3/year, which accounts for 13.3% of global WF_{prod} value. The difference in the WF_{prod} for both the countries is just 25 Gm^3/year. Globally, US is placed at 3rd position after China and India with national WF_{prod} of 1053 Gm^3/year. Agricultural production tends to take maximum share in total WF_{prod} globally (92% of the total value) and also individually for each country. For India, the percentage share of agriculture to total WF_{prod} lies very close to the global percentage share, i.e., 92.5%. However, this value is 13% of global WF_{prod} value of agriculture. Highest share of global WF related to industrial production lies with China at 22%, whereas India's share is 8.8% of the global value. The total WF_{prod} value for India is 1182 Gm^3/year, out of which 64% is green WF, 21% is blue and 15% grey. Details of India's water footprint for production have been summarized in Table 1.

In terms of blue WF_{prod}, India has the largest share of WF within its territory across the globe, i.e., 243 Gm^3/year, which is 24% of the total global blue WF_{prod}.

Table 1 India's water footprint of national production (Mm^3/year)*

Water footprint (Mm^3/year)	Crop production	Grazing	Animal water supply	Industrial production	Domestic water supply
Green	716,004.28	42,644.30	–	–	–
Blue	231,428.05	–	4706.72	1760.50	5224.00
Grey	99,429.22	–	–	33,449.50	47,016.00

* Source of data [8]

As per the analysis, irrigation of wheat, rice and sugarcane takes approximately 73% of India's blue WF_{prod}.

3.2 Water Footprint of Consumption (WF_{cons})

For the years 1996–2005, the global water footprint of consumption (WF_{cons}) is 8525 Gm^3/year. Similar to the value of WF_{prod}, India has 2nd largest value of WF_{cons}, i.e., 1144 Gm^3/year, which accounts for 13.4% of Global WF_{cons} value. In India, the green WF accounts for 65% of the total WF_{cons} value, blue WF accounts for 20.1% and Grey WF accounts for 14.9% of the total share. Also, India accounts for 12% of global green WF_{cons}, 24.4% of the global blue WF_{cons} (highest among all the countries) and 12.7% of the global grey WF_{cons}. Out of India's total WF_{cons}, 93.1% of the WF_{cons} is contributed by agricultural products (this value is 13.6% of the total share of agricultural products in global WF_{cons}), 2.3% by industrial products and 4.6% by domestic water. Details of India's water footprint for consumption have been summarized in Table 2 and Fig. 1.

Since calculations of water footprint are based on consumption patterns of populations, therefore, nations with large population tend to have large water footprint. When we look at the per capita consumption patterns of water footprint, then the global average value is 1,385 m^3/year/capita for the years 1996–2005. The highest per capita consumption has been observed in Mongolia (3775 m^3/year/capita), Niger (3519 m^3/year/capita) and Bolivia (3468 m^3/year/capita). It is interesting to note that India is at 150th place globally with 1089 m^3/year/capita consumption which is less

Table 2 India's water footprint of national consumption (Mm^3/year)*

Water footprint (Mm^3/year)	Agriculture		Industry		Domestic
	Internal	External	Internal	External	
Green	720,644.0	23,546.0	–	–	–
Blue	221,346.8	2179.1	1261.9	98.5	5224.0
Grey	96,332.9	1885.5	23,850.5	1219.8	47,016.0

* Source of data [8]

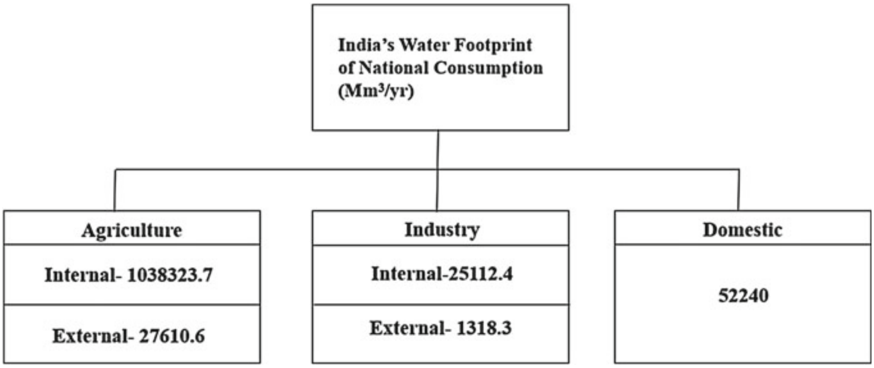

Fig. 1 India's water footprint of national consumption (Mm^3/year) (*Source* of data [8])

than the global average. Also, the WF_{cons} is high in countries like Mongolia, Bolivia and Niger because of high meat consumption and high WF associated with its production processes. The global average blue WF of consumption is 153 m^3/year/capita, which is 11% of the total per capita WF. The gap in blue WF per capita between countries is immense with Turkmenistan having the largest blue WF of all countries, i.e., 740 m^3/year/capita on average, Saudi Arabia (447 m^3/year/capita) and India having 218.9 m^3/year/capita.

3.3 *External Water Dependency of Countries*

In agricultural domain, almost 19% of the entire WF_{prod} is linked to the agricultural production that is used for export; whereas in the industrial sector, this value is 41%. The reliance of countries on external water footprint varies from country to country. Globally, external water footprints of different countries add upto 22% of the aggregate global water footprint of consumption. Some European countries, such as the United Kingdom, Italy, Netherlands and Germany, have external WFs as high as 60–95% of their total WF_{cons}, whereas some countries, like Sudan (3.9), Niger (2.5), DR Congo (2.9), Chad (0.8) and Ethiopia (2.3), have very insignificant external WFs, less than 4% of their total WF_{cons}. India too has a very small external WF_{cons}, i.e., 2.5% of its total WF_{cons}. Countries like Cyprus (71%), Israel (82%), Yemen (76%), UAE (76%) and Lebanon (73%) have large external WF mostly due to scarcity of their domestic water resources. However, there are some exceptions; many European countries that have the scope of expanding agriculture and reducing imports also tend to depend upon freshwater resources from other countries.

4 Conclusion and Recommendations

Agriculture sector has been analysed to share the maximum contribution, i.e., almost 92% to the global total WF_{prod} for the years 1996–2005. Green water footprint in general accounts for nearly 80% of this total contribution and has been recorded higher than blue water footprint even in irrigated agricultural areas. Therefore, to improve the water use efficiency, researchers have suggested to increase water productivity and consequently food production in rain-fed agriculture. Such a solution will therefore not require additional blue water resources.

Also, India has a very high share of global WFs both for production and consumption estimates. This can be partly attributed to the high population of the country and partly to the consumption patterns and the inefficient production processes. Hence, the information provided by the study can help governments to endeavour in the direction of sustainable water use by improving production schemes (to improve water use efficiency) as well as consumption schemes (to improve consumption patterns) so that the water footprint-intensive products are replaced by new products that use less water in their manufacturing and local use. It can also be used to design a strategy considering different aspects of water conservation, by incorporating the blue, green and grey water footprint values and their regional variations to increase water productivity in various sectors and to reduce environmental impacts.

References

1. Ercin AE, Hoekstra AY (2014) Water footprint scenarios for 2050: a global analysis. Environ Int 64:71–82
2. Hoekstra AY (ed) (2003) Virtual water trade: proceedings of the international expert meeting on virtual water trade, 12–13 December 2002, value of water research report series No 12, UNESCO-IHE, Delft, Netherlands
3. Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM (2011) The water footprint assessment manual: setting the global standard, London, UK: Earthscan
4. Franke NA, Boyacioglu H, Hoekstra AY (2013) Grey water footprint accounting: tier 1 supporting guidelines. Delft: UNESCO-IHE
5. Kampman DA, Hoekstra AY, Krol MS (2008) The water footprint of India. Value Water Res Report Ser 32:1–152
6. Wang R, Zimmerman J (2016) Hybrid analysis of blue water consumption and water scarcity implications at the global, national, and basin levels in an increasingly globalized world. Environ Sci Technol 50(10):5143–5153
7. Hoekstra AY, Mekonnen MM, Chapagain AK, Mathews RE, Richter BD (2012) Global monthly water scarcity: blue water footprints versus blue water availability. PLoS One 7(2)
8. Mekonnen MM, Hoekstra AY (2011) National water footprint accounts: the green, blue and grey water footprint of production and consumption, Value of Water Research Report Series No. 50, UNESCO-IHE, Delft, The Netherlands
9. Mekonnen MM, Hoekstra AY (2010) A global and high-resolution assessment of the green, blue and grey water footprint of wheat. Hydrol Earth Syst Sci 14(7):1259–1276
10. Mekonnen MM, Hoekstra AY (2010b) The green, blue and grey water footprint of crops and derived crop products, Value of Water Research Report Series No. 47, UNESCO-IHE, Delft, The Netherlands

11. Mekonnen MM, Hoekstra AY (2010c) The green, blue and grey water footprint of farm animals and derived animal products, Value of Water Research Report Series No. 48, UNESCO-IHE, Delft, The Netherlands
12. FAO (2010) AQUASTAT on-line database, Food and Agriculture Organization, Rome, http://faostat.fao.org (retrieved 12 Dec 2010)
13. UNSD (2010) UNSD environmental indicators: inland waters resources, UN Statistic Division, http://unstats.un.org/unsd/ENVIRONMENT/wastewater.htm. Accessed 20 January 2011
14. ITC (2007) SITA version 1996–2005 in SITC, [DVD-ROM]. International Trade Centre, Geneva

Assessment of Nitrate Fluxes in Intensive Aquaculture Region in Godavari Delta Using Spatial Interpolation Kriging

T. V. Nagaraju, B. M. Sunil, Babloo Chaudhary, and T. Rambabu

Abstract In areas with a high concentration of intense aquaculture, nitrate pollution and nutrient enrichment are growing concerns. With predicted future climate changes, these problems are expected to intensify for aquifers and surface waters. The possibility exists to reduce some of these worries through land management and utilization modifications. However, there is much ambiguity surrounding how these alterations will relate. This article uses conventional kriging and empirical Bayesian kriging (EBK) to estimate nitrate levels in India's intensive aquaculture zone, the Godavari delta. The stable, exponential, rational quadratic, and Gaussian models were used to fit experimental variograms using weighted least squares. The number of neighbors that generated the best cross-validation outcome has been further investigated for the model with the shortest residual sum of the squares. Kriging's statistical approaches provided the best root mean square error (RMSE) values overall. No additional summary statistics shed any light on the regression method's selection or settings. After thorough testing, we concluded that many parameters might be better detected using cross-validation.

Keywords Aquaculture · Nitrates · Ammonia · Kriging interpolation

T. V. Nagaraju (✉)
Department of Civil Engineering, S.R.K.R Engineering College, Bhimavaram, India
e-mail: varshith.varma@gmail.com

B. M. Sunil · B. Chaudhary
Department of Civil Engineering, National Institute of Technology Karnataka, Mangalore, India

T. Rambabu
Water Environment and Technology (WET) Center, S.R.K.R Engineering College, Bhimavaram, India

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1 Introduction

Aquaculture business growth is constrained by a lack of resources, including land, water, and fishmeal, and other reasons, including environmental contamination. All elements employed in the process but left in the system after harvesting are considered aquaculture wastes [1]. Unused feed, excrement, chemicals, and pharmaceuticals are the main waste products from aquaculture systems. Waste can also include escaping fish, diseases, and dead shrimp with changed shells. Feed-derived waste, including unconsumed food, undigested nutrient residues, and incontinence products, is the principal source of potentially harmful waste that is either released in canals or made accessible for reuse inside the pond [1, 2]. The nutrients with phosphorus and nitrogen bases are primary suspended particles dissolved in the feed-derived wastes [3].

The efficiency of nitrogen in shrimp assimilation has significant effects on the yield of inland shrimp farming as well as the quality of the water. On average, results from the cultivation of the P. vannamei shrimp variety range by roughly 25%: Meal and soybean meal are the most expensive ingredients in formulated feeds, and an increase in the efficiency of nitrogen digestion and use will therefore enhance the shrimp production. The target organism recovers 11 to 36% of the nitrogen provided as feed or other nutrient input [4]. The inherent efficiency of nutrient use by shrimp suggests that the ability of aquaculture ponds to assimilate nitrogenous effluent may be a limiting factor for nitrogen loading, which could negatively affect water quality and shrimp growth. In aquaculture ponds, dissolved inorganic nitrogen buildup is the factor most likely to restrict the feeding rate after dissolved oxygen. Protein catabolism results in the excretion of ammonia, which can be hazardous if left to build up. Hyperactivity, convulsions, loss of equilibrium, lethargy, and coma are symptoms of ammonia intoxication. However, rather than manifesting as acute toxicity that causes mortality, ammonia toxicity in aquaculture ponds is most likely represented as the sublethal inhibition of shrimp growth or immunocompetence. The pH, temperature, alkalinity, and total ammonia concentration measured at the shrimp shell affect how hazardous unionized ammonia [5]. At high pH and temperature, ammonia is more toxic to shrimp, which causes the ionization equilibrium to change in favor of the poisonous, unionized gaseous form. In the late afternoon, low alkalinity ponds that are poorly buffered are more likely to have high pH and unionized ammonia. Ammonia excretion makes a sizable contribution to the nitrate flux in aquaculture ponds [6].

Along with senescent phytoplankton and other small amounts of organic materials, shrimp emits solid fecal wastes that settle into the sediment. Another potentially harmful nitrogenous molecule that could build up in shrimp culture ponds is nitrite. During nitrification and denitrification, nitrite is emitted as a byproduct. The competitive binding of nitrite to hemoglobin, which results in methemoglobin, which is incapable of carrying oxygen, is how nitrite poisoning is manifested [7]. Ponds whose primary productivity depends on the growth of autotrophic food webs may reduce fish production due to nitrogen. Receiving waters may become less clean due to nitrogen in fishpond effluents. Large amounts of nutrients may be released into the environment because of the inherent efficiency of nutrient use [8]. The effluent from freshwater fish and prawn ponds and marine fish and shrimp ponds has higher total nitrogen and ammonia concentrations than influent water concentrations, whereas nitrate levels have decreased. Most of the nitrogen released by fishponds is linked to detrital and algal biomass. In general, ponds discharge less nitrogen into the environment than do raceways and cages. The water exchange rate affects the nitrogen outflow from shrimp ponds, which is variable [9].

This paper assesses the concentration of nitrates coming from inland aquaculture ponds and their potential for spreading. In this case, geostatistical methods were used to examine the spatial variability of groundwater nitrates. The spatial distribution of nitrates in the research area was mapped using kriging.

2 Methodology

2.1 Study Area

The Godavari delta region is located between the latitudes of 16° 71′ 07″ and 16° 98′ 91″ and the longitudes of 81° 38′ 32″ to 82° 24′ 75″. The central delta, the Bay of Bengal, the Godavari River, and the Upputeru River encircle this area from the north, south, east, and west [10]. Rainfall for ten years is 785.6 mm. From north to south, the elevation rises steadily; in the research region, the average elevation difference is between 0.5 and 1 m.

After state bifurcation in recent years, the government's policies in the aquaculture sector have emphasized the vast scale. Large farming subsidies are given to this industry each year. The fast spread of aquaculture is evident by the increased emphasis on power subsidies for aeration systems. According to the land use and land cover, aquaculture ponds and agricultural lands predominate in the studied region (Fig. 1).

2.2 Geostatistical Analysis

To create forecast models of the nitrate levels in the intensive aquaculture zone, kriging and co-kriging analyses were used. A consistent range of values can be forecasted between the known locations using the geostatistical approach known as kriging. It is employed to estimate the unknown surface from a dispersed set of existing points. Kriging weights are controlled using the variogram model. The mathematical definition of a variogram is a statistic of semi-variance as a distance variable.

$$\mathrm{Z(n)} = 0.5\mathrm{N(d)} * \sum\left[\mathrm{m(yj)} - \mathrm{m(yj - d)}\right]^2 \tag{1}$$

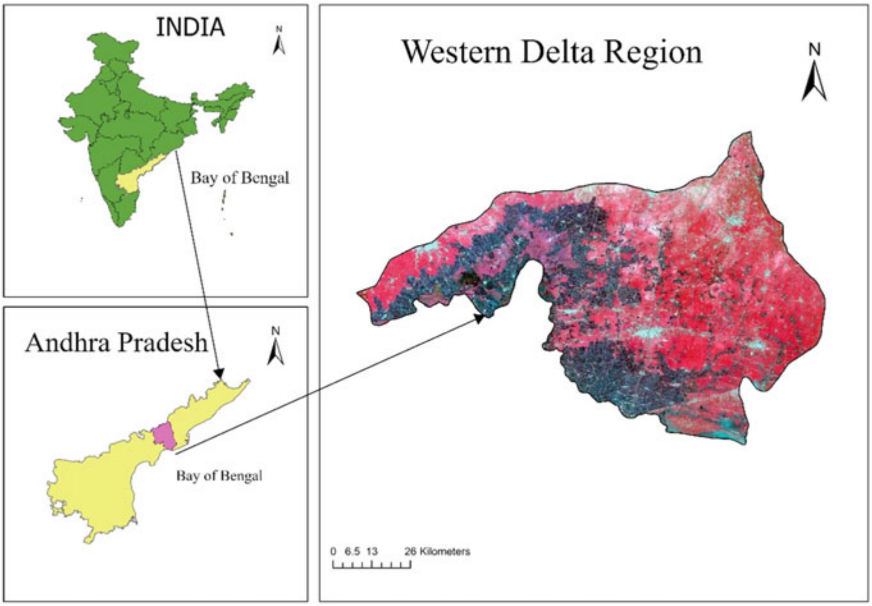

Fig. 1 Godavari delta region

where m(yj) is the measured sample at point yj, m(yj + d) is the measured sample at point (yj + d), and (d) is the semi-variance. N(d) is the number of pairings separated by distance or lag d. By applying a mathematical model to the observed measurements, the spatial organization of the data is established. The input data for kriging are also provided by the mathematical models, together with details on the architecture of the spatial heterogeneity. The explanatory factors matched the framework, demonstrating that these parameters had a linear association in their helpful ranges [11]. In order to predict the observational variogram of data points, linear, spherical, Gaussian, and exponential models were applied.

The ordinary kriging method uses spatially varying variance to achieve the most accurate linear reliable estimates and is a widely used geostatistical interpolation technique.

The multidimensional version of kriging, which includes additional factors, is the co-kriging estimator. It is a highly dynamic interpolation method that employs numerous datasets and enables users to explore maps of correlations.

In order to account for semi-variogram prediction variability, EBK offers a range of semi-variogram models. Due to its reliance on constrained, probabilistic estimates, the EBK is more accurate and preferable to other geospatial modeling techniques. This is different from other kriging approaches that are currently in use, which depend on weighted regression prediction. Compared to other traditional kriging approaches, EBK has numerous advantages, including a reduced need for dynamic modeling, more precise conventional error and projection predictions for standard datasets, and an accurate forecast of significantly non-static information.

3 Results and Discussion

3.1 Nitrate Fluxes in Godavari Delta Region

A cross-sectional investigation was carried out to track the nitrate content in the study area chosen at random groundwater during the pre-monsoon. Groundwater samples were collected at different locations in the study area, and samples were moved to a research facility in a temperature-controlled environment. A nitrate evaluation was carried out as quickly as feasible using the established techniques. Table 1 displays the findings of nitrate concentration in various aquaculture intensities in the research area. The findings demonstrated a significant difference in the average nitrate concentration across the study area, in which intensive aquaculture zones had the highest observed nitrate amounts. Additionally, the measured nitrates in 33%, 46%, and 21% of samples are from the aquaculture's intensive, semi-intensive, and traditional zones, respectively. Research has indicated that using intensive feed and chemicals is the primary cause of nitrate pollution (see Fig. 2). Overusing nitrogen shrimp feed promotes groundwater pollution while also spreading it geographically. In the same study area, previous research work classified the delta region into three zones such as intensive, semi-intensive, and traditional based on the intensity of the aquaculture [10].

The nitrate content in groundwater can be influenced by point and non-point sources, including leaching agrochemicals in aquaculture use and leaching through sewage discharges in residential use.

Table 1 Statistics of the nitrates (ppm) in different zones

Zones	Minimum	Maximum	Average	Standard deviation
Intensive	54	98	66	11.92
Semi-intensive	27	42	35	4.68
Traditional	6	24	12	5.63

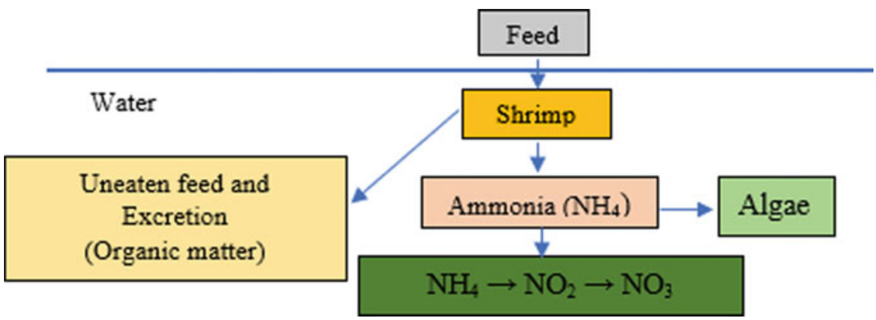

Fig. 2 Formation of nitrates in aquaculture ponds

3.2 Geospatial Analysis of Nitrates

Assessment of nitrates throughout intensive aquaculture practice zone has received little attention recently in an exploratory study. At the same time, many elements of the issue were explored extensively in ongoing information. Instead, there was not too much focus on the spatial variability approaches to assess nitrates flux.

The nitrates using spatial interpolations were assessed using kriging in the ArcGIS Pro software's environmental tool. The difference in the measured and predicted data is used to evaluate the projected nitrates in the study area.

Figure 3 displays the interpolation-based prediction maps for nitrates. The models were only assessed once and used uniformly throughout each validation set to evaluate the potential and compare the estimation methods. The kriging tool supports many stable, exponential, rational quadratic, and Gaussian models to produce optimum interpolations. The training dataset, which comprised 70% of the data, was chosen randomly, and the test semi-variogram variables and classifiers were derived from the observed data. The semi-variograms Gaussian and rational quadratic models were chosen, which best resembled the observed semi-variogram in each example (Fig. 4). In every instance, nugget/sill ratios showing less than 25% imply that the models perform better. The measured and predicted values plot of kriging interpolation for nitrates are shown in Fig. 5.

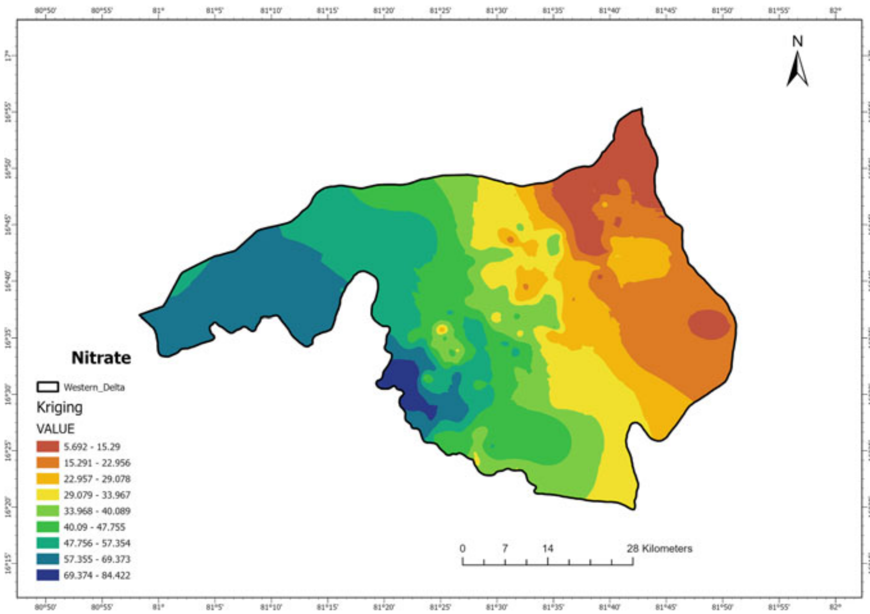

Fig. 3 Spatial variability of nitrates

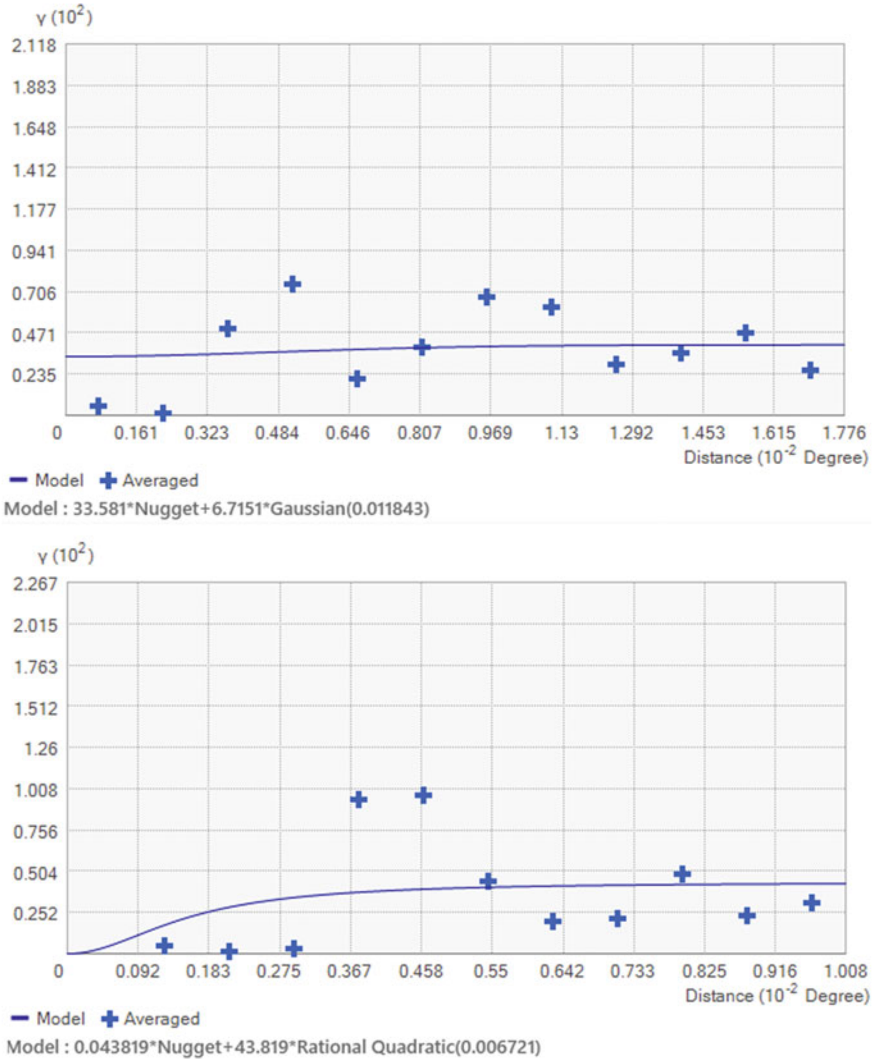

Fig. 4 Semi-variograms of nitrate model

4 Conclusions

One of the main issues with intensive aquaculture ponds is nitrates, which puts environmental pressure on the subsoil and groundwater. Ponds used for aquaculture are typically considered a non-point source of pollution, making it difficult to pinpoint the exact polluter. As a result, indicators that indicate the linear relation between contamination and aquaculture operation in the context of site features are required to enable efficient policy regulation.

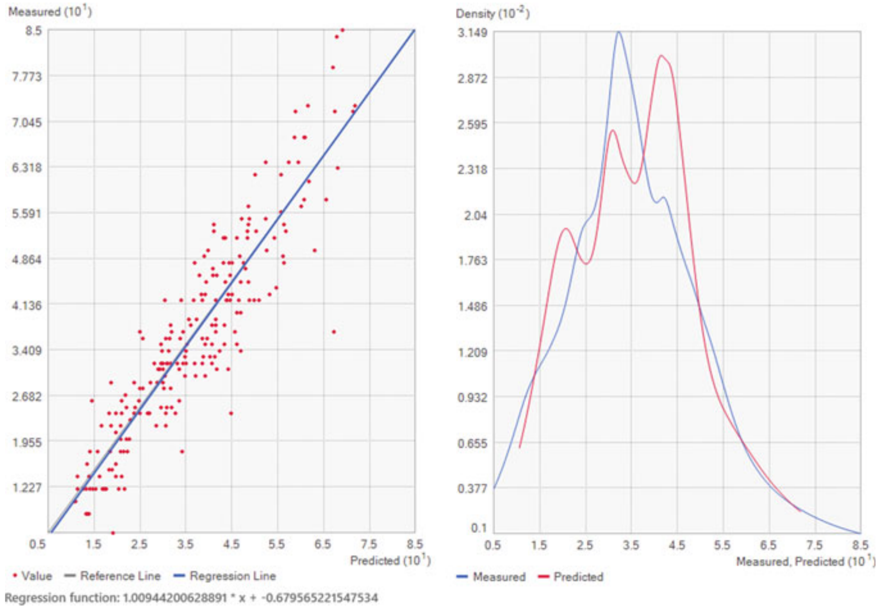

Fig. 5 Measured and predicted nitrates of the study area using kriging

This research work presents a method for identifying groundwater contamination assessment. The suggested method evaluates the effectiveness of the nitrate prediction based on the samples taken from the wells. Using indicator kriging to predict the odds of nitrate concentration and vulnerability and risk assessment is a potent and trustworthy way of determining the nitrates flux in the Godavari delta region.

The interpolated nitrate maps using kriging demonstrate the good performance of the approach and the established association between the predicted data and actual data. The validation findings reveal the constructed model and geostatistical metrics such as the nugget, standard error prediction, and range values to have the best fits with more significant coefficients of R^2 (0.935).

The suggested method could be used in subsequent research to evaluate and adapt the monitoring wells depending on the kinds of contaminants in the groundwater.

References

1. Nie X, Mubashar M, Zhang S, Qin Y, Zhang X (2020) Current progress, challenges and perspectives in microalgae-based nutrient removal for aquaculture waste: a comprehensive review. J Clean Prod 277:124209
2. Mir TA, Jan M, Rabani MS (2022) Microbial intervention for degradation of agricultural wastes. In: Environmental biotechnology, pp 87–111. Apple Academic Press
3. Herath SS, Satoh S (2015) Environmental impact of phosphorus and nitrogen from aquaculture. In: Feed and feeding practices in aquaculture, pp 369–386. Woodhead Publishing

4. Burford MA, Costanzo SD, Dennison WC, Jackson CJ, Jones AB, McKinnon AD, Trott LA (2003) A synthesis of dominant ecological processes in intensive shrimp ponds and adjacent coastal environments in NE Australia. Mar Pollut Bull 46(11):1456–1469
5. Venkateswarlu V, Seshaiah PV, Arun P, Behra PC (2019) A study on water quality parameters in shrimp L. vannamei semi-intensive grow out culture farms in coastal districts of Andhra Pradesh, India. Int J Fisheries Aquatic Stud 7(4):394–399
6. Zhong D, Wang F, Dong S, Li L (2015) Impact of Litopenaeus vannamei bioturbation on nitrogen dynamics and benthic fluxes at the sediment–water interface in pond aquaculture. Aquacult Int 23(4):967–980
7. Camargo JA, Alonso Á (2006) Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. Environ Int 32(6):831–849
8. Rashid M, Hussain Q, Khan KS, Alwabel MI, Hayat R, Akmal M, Alvi S (2021) Carbon-based slow-release fertilizers for efficient nutrient management: synthesis, applications, and future research needs. J Soil Sci Plant Nutr 21(2):1144–1169
9. Nagaraju TV, Sunil BM, Chaudhary B, Prasad CD, Gobinath R (2023) Prediction of ammonia contaminants in the aquaculture ponds using soft computing coupled with wavelet analysis. Environ Pollut 331, 121924
10. Nagaraju TV, Malegole SB, Chaudhary B, Ravindran G (2022) Assessment of environmental impact of aquaculture ponds in the western delta region of Andhra Pradesh. Sustainability 14(20):13035
11. Deepika BV, Ramakrishnaiah CR, Naganna SR (2020) Spatial variability of ground water quality: a case study of Udupi district, Karnataka State. India. J Earth Syst Sci 129(1):1–20

Climate and Water-Related Disasters and Eco-DRR (Disaster Risk Reduction) Sensitivity in Island Nations: Overview Analysis

Padmi Ranasinghe, Nidhi Nagabhatla, and Kelly Vrijens

Abstract Atmospheric, geological, or hydrologic natural hazards occur at a variety of scales, from local to regional levels. These hazards lead to disasters when combined with vulnerability conditions and inadequate measures to mitigate the consequences. Disaster risk reduction (DRR) is a proactive approach aimed at reducing disaster risks by systematically analyzing the multiple factors that contribute to disasters. Integrated DRR involves building resilience in communities by (a) enhancing capacity building and knowledge sharing; (b) implementing mechanisms like early warning systems or solutions that can support the prevention of loss of lives and assets; (c) offering policy advice at the intersection of natural and social sciences, other areas (culture, education, communication, etc.); (d) boosting collaboration with key actors, including governments from national, state, and local level, civil societies, academia, and international organizations. An ecosystem-based approach to disaster reduction (Eco-DRR) has gained much attention around the world. The vulnerability of small island nations to natural hazards is high, and the consequences of disasters are devastating. Due to geographic location and limited resources, islands are highly susceptible to natural hazards such as hurricanes, water scarcity, earthquakes, tsunamis, and volcanic eruptions. The impact of these disasters can be long-lasting and far-reaching. In this synthesis, to highlight integrating ECO-DRR contributes

P. Ranasinghe (✉)
College of Architecture, Planning and Public Affairs, University of Texas at Arlington (UTA), Arlington, TX, USA
e-mail: Padmi.ranasinghe@mavs.uta.edu; pranasinghe@cris.unu.edu

P. Ranasinghe · N. Nagabhatla
Institute on Comparative Regional Integration Studies (UNU-CRIS), United Nations University, Bruges, Belgium
e-mail: nnagabhatla@cris.unu.edu; nagabhn@mcmaster.ca

N. Nagabhatla
School of Geography Earth Science and Society, McMaster University, Hamilton, Canada

K. Vrijens
United Nations University - Maastricht University (UNU-MERIT), Maastricht Graduate School of Governance, Maastricht, The Netherlands
e-mail: k.vrijens@student.maastrichtuniversity.nl

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significantly to reducing disaster risks. Effective ECO-DRR remains crucial for island communities to build resilience and prepare for the potential consequences of disaster impacts. In addition, stakeholders in these nations require systematic efforts to assess and manage direct and indirect factors that exacerbate the effects of disasters, such as resilient infrastructure in the water sector and other sectors.

Keywords Eco-DRR · Risk governance · NBS · Hazards · Island nations

1 Introduction

Increasing global temperature due to anthropogenic activities is a global problem affecting people, communities, ecosystems, economic, and social engines. It contributes to a high frequency of disasters from natural hazards, 3 times more likely than 5 decades ago because of climate change [57] and estimated that more than 50 million people were affected by water and climate-related incidents while fighting COVID-19 in 2020, including intense floods, heatwaves, hurricanes/typhoons, landslides, and sea-level rise [57]. In the context of climate-induced disasters, a disaster is defined as "serious disruptions to the community or society at any scale due to hazardous events interacting with conditions of exposure, vulnerability, and capacity, leading to human, material, economic, and environmental losses adversely affecting people's health, safety, and access to food and water" (UNDRR 2022, [44, 46]). The World Economic Forum's Global Risk Perception Survey 2022 states that climate change, extreme weather, and biodiversity loss pose the greatest risks to social cohesion and economic divergence within the next decade. It is also estimated that the risk of extreme weather will increase by 42.2%in the next five to ten years. While the Paris Climate Agreement 2016 establishes 1.5°C as the goal for the world, many argue that more needs to be done to achieve that goal to cope with increasing climate- and water-related risks to countries and communities in coming years [50]. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC),describes these extreme climate events as the result of human activities that cause a successive warming world leading to water-related extremes worldwide. Hurricanes or typhoons are the most devastating disasters yet, causing extensive property damage and injuring many people due to flooding, storm surges, and wind (WHO 2019). The major crisis the water sector is experiencing is clearly related to climate change and hydrological cycle alteration.

The COVID-19 pandemic-related economic obstacles and social divisions, as well as geopolitical tensions continue to hamper climate change mitigation efforts. Despite this, the growing concern about climate action failure has resulted in a lack of confidence in the world's ability to effectively tackle the issue. Extreme weather events created catastrophic events worldwide, including the European floods in July 2021. Overall, these events affected at least 140 million people and caused over 17,000 fatalities and billions in economic damages [61]. The trend continued in 2022, with severe weather and climate disasters affecting millions and causing billions in losses globally, from extreme floods to heat waves and droughts. One such devastating event was the floods in Pakistan [51]. The simultaneous impacts of these climate extremes and the COVID-19 crisis created significant impact on livelihoods, critical infrastructures, psychology, health, and the economy and among the most vulnerable groups to climate change are those who are living in poverty [21].

Developing countries and small islands are facing multiple challenges, such as high frequency and severity of natural disasters, as well as the impacts of climate change, becoming more acute. Especially in these nations, extreme weather events create have devastating effects on their infrastructure, economies, and communities. Increasing numbers of these disasters also make these island nations more vulnerable to future shocks by exceeding the global average, making them more vulnerable to further disasters [18]. In spite of an increasing population rate, one-quarter of the population lives below the poverty line. Therefore, governments must prioritize people who live in vulnerable settings as well as ensure effective disaster risk management in order to prevent major problems with water supply and sanitation (ADB 2021, UNDRR 2023).

Healthy ecosystems have a significant role to play in strengthening community resilience, and that is something that cannot be ignored. Taking a holistic, integrated approach to risk management is crucial to ensure taking into consideration and evaluating the numerous effects of climate change on the communities, regardless of whether they are affluent or not. This approach must consider the significant challenges that natural environmental hazards, in conjunction with climate change, water, and land use changes, support the service sectors, particularly water provisioning. The multilateral environmental agreements, as well as policy measures and governance of water and the environment in accordance with international conventions, offer a systemic approach to this problem, and Eco-DRR could be the key solution. In this context, the study presents some key narratives to explain interlinkages and interconnections and divide our arguments into two sections. Noting that sustainable development requires greater disaster preparedness, as well as improved disaster prevention and climate adaptation, therefore this chapter emphasizes the importance of a multidisciplinary approach to DRR in selected island nations (Fig. 1), drawing attention to the critical role that collaboration and partnerships play in building resilience while emphasizing on Eco-DRR as a strategy. The primary objective of this study is also to evaluate the level of Eco-DRR sensitivity and responsiveness in the disaster management policies of island nations, with a particular emphasis on the water sector.

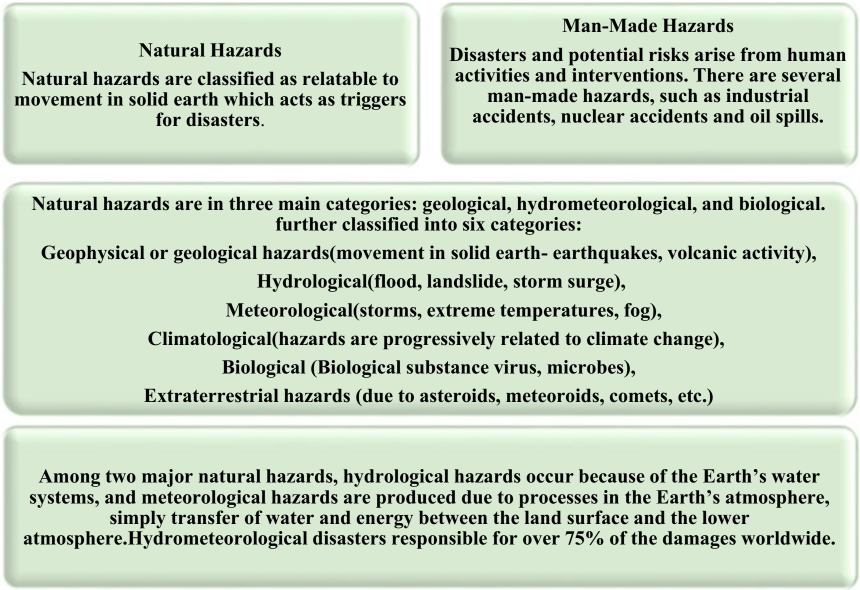

Fig. 1 Common understanding of hazards and disasters

2 Concepts and Content

2.1 Natural Hazards and Disasters and the Water Connection

Any type of disaster is an "event that disrupts or destroys a community's or society's functioning at any hazardous event due to its interaction with conditions of exposure, vulnerability, or capacity, resulting in loss of human life, material loss, economic loss, and environmental damage" [58]. Disasters are generally classified into natural disasters, man-made disasters, and hybrid disasters; natural disasters occur because of natural forces and man-made disasters are those caused by human decisions and hybrid disasters are those that result from both natural and man-made factors [47]. The water footprint of disasters is notable: hydro-metrological hazards impact communities in certain ways reflected in each type of disaster. Hydro natural disasters expanded as fluvial, pluvial flooding, flash floods, water sprouts, storm surges, etc., and metrological disasters including hurricanes, tornados, snowstorms, extreme temperatures, heat waves, and droughts [36]. Disasters occurrence worldwide has increased over the past few decades, with over 90% of these disasters being linked to climate and hydro-meteorological conditions [3]. More details are in Fig 1.

2.2 Disaster Risk Reduction and Risk Governance

Depending on the scale of the disaster, destruction causes economic losses, and social hardship, and impedes sustainable development. It is not only the existence of threats that leads to disasters. Instead, often it is the way humans manage these threats that creates the conditions for them to become disasters. Disasters can be reduced by providing an immediate and efficient means of response. Often, social, political, and economic context contributes to disasters, and systematic risk analysis and prevention measures are important [3]. Disasters are not equally effective on everyone; especially poorer communities are more vulnerable and reported more deaths than developed countries [31]. People who live in poor, exposed, and unprepared communities are most likely to suffer from disasters, where the number of victims is 300 times greater than in well-prepared communities with resilient infrastructure. World Bank (2023) states that natural catastrophe losses in 2020 increased to $210 billion worldwide from $166 billion in 2019, with 91% of fatalities caused by climate and water hazards occurring in developing nations. Children, women, persons with disabilities, the elderly, and indigenous people are disproportionately affected by disasters, particularly in low-income, developing countries (World Bank 2023), [31]. In disaster settings, the interlinkages between human, water, and food security become clear and it is important that response and recovery pathways are constructed taking note of the specific needs of such socio-economic groups [60].

Risk is a concept that is repeatedly used in academic research related to climate change and disasters and defines risk as a fast, instinctive, and intuitive reaction to danger and the Risk equation generally known as RISK = HAZARD + VULNERABILITY + EXPOSURE [3, 58]. The concept of DRR, therefore, implies action across all aspects of the risk equation. For example, it implies reducing the vulnerability of people, properties, assets, and the environment and reducing exposure to risks. More specifically is the concept and practice of reducing disaster risks by systematically analyzing and reducing the causal factors of the disaster (UNESCO 2023). While UNDRR [53] highlights Disaster Risk Reduction (DRR) is the notion and practice of "*reducing disaster risks through systematic efforts to analyze and manage the causal factors of disasters, including through reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment, and improved preparedness for adverse events*". The International Risk Governance Council considered that the risks are also associated with benefits and opportunities and are often accompanied by change. As a result of considering all aspects of the risk equation as a cross-sectoral approach, it is possible to prevent disasters or considerably lessen their consequences [3, 6]. As per UNDRR [58], investing in prevention is up to 15 times less expensive than rehabilitation, and most of the major risks facing humanity today are associated with the environment, such as climate change, water stress, biodiversity loss, ecological disasters, and pandemics (UNDRR 2022, [48]).

Vulnerability is a crucial element in DRR, as it highlights "the human aspect of disasters and encompasses the various physical, environmental, and socio-economic factors that raise the susceptibility of individuals, communities, properties, or systems to the impacts of hazards" [38, 59]. Several factors that determine how much of an effect to a community is exposed to risks and disasters, it is not only the severity of hazards, the number of people or assets exposed, but also their susceptibility to losses and damage [58]. Understanding and addressing vulnerability is essential for effective DRR and building resilient communities [58]. Reducing vulnerability to reduce disaster risk is critical and vulnerability can be outlined in three main elements: exposure, adaptive capacity, and sensitivity (Bollettino et al. 2020). It can be explained by different levels of vulnerability and exposure that some non-extreme hazards can cause extreme consequences and disasters, whereas others do not [58]. The inability to reduce the severity and frequency of natural hazards highlights the importance of reducing vulnerability as an effective means of DRR.

Some studies claim that risks can be measured either objectively or from a more intuitive subjective viewpoint [9, 10, 23]. Objectively, risk can be measured by assessing the magnitude and frequency of a disaster occurrence [10]. Alternatively, risk is subjectively determined in the form of emotions like fear, anxiety, and helplessness [63]. It can be stated that risks are socially constructed and politically negotiated. And socio-cultural aspects impact the way individuals interpret natural phenomena. People's beliefs and perceptions about disaster risk play a significant role in shaping the perception of disasters and disaster risk management and it is vital to comprehend and address these internalized beliefs and perceptions of risk in order to improve DRM strategies [8].

Risk perceptions are an important aspect of Disaster Risk Management (DMR) and DMR is conceptualized by the UNDRR (2022) as "*the application of disaster risk reduction policies and strategies to prevent new disaster risk, but also, to reduce existing disaster risk and contributing to the strengthening of resilience and disaster losses*". In a nutshell, resilience is "*the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate to, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions*" [59]. It is a dynamic process that involves both pre-disaster preparedness and post-disaster recovery. The concept of resilience is multi-dimensional and includes multiple (physical, economic, social, and environmental) aspects. It is important to understand the resilience of communities and systems to disasters, as this information can be used to guide DRR strategies and improve disaster preparedness and response [7].

DRM encompasses the practical implementation of DRR policies or programs to achieve disaster risk goals; DRR, in contrast, is defined as the "prevention of existing disaster risk to better build resilience and limit adverse impacts of hazards" [4, 49]. Effective DRM also refers to building community resilience and implementing disaster risk reduction (DRR) measures (like the early warning and response systems) at local, sub-national, and national government levels to tackle disaster impacts [11, 42]. That risks are situated at a point where hazards and communities interact and that an effective disaster risk management strategy entails different aspects of risks in societies [49]. These risks to consider include political, economic, environmental, and meteorological factors. Therefore, the traditional approach to DRM is based on the disaster cycle, which is a conceptual model separating the cycle into phases before, during, and after the disaster which requires different interventions in mitigation, preparedness, response, and recovery [58]. While the model serves as a great guiding tool for disaster risk managers, it does not capture all factors and improves DRM policies [49]. In the principle of DRR and DRM, it must be accompanied by effective strategies for building resilience, community engagement, and community empowerment [31].

UNDRR [58] identifies disaster Risk Governance as the "*system of institutions, mechanisms, policy and legal frameworks, and other arrangements to guide, coordinate, and oversee disaster risk reduction and related areas of policy*" and the principles of good governance are beneficial to apply to identifying, assessing, managing, and communicating risks. Therefore, good governance has to be transparent, inclusive, collective, and efficient so that disaster risks are reduced, and new ones are avoided [19, 58]. By improving risk governance, societies can maximize benefits from change while minimizing risks associated with it and a crucial element of managing global, systemic risks is governance, which determines how authority is exercised, decisions are made, and actions are taken [25]. Effective governance of these risks requires collaboration between nations and the integration of various stakeholders, including government entities, industries, academic institutions, and civil society. The participation of these groups is necessary to ensure a cohesive approach to mitigating global risks [25]. Recent advances in disaster resilience, risk reduction, and governance have paved the way for numerous overarching frameworks to be used to discuss issues related to disaster recovery, vulnerability, and inequity [31].

In the related context, public policies are attempted to tackle critical issues related to water-related disasters, climate change, and disaster risks (Liu, Borazon & Muñoz 2021). Legislations and plans for DRR and DRM are required, and disaster risk reduction and climate change adaptation (DRR-CCA) measures are complemented by local risk governance policies and public policies have introduced radical transformations to ameliorate DRR-CCA measures from being reactive to proactive strategies. This means that these policy measures foster resilience in the country through early warning systems (EWS) and developing programs to adapt to climate change and address disaster impacts (Delloro & Gonzalez 2021, p. 204). Both these legal instruments for disaster risk governance (DRG) entail strategies to build resilience on a community level to identify hazards, quantify risks, and develop mechanisms to manage and decrease risks (Bohland et al. 2018, p. 91; [14]).

3 What is Eco-DRR?

Natural hazards are becoming increasingly catastrophic due to climate change, urban pressure, and inadequate disaster preparation; the need for climate risk reduction (DRR) and the need for climate change adaptation strategies is urgent to mitigate the risks of extreme events and increase resilience to disasters, particularly among those who are most vulnerable. Ecosystem-based disaster risk reduction (Eco-DRR) is a fairly new concept as falls within the broader umbrella of nature-based solutions and measures and aligns with ecosystem-based adaptation (EbA) that was discoursed in a similar context, but is more focused on climate change, rather a disaster setting. Per Ruangpan et al. [45], EbA focuses on long-term changes within the climate change, conservation of biodiversity and ecosystem services, while Eco-DRR is more focused on immediate and medium-term impacts from the risk of weather, climate, and non-climate-related hazards. Eco-DRR emphasizes ecosystem conservation, restoration, and sustainable management as key elements for Disaster Risk Reduction to achieve sustainable and resilient development [29, 43, 45] By utilizing the benefits that nature offers to human society longer term, both Eco-DRR and EbA strategies aim to enhance disaster risk reduction and climate adaptation efforts [57].

Ecosystem services, such as providing regulatory (hydrological cycle and flow maintenance, flood protection, mass stabilization, erosion control, etc.), provisioning (surface and groundwater, etc.), and cultural benefits for people [32]. Wetlands, forests, and coastal systems that are well managed serve as effective natural infrastructure that reduces physical hazards and enhances individual and community resilience. Furthermore, ECO-DRR focuses on decreasing the vulnerability to natural hazards by utilizing the protective capacities of well-functioning ecosystems. This approach is based on the understanding that healthy ecosystems play a crucial role in preventing and mitigating disasters. Eco-DRR promotes the preservation of healthy ecosystems, reducing exposure to risk and increasing resilience to natural hazards by avoiding human settlements in natural disaster-prone areas. Additionally, it emphasizes the importance of considering the ecological and social dimensions of DRR strategies in its approach to social-ecological interactions.

The adoption of Eco-DRR offers numerous advantages in reducing disaster risk and enhancing community resilience. These benefits encompass a range of hazard types, and the approach is effective both before (preparation) and after (managing impact) a disaster event. Eco-DRR can lead to cost savings in both implementation and ongoing operations and maintenance; moreover, it provides ecosystem services, regardless of whether a disaster strikes. It plays a crucial role in addressing systematic risk within socio-ecological systems [57]. While eco-DRR plays a significant role in adaptation to climate change, it can also help facilitate obligations to international environmental governance obligations such as Convention on Biological Diversity, United Nations (UN) Framework Convention on Climate Change (UNFCCC), the Ramsar Convention on wetlands, and the UN Convention on Combating Desertification and the SDGs [3, 45].

For natural hazards related to water, such as floods, landslides, droughts, and flash floods, ecosystem approaches play a key role in reducing disaster risk, improving water quality, and improving habitats. Matić et al. [31] emphasize the Natural Water Retention Measures (NWRMS) in the Danube River Basin is being improved in terms of retaining water from the hydrological response unit to the basin-level scale, and the Tisza River Basin Management Plan for Environment and Flood Risk focuses on interlinking water quantity, water quality, and key water quantity management issues like floods, excess water, droughts, water scarcity, and climate change in order to enhance water quality and management. Natural Water Retention Measures

(NWRMs) are *"multifunctional measures that aim to protect and manage water resources and address water-related challenges by restoring or maintaining ecosystems as well as natural features and processes with a focus to enhance the water retention capacity of aquifers, soils, and ecosystems* [31]". It is indicated whether the implementation is in an urban or rural area, designed to be applied at catchment- or basin-level to improve retention capacity by increasing the safety of existing large dams, NWRMs attenuating reservoir capacity to meet the projected outcome and it may also be necessary to take a multidisciplinary approach as well as coordination between separate sectors and stakeholders in a horizontal and vertical manner, both at a local and national level [31].

Eco-DRR remains as a framework, while Nature-based solutions (NBS) serve as an umbrella or a solution to the widespread problem. Nature-based solutions are defined as "*solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits, and help build resilience*" [16, 26]. Nature-based solutions enable cities and landscapes to incorporate a broader range of natural components and processes by implementing resource-efficient, locally adapted, and systemic approaches [1]. Conservation and restoration of ecosystems, as well as their services, are essential for the successful implementation of NBS in urban and rural areas. The use of nature and natural processes provides multifunctional and integrated solutions to many problems that is faced today [31, 41, 47].

During the past twenty years, floods and storms have been the most common disasters, and the number of major floods has more than doubled, from 1389 to 3254, while storms have increased from 1457 to 2034 [56]. In areas prone to flooding, in depth analysis of flood risk is crucial to improve community knowledge and awareness of the causes of flooding and associated risks. Individuals and properties in flood-prone areas can be protected by implementing appropriate flood management measures and by incorporating landscape-based mitigation strategies in order to mitigate the risk of flooding. There are complex flood hazards as well as limited mitigation strategies, which have all resulted in exacerbated impacts on flood-prone areas. However, flood risk governance represents one of the sustainable solutions for climate resilience that can be applied. The "Room for the River" program in the Netherlands serves as a successful example of reducing flood risk through revised water resource management policies that incorporate nature. In Japan, similar approaches allow for the restoration of flood plains, relocation of polders, and dikes, resulting in increased space for rivers and improved ecosystem health (Environment Ministry-Japan 2016). In some instances, the combination of "green" approaches with "gray" engineering structures or hybrid modality enhances the effectiveness of flood mitigation and DRR [57].

There is a direct correlation between the degradation of ecosystems and climate change, whereby ecosystem degradation exacerbates the negative effects of climate change, which, in turn, leads to further degradation of ecosystems because of climate change-related disasters. Further, environmental degradation plays a significant role in reducing societies' adaptive capacity to reduce disaster risks [31]. As ecosystems become degraded, the provision of crucial ecosystem services are reduced, susceptibility to both natural and man-made disasters. There is a growing need for comprehensive and integrated risk management in light of climate change. As a means of enhancing a high level of resilience to disasters and preparing communities for coping with such events in the future, thriving ecosystems are essential for successful communities.

4 Eco-DRR and Risk Governance Framework

Since there are multiple factors and ways to accomplish DRM, the member states of the United Nations developed international DRR frameworks that can be used by organizations and national governments in their specific contexts. These frameworks include the Hyogo Framework for Action 2005–2015 and the Sendai Framework for Disaster Risk Reduction 2015–2030 [49]. The Hyogo framework outlines 5 priorities that do not solely reduce the risks of disasters but also aim to find solutions to lower vulnerability in the community and enhance DRR/DRM strategies in all sectors, including the water sector. With the objective to ensure that disaster risk reduction is a national and local priority as well as strong institutional support for implementation, it is also necessary to identify, assess, and monitor disaster risks and enhance early warning and build a culture of safety and resilience across all levels through knowledge, innovation, and education; to reduce the underlying risk factors. To achieve the goals outlined in this framework, regional and international institutions are called upon to act to reduce disaster risks and to enhance international cooperation in developing science-based methods for reducing disaster risks (UN-SPIDER 2022). There have been significant improvements in disaster risk reduction since the Hyogo Framework for Action 2005–2015 was signed, but still disasters remain an enormous problem worldwide. The commitment to disaster risk reduction and resilience was explicitly expressed in the outcome document of the 2012 UN Conference on Sustainable Development (Rio + 20) as part of the "The Future We Want" initiative [30]. It highlighted that disaster risk reduction and disaster resilience are extremely important in eradicating poverty and ensuring sustainable development. The Sendai Framework for Disaster Risk Reduction further builds on what has been outlined in the previous framework by defining four main areas for improved disaster risk reduction worldwide and it shifted from "disaster management" to "disaster risk management" emphasizing the importance of focusing on risk, rather than just 'disaster management' [30, 52].

The Sendai Framework was adopted in Japan, on March 18, 2015, which aims to reduce disaster risk and to reduce the loss of lives, livelihoods, health and economic, physical, social, cultural, and environmental assets of individuals, businesses, communities, and countries over the 15 years (UNDRR 2015). The Sendai Farmwork encouraged signatories to engage in eco-system-based solutions in risk management as part of risk management, the appreciation of nature and eco-system-based solutions took a significant step forward, as the framework states it "strengthens the sustainable use and management of ecosystems and implements integrated environmental and natural resource management approaches that incorporate disaster risk reduction" and also focuses on the adoption of measures that are designed to address the three dimensions of disaster risk (exposure to hazards, vulnerability and capacity, and hazard characteristics) as a means of preventing the creation of new risk, reducing existing risk, and increasing resilience (UNDRR 2015). According to the Sendai Framework for Disaster Risk Reduction 2015–2030, seven clear targets and four priorities for action to prevent new and reduce existing disaster risks: "(i) Understanding disaster risk; (ii) Strengthening disaster risk governance to manage disaster risk; (iii) Investing in disaster reduction for resilience; and (iv) Enhancing disaster preparedness for effective response, and to 'Build Back Better' in recovery, rehabilitation, and reconstruction" (UNDRR 2015). The framework focuses on the adoption of measures that address the three dimensions of disaster risk (exposure to hazards, vulnerability and capacity, and hazard characteristics) to prevent the creation of new risks, reduce existing risks, and increase resilience [33]. In order to bring this framework to life, approaches such as Eco-DRR hold promise for being applied to various sectors as part of this framework.

International framworks continue to encourage governments to take a more ecosystem-based approach to disaster risk reduction as aligned to the Sendai framework to support ecosystem-based approaches [43]. The UN COP 21 in Paris urged governments to "consider using ecosystem-based approaches to climate change adaptation and disaster risk reduction to provide communities with safety nets in times of climate shocks and natural disasters" and at the G7 conference held in Japan in 2016, scientists and academies urged nations to take stronger steps toward reducing disaster risk by taking stronger safety measures "promotion of ecosystem-based approaches and green infrastructure" [29]. The Sendai Framework for Disaster Risk Reduction 2015–2030 provides a roadmap for DRR, but other global agendas, such as the Paris Climate Agreement, Sustainable Development Goals, New Urban Agenda, Biodiversity Agenda, and Water Security cannot be fully realized without incorporating DRR into their goals. These international instruments are interconnected, and addressing DRR is key to achieving the targets set by these agendas (UNESCO 2023).

The issue of DRR in island nations, particularly in the Global South, is a pressing political challenge, even disasters frequently cause economic, human, and environmental costs. Despite the need for guidelines to address DRR for vulnerable populations, current policies remain limited. To address this challenge, a comprehensive and integrated approach is necessary, combining various risk reduction strategies, including Eco-DRR, hybrid solutions, early warning systems, and other integrated measures to prevent and prepare for disasters. The implementation of Eco-DRR recognizes the important role of healthy ecosystems in reducing the impacts of disasters and strengthening community resilience by depending on and utilizing ecological resources. The use of EDO-DRR in the water sector is particularly critical, as water balance and flux are impacted by factors such as climate change, land use change, water use change, and population growth. The EU and many developed countries have become increasingly aware of the importance of nature in the mitigation of disaster

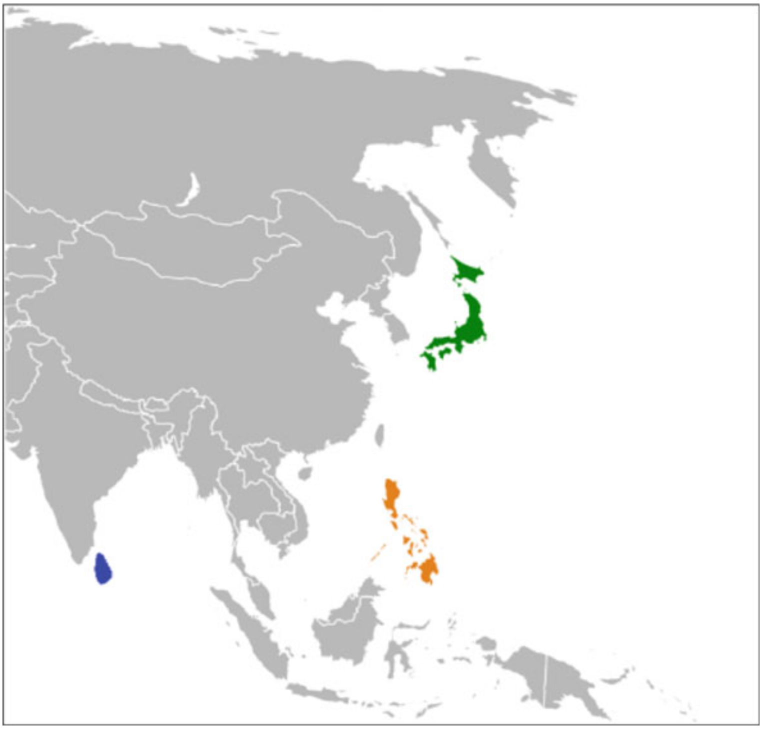

Fig. 2 Map of selected Island Nations-Japan, Philippines, and Sri Lanka *Source* [27, 36, 40, 45, 58]

risks and adaptation to climate change, and as such, they have supported the integration of "green" solutions into local strategies for disaster risk reduction in recent years [16, 37]. It illustrates that there is a growing political understanding in developed countries that ecosystem services play a significant role in reducing disaster risk and promoting sustainable development [3]. According to the literature available, restoring and maintaining ecosystem functions are often more cost-effective than investing in hard, gray infrastructure, and complementary portfolios of natural and built infrastructure solutions are gaining popularity in disaster risk reduction in many countries, but more attention is required from island nations particularly from the global south.

5 Key Observations and Discussion Points

There is no doubt that climate change negatively affects communities around the world, and island nations are particularly prone to the disruptions and disasters associated with climate change (Liu et al. 2021). Considering the high potential for facing hydro-meteorological hazards, three highly affected island nations in the Asia region were selected for the study. The Global Risk Report states that among the island nations in the Asia–Pacific region, Japan, the Philippines, and Sri Lanka were among the most flood-affected countries in the last five years. The desk review method was used to analyze the Eco-DRR sensitivity of the national policies. To obtain information about the disaster management policies of the selected countries, official government reports and records were consulted, and the Eco-DRR sensitivity in the Policy objectives, strategies, and policy statements was assessed (Fig. 2).

5.1 Japan

With the growth of the population in Japan and the limited flat area in which it is located, residential development has expanded even into areas that are subject to natural disasters. Several social infrastructure projects have been implemented to protect such areas. Frequently occurring earthquakes generate tsunami waves far beyond the design limits of such structures, causing massive damage. Natural disasters are more prevalent in Japan than in many other countries due to various factors. In addition to the extreme climatic variations in the region, including seasonal rain fronts and typhoons, the area is also known for its rugged terrain, with numerous faults and steep slopes, located within the Pacific earthquake belt, resulting in a frequent occurrence of earthquakes. Since Japan is located in a region of the Pacific Peninsula on the coast, it is also subject to tsunamis, and since it is a country that occupies one-tenth of the planet's volcanoes as a result of being inside this circum-Pacific region [35]. As well as the immense human toll that has been caused by the Great East Japan tsunami (GEJT) and the Indian Ocean tsunami (IOT) of 2004, there have been profound environmental impacts that will continue to affect the Asian region for many years to come [15]. As a result, Japan adopted an approach to disaster-resilient community development based on the principles of "human safety first" and "*disasters have no predictable boundaries*", combining institutional and physical measures to "*reduce disaster risks*" and "*ensure safe evacuation*" during times of mega-tsunamis and other calamities [34]. An ecosystem-based approach to disaster risk reduction is not a new concept to Japan and has a long history of taking scientifically sound, environmentally sensitive, and effective steps to reduce disaster risks as well as to mitigate and adapt to climate change. According to past disaster lessons learned, the Japanese have always conserved/used local ecosystems to prevent disasters, adjusted land use and other living patterns to minimize damage, and adopted a wide range of creative approaches to mitigate damage. As a natural buffer system and as a disaster mitigation measure, coastal forest areas have been used in Japan for more than 100 years as a natural buffering system. The effectiveness of these measures is limited by the decline of forests; the velocity and depth of water, and the wind force exceeding the capacity of coastal forests to mitigate [15]. Therefore, the country is using hybrid method where appropriate to minimize the disaster impact.

The disaster risk reduction framework of Japan consists of various laws and policies, institutional arrangements, and several centralized and decentralized programs.

Japanese Disaster Countermeasures Basic Act, passed in 1961 and amended in 1997, establishes the disaster management system and provides a framework for disaster prevention, response, and recovery. However, the Act does not explicitly refer to Eco-DRR approaches despite Japan having several Eco-DRR programs and practices. The Climate Change Adaptation Act No. 50 of 2018, which can be seen as an extension to the Act on Promotion of Global Warming Countermeasures (Act No. 117 of 1998), aims to implement adaptation measures based on "reliable scientific information" and has made it compulsory for the Ministry of Environment to carry out climate change impact assessments. Nevertheless, the Eco-DRR is also not recognized in this Act. According to the National Plan for Adaptation to the Impacts of Climate Change, 2015 and most recently updated in 2021 [20], there has been high priority given to the restoration of ecosystems, including terrestrial, freshwater, coastal, and marine ecosystems, which includes directions for agriculture, water environments, and fisheries, as well as other ecosystems and economic activities, all of which have been prioritized. The Eco-DRR, however, has not been mentioned in the section covering water-related disasters in the disaster response plan. There are multiple levels of Japanese eco-DRR initiatives, public, private, and community, as well as national community-based. There are several eco-DRR support programs available.

In recent times, DRR strategies are taking a context-specific approach harnessing the multiple functions of ecosystems, such as the provision of food and water. The country seeks to reduce the vulnerability of society and build disaster-resilient communities and "*Green Infrastructure*" approach has gained attention [34]. HDS (hybrid defense system) combines ecosystems with engineered infrastructure to avoid disaster risks in highly vulnerable areas. By using vegetation buffers/green infrastructures along with engineered structures/gray infrastructure, wave energy can be reduced, and floating debris can be prevented from accumulating. ECO-DRR concepts integrated into several flood management programs: Uda River, development of master plans for the Ohashi River area, conservation and revitalization of forest ecosystems, and restoration of wetlands [34]. Various hybrid ecosystems and artificial structures exist, such as seawalls and nakatsus that provide protection from high tides. During the Great East Japan Earthquake (GEJE) of 2011, Japan experienced a devastating earthquake, a tsunami, and a nuclear disaster. Providing a perspective on both the policy and implementation of rebuilding after the Great East Japan Earthquake, it shows how ecosystems like coastal forests, traditional knowledge, and protected areas play a significant role in disaster risk reduction [17]. Many Japanese policies and programs demonstrate a high degree of eco-DRR sensitivity, which can serve as a model for other island nations and countries to follow in their policy and program development in the future.

5.2 The Philippines

The Philippines is an archipelago located on the western arm of the Pacific Ocean, at the Pacific Ring of Fire, that is located in the South-East Asian region with 7641 islands [2]. Because there is a large coastal population, Philippines inhabitants are at risk and vulnerable to the consequences of climate change and disasters, mainly from coastal storms, typhoons and resulting floods, and seawater intrusions. The country has ranked as the third-most vulnerable country to climate change and among the most disaster-prone countries worldwide (Bollettino et al. 2020) with = 60% of the country's total land area exposed to disasters and >75% of the population affected by disasters [55]. Approximately 20 typhoons are experienced by the country each year, causing flooding, landslides, and storm surges, which can pose a threat to both urban and rural communities. As a result of sea-level rise and a scarcity of water, the country is one of the most vulnerable to climate change (Partners for Resilience 2013, [2]. Deforestation and loss of agricultural lands have been attributed to the growing population of the country. Considering the frequent weather extremes that negatively affect the population. The Philippines government enacted the Climate Change Act in 2009 (Republic Act of 9729), providing a policy framework to mitigate and adapt to climate change. The creation of the Climate Change Act in 2009 led to the enactment of the Disaster Risk Reduction and Management Act in 2010 (Republic Act of 10,121) [55]. Climate Change Act of 2009 established the Climate Change Commission (CCC) as the central agency responsible for planning, guiding, monitoring, and regulating matters related to climate change in the Philippines. The Philippines Disaster Risk Reduction and Management Act of 2010 aims to eliminate the root causes of vulnerabilities to disasters, develop institutional capacity for disaster risk reduction, and improve the resilience of local communities, but no evidence has been found that the Act does not explicitly mention Eco-DRR (Republic of the Philippines, 2009). Under the theme of "enhancing adaptive capacity and resilience of communities and natural ecosystems to climate change" and "adopting the total economic valuation of natural resources while ensuring biodiversity conservation" (NCCAP), as part of the Climate Change Commission's efforts to connect and make responsible citizens of surrounding ecosystems, it has implemented several programs at the national, sub-national, and local levels and developed a series of Eco-DRR promotional guides, including "the importance of a ridge-to-reef" ecosystem approach to land use planning and implementation, and guidelines for the development of capacity building skills [12]. The Satoyama/Satoumi modalities for promoting community engagement in ecosystem management in a sustainable manner have also been utilized for the restoration and conservation of ecosystems to reduce disaster risk [28]. A Master Plan for Climate Resilient Forestry Development 2016 "promotes forest ecosystems and communities' resilience to climate change, meeting the needs of forest ecosystem goods and services, and promoting responsive governance mechanisms". In accordance with Cabinet Cluster 24 on Climate Change Adaptation and Mitigation, 2017, the environment and natural resources are protected and conserved. It promotes "climate change resilience in rural communities, the conservation of natural resources through the use of ridge-to-reef approaches, and ecosystem protection through law enforcement". The Philippine National Climate Risk Management Framework of 2019 of the Climate Change Commission's Resolution 2019–001, provides a framework for a science-based planning system that is linked to Eco-DRR.

The Asian Development Bank (ADB) has invested in nature-based solutions in several sectors within the Philippines, including water-related investments, to strengthen its competitive advantage and strength [58]. As part of the NBS integration, technical assistance will also be provided for piloting sponge cities to reduce urban flood risk, coastal protection with green and gray infrastructure, and drought and flood management with integrated watershed management, as well as helping develop projects to reduce and mitigate flood risks in six major river basins in the Philippines with assistance from the ADB. Flood management practices such as "Room for the River" restore the river's natural landscape to give water more space. According to UNDRR, Prevention Web (2022), every river basin presents its own challenges and opportunities in terms of flood risk management, as highlighted by the Philippines flood risk management project. Using approaches such as natural river management develops a holistic strategy. For a strategy to achieve maximum impact, it must consider social, environmental, engineering, policy, and institutional factors. The success of nature-based solutions depends on stakeholder participation, and communities should weigh the trade-offs between measures and discuss how solutions can be incorporated into development processes [24]. A table of listed programs were attached in the appendix.

The World Bank's WAVES Program has proven that mangroves in the Philippines reduce flooding damage by 25 percent each year, and these results support policy and are emphasized rigorously in the engineering and insurance sectors [59]. Coastal habitats such as mangroves, coral reefs, and salt marshes reduce flooding and erosion, protecting people and property from storms, sea-level rise, and king tides; however, the Philippines, as with many other countries, faces a severe threat to these ecosystems. The Philippines is one of seven countries that are developing national capital accounts in collaboration with the WAVES program. These accounts rely on natural capital accounting to measure and value nature's services. There are immediate implications for a number of programs in the Philippines, including the Philippines Integrated Area Development, the National Greening Program, the Risk Resilience, and Sustainability Program, Green Climate Fund, and the People Survival Fund, as well as the local government Comprehensive Land Use Plans [59]. A number of international organizations have supported Nature-based Solutions and Eco-DRR in recent initiatives in the Philippines and incorporated them into other disaster management policies. Thus, coastal and other communities will be more resilient to floods and climate-related disasters in the future.

5.3 Sri Lanka

Sri Lanka is the second most affected country according to the Global Climate Risk Index (CRI) 2019, which measures the level of exposure and vulnerability to natural hazards. The indicator considers the fertilities per 100,000 inhabitants, the loss of purchasing power parity, and the loss of gross domestic product per capita. The World Risk Index, which is composed of the level of exposure, vulnerability, susceptibility, coping capacity, and adaptive capacity, places Sri Lanka as a medium-risk country with a risk level of 7.57 (World Risk Report 2020). According to the Department of Irrigation, among the 103 river basins in the country, 25 river basins have been identified as high flood-prone catchments in Sri Lanka (IDSL 2021). Further, excessive rainfall throughout the country is a key driver inducing flood-prone conditions. The Hazard Profile developed by the Disaster Management Center classifies the whole country as prone to flooding (Hazard Profiles of Sri Lanka 2021). While the Department of Meteorology projects the mean annual rainfall variation from under 900 mm to over 5000 mm, ranging from dry to wet regions, the monsoon, depressions, and convection influence the annual rainfall and water flux, thereby the availability and provision of services for citizens and communities (Climate of Sri Lanka 2021). In 2004, the Indian Ocean Tsunami (IOT) at 9.1 magnitudes was the largest tsunami in recorded history, killing more than 230,000 people in the region, including more than 30.000 Sri Lankans [22]. A lack of awareness, early warning systems and preparedness contributed to a high death toll in the South Asian region including Sri Lanka during the 2004 IOT [48]. It is necessary to detect early warning signs, educate people about disaster risks, take mitigation measures, and evacuate disaster-prone areas to protect people and infrastructure, and these elements seem inadequate in Sri Lanka. During the 2004 Indian Ocean tsunami, people noticed that fewer people died in areas where mangroves and sand dunes were intact [54]. It has been reported that in the Yala National Park in Sri Lanka, where there are sand dunes that absorb wave energy, only 5 cm of water was swept in. However, in areas where natural sand dunes have been removed, tsunami tidal waves reached 7 m and were strong enough to cause the death of many people [55]. Further, where mangrove forests are more abundant, the area less affected by storm surges. This scenario contributed to people's understanding of the importance of healthy coastal ecosystems in terms of Disaster Risk Reduction and later integrated as a strategy.

With a wide array of policy, legal, and institutional policy frameworks in the management and regulation of ecosystems including protection and conservation agendas, Sri Lanka's main focus remained on terrestrial ecosystems, and with this trend, the coverage of the existing policy framework on Eco-DRR speaks mostly to land resources management-oriented plans. For example, the National Land Use Policy (2007) ensures appropriate land use, including protection, conservation, and sustainable use of the country's land resources, to ensure food security, economic development, and productivity maintenance of the land. The National Physical Planning Policy and Plan (2017–2050) recognized the value of ecosystems and ensure the conservation of ecosystems by balancing the competing interest of development and environmental conservation.

The urban landscape of Colombo (the capital of the country) is dotted with a teeming network of wetland ecosystems, including freshwater lakes, swamps wet woodlands, and wet grasslands [62]. As a natural defense against flooding, wetlands act as giant sponges, absorbing flood waters and discharging them once the water recedes. Ramsar Colombo wetlands have been neglected over the years, and with some support of the World Bank, Colombo's wetlands are being preserved and revitalized. As part of the Metro Colombo Urban Development Project (MCUDP), mitigate floods, upgrade urban areas, and conserve wetlands in order to prevent flooding in the future, while repositioning parks and wetlands as the center of city life ([62], Rajapakshe et al. 2022).

With the vision of "Safeguarding the Environment" while ensuring ecological sustainability for the Present and the Future, the National Environmental Policy (2022) was adopted. It covers land and water resources, biodiversity and ecosystems, pollution prevention, control and waste management, climate change, and other environmental challenges, coastal and marine resources, and built environment and green development aspects [34]. The mission of the Environmentally Sensitive Areas Policy (2022) is "enabling platforms at all levels for a participatory and conscious decision-making process for the public and private sector, and communities in land use planning and sustainable land management in Environmentally Sensitive Areas, as nature-based solutions to enhance the integrity of conservation, resilience to climate change, and wise use of natural capital in development" to a fair extent strategizes the protection and conservation of ecosystems for DRR. Overall, the policy support structures for the application of Eco-DRRor nature-based solutions are still not integrated into the National Strategy of DRR, and or a key part of the National Strategy of Adaptation to Climate Change. The Eco-DRR integration into the National DRR strategy, and sector-specific guidelines and policies and adaptation, for example, adoption by the water sector remain largely a work in progress.

In these three case studies, policymakers are paying increasingly close attention to climate change adaptation strategies and eco-DRR approaches as climate change impacts and disasters intensify. Cuevas et al., (2016) state these strategies as "an adjustment of natural systems in response to expected climate stimuli to moderate harm". Nonetheless, it is critical to note that people's actions or inactions in preparing for a disaster are influenced by their beliefs about climate change and disasters. Understanding how policymakers and experts discursively frame climate change and disasters to influence people's risk perceptions and enhance the understanding of how climate change and disasters are portrayed and perceived provides information for policymakers on how to design their awareness-raising strategies to nudge inhabitants to be more environmentally conscious effectively. In that context, evidence-backed information from policymakers and scientific experts about risk can help bridge the differences in cultural worldviews, and their perceptions of risk can be observed. Understanding various cultural dynamics offers policymakers appropriate tools to tailor public policies to a particular group.

6 Conclusions

As a result of climate change, disasters have become more frequent and intense, which has made communities, particularly those in small island developing states and island nations, more vulnerable. The impacts of these hazards on infrastructure and provisioning abilities only exacerbate their already complex socio-economic concerns. Based on the context explained in the above sections, we reiterate the importance of collaboration and partnerships among governments, civil society, academic institutions, state agencies, and international organizations in the development of a Global Disaster Risk Management strategy (including Eco-DRR) and for developing guidance and policy support systems for integrated water management and water security using an ecosystem-based approach.

The study also reiterate the correlation between disaster risk assessment, ecological sustainability, and water management, keeping the focus on island nations to provide a reference for regions and nations to create "fit to purpose" plans for specific settings. We acknowledge that Eco-DRR strategy application in the water management (or other resource management like land, soil, or wetlands) sector would require a diverse range of actors to come together to share knowledge, build joint capacity agencies and institutions, and facilitate the DRR network to be inclusive. Further, the Eco-DRR approach offers capabilities in reducing climate change risk, enhancing adaptation and mitigation, serving as a carbon sink, and promoting conservation and restoration, which are all synergistic outcomes. Implementing the Eco-DRR strategy is seen as a "no regrets" option, offering disaster risk reduction, and tracking of climate change impacts through the adoption of best practices and learning from case studies. This chapter provides insights into such, in the context of addressing DRR for island communities. This review contributes to the wider body of knowledge in this field. Moreover, a multi-stakeholder approach can also ensure that the unique needs and perspectives of island communities are considered in the development and implementation of DRR strategies. Noting the growing understanding and widening knowledge of the fact that healthy ecosystems can prevent or/and mitigate threats, reduce vulnerability through sustaining livelihoods, and reduce exposure for vulnerable groups. We conclude that ecosystem management is an integral component of disaster risk management and reiterate that Eco-DRR could be a "win–win" and "no-regret" approach if this framework is utilized well. This approach bears the potential to integrate factors that affect all the elements of the disaster risk equation. We restate that working together, across sectors and borders, mitigates the impacts of climate change and secures a safer, more water-resilient future for all.

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Appendix

See Table 2.

Table 2 NBS program for Eco-DRR in the Philippines

Room for the River* approach with gray infrastructure				
River Basin	Proposed nature-based solutions with traditional and non-structural interventions		Goals	Benefits
Buayan–Malungon	Planting and restoring mangroves	Demolition of the old Buayan bridge and dike Construction of jetties on each side of the Buayan river Drainage improvement	Protecting flood vulnerable population Improving flood conveyance Reducing coastal flooding impacts	Health impact reduction Recreation potential Potential fish spawning ground Increase in biodiversity
Tagum–Libuganon	Restoring the Ising wetland Creating a green river connection between Tuganay and Ising rivers	Protecting urban centers by constructing local protection structures Improvement of river and drainage works Building bridges and culverts in the road to accommodate peak runoff during 100-year events Comprehensive land use planning	Protecting flood-vulnerable populations Increasing flood retention/ drainage capacity Improving water quality and biodiversity	Recreational bird watching and fishing Increased agricultural production as a result of reduced waterlogging Water purification and sediment trapping

(continued)

Table 2 (continued)

Room for the River* approach with gray infrastructure				
Abra	Restoring and accommodating natural river meandering Erosion protection with vegetation strips	Protecting urban centers by constructing local protection structures Quarrying in strategic areas Implementing land use management Resettling vulnerable communities	Protecting flood vulnerable populations Reducing riverbank erosion and flooding Promoting livelihoods	Improved agricultural production, livelihoods and job opportunities Low investment costs with less river ecosystem disturbances Improved water transportation

Source The table is a replicate from [24], UNDRR-Prevensionweb [58]

References

1. Adam W, Whelchel, Reguero BG, van Wesenbeeck B, Renaud FG, Advancing disaster risk reduction through the integration of science, design, and policy into eco-engineering and several global resource frames. Int J Disaster Risk Reduct. https://doi.org/10.1016/j.ijdrr.2018.02.030
2. ADRC (2023) Information on disaster risk reduction of the member countries-Philippines (the). Retrieved from AsianDisaster Reduction Center: https://www.adrc.asia/nationinformation.php?NationCode=608&Lang=en
3. Adriadapt (2023) AdriAdapt. Retrieved from Disaster Risk Reduction using eco-system services—Eco-DRR: https://adriadapt.eu/
4. Alexander D (2013) Resilience and disaster risk reduction: an etymological journey. Nat Hazards Earth Syst Sci 13:2707–2716. https://doi.org/10.5194/nhess-13-2707-2013(2013)
6. Bo-Young H, Heo W-H (2019) Economic analysis of disaster management investment effectiveness in Korea. Sustainability. https://doi.org/10.3390/su11113011
7. Bogardi JJ, Fekete A (2018) Disaster-related resilience as ability and process: A concept guiding the analysis of response behavior before, during and after extreme events. Am J Clim Change 54–78
8. Bronfman NC, Cisternas PC, Repetto PB, Castañeda JV, Guic E (2020) Understanding the relationship between direct experience and risk perception of natural hazards. Risk analysis 40:2057–2070. https://doi.org/10.1111/risa.13526
9. Cameron TA (2005) Individual option prices for climate change mitigation. J Publ Econ 283–301
10. Combest-Friedman C, Christie P, Miles E (2012) Household perceptions of coastal hazards and climate change in the Central Philippines. J Env Manag 137–148
11. Cvetković D, Nešović A, Terzić I (2021) Impact of people's behavior on the energy sustainability of the residential sector in emergency situations caused by COVID-19. Energy build 230:110532. https://doi.org/10.1016/j.enbuild.2020.110532. Epub 2020 Oct 9. PMID: 33071442; PMCID: PMC7546652
12. CLPU (2013) CLPU Guidebook, a guide to comprehensive land use plan preparation. Retrieved from League of Cities of the Philippines Secretariat: https://lcp.org.ph/UserFiles/League_of_Cities/file/HLURB_CLUP_Guidebook_Vol_1_11042015.pdf
13. Davoudi S, Lawrence J, Bohland J (2018 [October]) Anatomy of the resilience machine. The resilience machine. https://doi.org/10.4324/9781351211185-2

14. Dedicatoria RMM, Diomampo CB (2019) Status of climate change adaptation in Southeast Asia region. In status of climate change adaptation in Asia and the Pacific. https://doi.org/10.1007/978-3-319-99347-8_8
15. Dissanayaka KDCR, Tanaka N, Vinodh TLC (2022) Integration of Eco-DRR and hybrid defense system on mitigation of natural disasters (Tsunami and Coastal Flooding): a review. Nat Hazards 110:1–28. https://doi.org/10.1007/s11069-021-04965-6
16. European Commission (2023). Nature-based solutions. retrieved from european research executive agency: https://rea.ec.europa.eu/funding-and-grants/horizon-europe-cluster-6-food-bioeconomy-natural-resources-agriculture-and-environment/nature-based-solutions_en#:~:text=The%20Commission%20defines%20nature%2Dbased,benefits%20and%20help%20build%20resilience.
17. Furuta N, Seino S (2016) Progress and Gaps in Eco-DRR policy and implementation after the great East Japan earthquake. In: Renaud F, Sudmeier-Rieux K, Estrella M, Nehren U (eds) Ecosystem-based disaster risk reduction and adaptation in practice. Advances in Natural and Technological Hazards Research, vol 42. Springer, Cham. https://doi.org/10.1007/978-3-319-43633-3_13
18. Gheuens J, Nagabhatla N, Perera EDP (2019) Disaster-risk, water security challenges and strategies in small island developing states (SIDS). Water 11:637. https://doi.org/10.3390/w11040637
19. Greiving S, Glade T (2013) Risk governance. In: Bobrowsky PT (eds) Encyclopedia of natural hazards. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-4399-4_298
20. Government of Japan (2015) National plan for adaptation to the impacts of climate change. Tokyo: Government of Japan
21. Hallegatte S, Fay M, Barbier E (2018) Poverty and climate change: introduction. Environment and development economics 23(3):217–233. https://doi.org/10.1017/S1355770X18000141
22. History (2023) The 2004 Tsunami wiped away towns with 'mind-boggling' destruction. Retrieved from History: https://www.history.com/news/deadliest-tsunami-2004-indian-ocean
23. Howe PD, Marlon JR, Mildenberger M, Shield BS (2019) How will climate change shape climate opinion? environmental reserach. https://doi.org/10.1088/1748-9326/ab466a
24. Isao E, Sagara J, van Wesenbeeck B (2022) How nature-based solutions can help reduce flood risks. Retrieved from UNDRR-Prevention Web: https://www.preventionweb.net/news/how-nature-based-solutions-can-help-reduce-flood-risks
25. IRGC (2023) What is risk governance? Retrieved from International Risk Governance Council: https://www.undrr.org/terminology/disaster-risk-governance
26. IUCN (2020) Global Standard for Nature-based Solutions. A user-friendly framework for the verification, design, and scaling up of NBS. First edition. Gland, Switzerland: IUCN
27. JICA (2013) Ecosystem-based disaster risk reduction (Eco-DRR), JICA,s Eco-DRR cooperation in developing countries. Retrieved from Forest and Natural Environment Group, Global Environment Department, Japan International Cooperation Agency (JICA): https://www.jica.go.jp/english/our_work/thematic_issues/disaster/c8h0vm0000bvqtv9-att/Ecosystem-basedDisasterRiskReduction.pdf
28. Klein JA, Tucker CM, Steger CE, Nolin A, Reid R, Hopping KA, Yeh ET, Pradhan MS, Taber A, Molden D, Ghate R, Choudhury D, Alcántara-Ayala I, Lavorel S, Müller B, Grêt-Regamey A, Boone RB, Bourgeron P, Castellanos E, Chen X, Dong S, Keiler M, Seidl R, Thorn J, Yager K (2019) An integrated community and ecosystem-based approach to disaster risk reduction in mountain systems. Environ Sci Policy 94:143–152. https://doi.org/10.1016/j.envsci.2018.12.034
29. Laddaporn R, Vojinovic Z, Di Sabatino S, Leo LS, Capobianco5 V, Oen5 AMP, McClain1,2 ME, Lopez-Gunn6 E (2020) Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. Nat Hazards Earth Syst Sci 20:243–270
30. Melissa LF, Acosta J, Wicker A, Whipkey K (2020) Short-term solutions to a long-term challenge: rethinking disaster recovery planning to reduce vulnerabilities and inequities. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph17020482

31. Matić BB, Karleuša B (2022) Ecosystem-based disaster risk reduction framework as a tool for improved river basin natural water retention capacity and environmental hazard resilience. Environ Sci Proc 21(1):40. https://doi.org/10.3390/environsciproc2022021040
32. Mizutori M (2020) Reflections on the sendai framework for disaster risk reduction: five years since its adoption. Int J Disaster Risk Sci, 147–151
33. MOE-Japan (2016) Eco-system based disaster risk reduction in Japan: a handbook for practitioners. Tokyo: Ministry of the Environment (Japan)
34. MOFA-JAPAN (2023) Disasters and disaster prevention in Japan. Retrieved from Ministry of Foreign Affairs, Japan: https://www.mofa.go.jp/policy/disaster/21st/2.html
35. Muhammad TC, Piracha A (2021) Natural disasters—origins, impacts, management. Encyclopedia, 1101–1131. https://doi.org/10.3390/encyclopedia1040084
36. Nadeera R, Palmer C, Dissanayake P, Yuwono TE (2022).Can nature-based solutions be an answer to the climate crisis? Retrieved from World Bank Blogs: https://blogs.worldbank.org/endpovertyinsouthasia/can-nature-based-solutions-be-answer-climate-crisis
37. Nicolas F, Sgobbi A, Happaerts S, Raynal J, Schmidt L (2017) Translating the Sendai Framework into action: the EU approach to ecosystem-based disaster risk reduction. Int J Disaster Risk Reduct, https://doi.org/10.1016/j.ijdrr.2017.12.015
38. Niekerk DV (2011) Introduction to disaster risk reduction. Potchefstroom, South Africa: USAID, the united states agency for international development, The African Centre for Disaster Studies NWU Potchefstroom
39. OCHA (2022 [2021]) Disasters in numbers. New York: Reliefweb
40. O'Sullivan F, Mell I, Clement S (2020) Novel Solutions or rebranded approaches: evaluating the use of nature-based solutions (NBS) in Europe. Frontiers in Sustainable Cities, Vol 2. https://doi.org/10.3389/frsc.2020.572527
41. Partners for Resilience (2023) Up-scaling ecosystem-based disaster risk reduction, Phillipine. Retrieved from Partners for Resilience: https://www.partnersforresilience.nl/en/programmes/up-scaling-eco-drr
42. Raza T (2018) Localizing disaster risk reduction and climate change adaptation in planners' and decision makers' agenda: Technical comprehensive model, Quezon City, Philippines. Procedia Engineering, https://doi.org/10.1016/j.proeng.2018.01.169
43. Republic of the Philippines CO (2009) Republic Act No. 10121. Manila: Republic of the Philippines
44. Rocque RJ, Beaudoin C, Ndjaboue R (2021) Health effects of climate change: an overview of systematic reviews Open 11:e046333. https://doi.org/10.1136/bmjopen-2020-046333
45. Ruangpan L, Vojinovic Z, Di Sabatino S, Leo LS, Capobianco V, Oen AMP, McClain ME, Lopez-Gunn E (2020) Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. Nat Hazards Earth Syst Sci 20:243–270. https://doi.org/10.5194/nhess-20-243-2020
46. Sorensen C, Saunik S, Sehgal M, Tewary A, Govindan M, Lemery J, Balbus J (2018) Climate change and women's health: impacts and opportunities in India. Advancing earth and space science 2(10). https://doi.org/10.1029/2018GH000163
47. Sowińska-Świerkosz B, García J (2022) A new evaluation framework for nature-based solutions (NBS) projects based on the application of performance questions and indicators approach. Sci Total Environ 787. https://doi.org/10.1016/j.scitotenv.2021.147615
48. World Economic Forum (2022) The global risks report. Zurich
49. Twigg J (2015) Disaster risk reduction. Good Practice Review 9. Humanitarian practice network, Overseas Development Institute. London, United Kingdom
50. United Nations International Strategy for Disaster Reduction. Sendai Framework for Disaster Risk Reduction 2015–2030. United Nations; Geneva, Switzerland (2015)
51. UNECE (2023) Sendai framework. Retrieved from UNECE: https://unece.org/sendai-framework
52. UNDRR (2017) Disaster risk and resilience. Retrieved from UNDRR-Prevension web: https://www.preventionweb.net/understanding-disaster-risk/key-concepts/resilience

53. UNDRR (2017) Understanding disaster risk, Vulnarability. Retrieved from UNDRR-Prevension Web: https://www.preventionweb.net/understanding-disaster-risk/component-risk/vulnerability
54. UNDRR (2019) Trees have major role in disaster risk reduction, Eco-Drr Course Agrees. Retrieved from UNDRR-Prevension Web: https://www.preventionweb.net/news/trees-have-major-role-disaster-risk-reduction-eco-drr-course-agrees
55. UNDRR (2020) The human cost of disasters: an overview of the last 20 years (2000–2019). Belgium: Centre for Research on the Epidemiology of Disasters, United Nations Office for Disaster Risk Reduction
56. UNDRR (2021) Nature-based solutions for disaster risk reduction. Geneva: United Nations Office for Disaster Risk Reduction
57. UNDRR (2023) Vulnerability. Retrieved from Understanding Disaster Risk: https://www.preventionweb.net/understanding-disaster-risk/component-risk/vulnerability
58. UNDRR (2023). Disaster risk reduction & disaster risk management. Retrieved from Understanding Disaster Risk: https://www.preventionweb.net/understanding-disaster-risk/key-concepts/disaster-risk-reduction-disaster-risk-management
59. UNDRR (2017) In The Philippines, Mangroves are a valuable flood defense. Retrieved from UNDRR-Prevention Web: https://www.preventionweb.net/news/philippines-mangroves-are-valuable-flood-defense
60. Valdez AIA (2018) The paradox of the salvage zone: examining the philippine coastal adaptation framework in the light of tropical cyclones and threats of sea level rise. The Melbourne law school 1–41
61. Walton D, Arrighi J, van Aalst M, Claudet M (2021) The compound impact of extreme weather events and COVID-19. IFRC, Geneva 34pc
62. World Bank (2018) Can Colombo reinvent itself as a Wetland City? Retrieved from World bank: https://www.worldbank.org/en/news/feature/2018/02/01/can-colombo-reinvent-itself-as-wetland-city
63. Zsido AN, Arato N, Inhof O, Matuz-Budai T, Stecina DT, Labadi B (2022) Psychological well-being, risk factors, and coping strategies with social isolation and new challenges in times of adversity caused by the COVID-19 pandemic. Acta Psychol (Amst). 225:103538. https://doi.org/10.1016/j.actpsy.2022.103538. Epub 2022 Feb 21. PMID: 35219042; PMCID: PMC8858700

Feasibility Study on the Use of Multilayer Plastic (MLP) Waste in the Construction of Asphalt Pavements

Aakash Singh, Ambika Behl, and Ashish Dhamaniya

Abstract In the last few years, considerable research has been carried out in the country to determine the suitability of plastic waste in the construction of bituminous roads. That research led to establishing that linear density polyethylene (LDPE) and high-density polyethylene (HDPE)-based plastic waste can be successfully used for road construction, but there is very limited research available on the use of polyethylene terephthalate (PET)-based multilayer plastic waste in road construction. In the present study, an attempt has been made to evaluate the feasibility of using multilayered plastic (MLP) waste in the construction of roads. The properties of asphalt mixes prepared with multilayered plastic (MLP) waste have been studied, and the efficacy of different types of waste plastic for coating the aggregates was also studied. The moisture resistance of MLP-based waste plastic asphalt mixes has also been studied in comparison to PE (polyethylene) plastic waste-based and control asphalt mix. The MLP waste-modified mix showed better stability and resistance to moisture damage when compared to the PE-modified waste plastic mix. The effect of waste plastics in reducing overall bitumen demand in the asphalt mix was also studied. The heating of waste plastic to coat aggregates has always posed a concern regarding air emissions. To address this concern, the environmental emissions were measured during the coating and mixing stage. In this study, an attempt is also made to evaluate the coating of waste plastic on the aggregates using a simple approach of coatability index.

Keywords Multilayered plastic waste · Plastic-coated aggregates · Coatability index · Bitumen · Control mix · Waste plastic mix

A. Singh · A. Dhamaniya
Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat Gujrat, India

A. Behl (✉)
CSIR-Central Road Research Institute, New Delhi, India
e-mail: ambikabhel.crri@nic.in

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1 Introduction

Plastic consumption in India has grown at a significant pace over the past five years, and so has its plastic waste generation. India produces 3.4 million tonnes of plastic waste in a year. Among the total municipal solid waste, about 4% of waste is plastic, out of which most plastic is generated from households, industries, food packaging, and water bottles. Likewise, a couple of states in India have a waterfront district that creates plastic waste from sports activities on the coastline. Improper loading of such waste collected outside the towns, cities, and villages creates undesirable and tumultuous conditions that influence the soundness of individuals living around it and make landfill issues bring about significant natural ramifications, adding to groundwater contamination. Central Pollution Control Board (Govt. of India) stated in its reports that only 60% of the total plastic waste is collected and recycled in India, and the remaining is uncollected and littered [1]. These wastes are the source of pollution as plastics are non-biodegradable and harmful to the environment for decades. Around 50% of the plastic consumed is used for packaging. The most utilized polymeric materials for packaging are polyethylene (PE)-based carry bags and multilayered plastics (MLP).

Bitumen, a by-product of crude oil distillation, is known for its adhesive properties, and it is used as a binding material in road construction. Bitumen is a visco-elastic material; it is brittle and hard in a cold environment and soft in a hot environment. Due to this behavior, the performance of these bituminous binders has been questioned many times [2]. To produce hot mix asphalt for road construction, the bituminous binder is heated up to 150–160 °C and coated over hot aggregates and then rolled. Environmental factors such as temperature, air, and water have a profound effect on the durability of bituminous mixtures. Longer exposure of pavements to water causes loss of adhesion at the bitumen–aggregate interface, which leads to moisture damage in pavements. The bituminous mix's resistance to moisture damage can be increased by using anti-stripping agents as additives, but they have limited use, and the process also increases the cost of road construction [3]. Polymer-modified binders are also recommended to be used for better moisture resistance of the asphalt mix. The use of waste plastic in the preparation of asphalt mixes has shown improved Marshall stability strength, fatigue life, reduction in overall rutting, and reduced low-temperature cracking of the bituminous surfacing [4]. Most of the waste plastics coming from the packaging industry are polyethylene-based and do not cause the release of any harmful gas at 1300C–1400C, and at this temperature, plastic is in the molten form, having an excellent binding property. The addition of waste plastics improves the stability, tensile strength, stiffness, void characteristics, and moisture resistance of bituminous mixtures [5].

Plastics mainly used for packaging are made up of polyethylene, polypropylene, and polystyrene, and their melting point varies from 1300 to 2000C. In the dry process, the shredded waste plastics tend to form a film-like structure over the aggregates when sprayed over the hot aggregate ranging 1500–1700C. Plastic-coated aggregates are better raw material for the construction of flexible pavement. Plastic-coated aggregates are mixed with hot bitumen as per the requirement of the mix, and the mixes are used for road construction. The evaluation of the waste plastic asphalt mix was done, and it was found that the waste plastic asphalt mix showed improved binding property and moisture resistance. The waste plastic mix showed improved Marshall stability value in the range of 18kN–20 kN, and the load-bearing capacity of the road is increased by 100% [6]. Another study investigated the performance of asphalt mixtures containing recycled polypropylene and found that mixes with the addition of recycled plastics showed improved physical and mechanical characteristics and provided a sustainable solution for the disposal of such waste [7]. As per IRC: SP: 98 [8], 6−8% of plastic waste (mainly PE and PP) by weight of bitumen can be used in asphalt road construction. A study was carried out to evaluate the effect of the addition of polyethylene-based waste plastic in the mix by using a dry process, and it was concluded that by adding polyethylene in the mix, aggregates exhibit better engineering properties, and the waste plastic asphalt mixture showed increased fatigue resistance, reduced permanent deformation, and also provided better adhesion between asphalt and aggregates [9].

In another study, it was observed that for stone mastic asphalt (SMA), the addition of shredded waste plastics could be used instead of stabilizers to control the drain down and enhance the performance of SMA mixtures [10]. A study for the comparative performance of shredded waste plastic asphalt mix and polymer-modified bitumen asphalt mixes was carried out, and the shredded waste plastic (SWP) was used instead of other stabilizing additives to prepare the SMA mixture. It was concluded that waste plastic in suitable dosage could be recommended in SMA [11]. Polythene fibers and waste plastic bottles (polyethylene terephthalate) were observed to be effective in SMA in retarding the drain down of bitumen and mineral filler [12]. Research also showed that coating of shredded waste plastic over the hot aggregates provides the mixture with better strength and performance [13, 14]. In most of these studies, PE (polyethylene)-and PP (polypropylene)-based waste plastics were used. Indian Road Congress (IRC) SP 98:2013 code also allows the use of PE-PP-based waste plastic in asphalt roads but multilayer plastics (MLPs) have not been studied in much detail.

Multilayer Plastic (MLP) is plastic with at least one layer of plastic as the main ingredient combined with one or more layers of materials such as paper, paper board, polymeric materials, and aluminum foil. The plastic component can be polyethylene terephthalate (PET), polypropylene (PP), or polystyrene (PS). Recycling MLPs is challenging, and the only way to process them to get rid of this waste is by incineration. Most of the MLPs (multilayered plastics) contain polyethylene terephthalate (PET) including other olefins, and their melting point is in the range 150−240 °C. To overcome the challenges of waste plastic management, especially MLP waste, the authors have explored the feasibility of incorporating MLP plastic waste in asphalt road construction. The properties of asphalt mixes prepared with multilayered plastic (MLP) waste have been studied and the efficacy of different types of waste plastic for coating the aggregates was also studied. The moisture resistance of MLP-based waste plastic asphalt mixes was studied in comparison to PE waste-based and control asphalt mixes. One of the major concerns in using waste plastic in road construction is whether the waste plastic is able to coat the stone aggregate or not. If a particular type of waste plastic is not able to coat the aggregates, then it will be present in the asphalt mix as a foreign material and hamper the performance of the asphalt mix. It is very difficult to evaluate the coating of waste plastic over stone aggregates with the naked eye, and expensive test instruments like scanning electron microscope (SEM) are required to confirm the coating of plastics over aggregates. Field engineers often don't have instruments like SEM available on site to check the coating of waste plastics on aggregates. The authors in this study have employed an easy method to evaluate the coating of waste plastics over aggregates in the field.

2 Materials Used

The coarse aggregates (10 and 20 mm NMAS) and fine aggregates (stone dust, lime powder) were obtained from a local quarry in compliance with the Bureau of Indian Standards (BIS) code [15]. VG-30 bitumen (viscosity-graded binder) conforming to IS: 73 [16] was procured from an Indian refinery (Indian Oil Corporation Limited).

2.1 Waste Plastics

In this study, three different types of waste plastics were used in the shredded form: MLP 1, MLP 2, and Polyethylene (PE)-based waste plastic (carry bags). MLP 1 contains 100% PET-based multilayered plastic (polyethylene terephthalate), whereas MLP 2 contains a combination of PET (polyethylene terephthalate) and PP (polypropylene) plastic. All three types of waste plastics were shredded up to 2–5 mm size, after proper cleaning and washing and were used at 3 different dosages in this study, i.e., 6, 8, and 10% by weight of the bitumen. The properties of waste plastics are illustrated in Table 1.

Table 1 Properties of waste plastic

S. No	Description	Tm, °C	Tc, °C	Findings
1	MLP 1	253.9	198.1	PET
2	MLP 2	158.5	117	PP and PET
3	PE	122.2	108.5	LLDPE/LDPE

Crystallization temperature (Tc), and melting temperature (Tm)

2.1.1 Characterization of Waste Plastics

The thermal behavior and constituents of plastics were studied using Differential Scanning Calorimeter (DSC). The thermal analysis was done to determine the crystallization temperature and melting temperature of the plastics. The instrument used was Mettler Toledo DSC. Table 1 shows the thermal properties of the plastics used in the study.

3 Experimental Program

3.1 Characterization of Asphalt Mixes

The bituminous mixes were prepared using the Marshall mix design procedure. The bituminous mixes prepared with the varying dosage of waste plastics were tested for Marshall parameters, ITS, TSR, resilient modulus, and dynamic creep. All the tests were done for 3 replicates, and the results reported are average. The results of waste plastic mixes were compared with the conventional unmodified bituminous mix. The samples for the evaluation of susceptibility to moisture damage were prepared at 7 ± 1% air voids. The moisture susceptibility of the bituminous concrete mixes with waste plastics was evaluated by measuring the tensile strength ratio (TSR) as per ASTM: D6931−12. The indirect tensile strength (ITS) of the mix is determined before and after conditioning of Marshall specimens, and the tensile strength ratio (TSR) is then calculated as the ratio of the original strength and retained strength after accelerated moisture conditioning.

Resilient Modulus is an important parameter to evaluate the performance of a mix and to assess the pavement response to traffic loading. All the specimens for the resilient modulus test were prepared at 5% air voids. The specimens were tested at 25, 35, and 45 ºC in accordance with ASTM: D7369−11 after their conditioning at the selected test temperature for 6 h. Repeated haversine load with a loading time of 0.1 s and a rest period of 0.9 s was used in all resilient modulus tests. The uniaxial repeated-load creep test was carried out to assess the rutting performance of control and modified asphalt mixtures. It was carried out in accordance with European standards [17]. A universal testing machine (UTM) was employed to assess the asphalt mixture's permanent deformation. A cyclic stress of 450 kPa, having a haversine waveform with a loading period of 0.1 s followed by a rest period of 0.9 s was applied during the test, and total accumulated strain (%) was recorded. Before conducting the test, all specimens were kept under a controlled temperature chamber for three hours to reach a uniform temperature of 60 °C. A seating stress of 10 kPa was applied to ensure positive contact between the loading plate and the specimen. The results of waste plastic mixes were compared with the conventional unmodified bituminous mix.

3.2 Effect of Waste Plastic Coating on Aggregates

Washed and dried aggregates were heated to a temperature of 200 °C for 2 h. Then shredded waste plastic was uniformly spread over the hot aggregate, ensuring that piling of plastic waste did not occur. A mix of plastic and aggregates was prepared in a Hobart mixer at 160−155 °C. The plastic-coated aggregates were cooled to room temperature and then evaluated for water absorption [15]. These plastic-coated aggregates were also evaluated for aggregate impact value (AIV) to check the effect of different types of waste plastics on aggregate strength. Velasquez et al. [18] and Bairgi et al. [19] used the coatability index to evaluate the coating of warm mix asphalt over aggregates. In this study, the same approach was used to check the coating of waste plastic over the aggregates. Coatability Index was calculated by using Eq. 1. Further, this coatability index is then co-related with the moisture susceptibility of the mix, i.e., tensile strength ratio. Figure 1 shows the different types of plastic-coated aggregates and control aggregates:

$$\text{Coatability Index} = \frac{\mathbf{Ao - Ac}}{\mathbf{Ao}} * 100 \tag{1}$$

where

Ao = Water absorption of control aggregates.

Ac = Water absorption of coated aggregates.

It can be observed from Fig. 1 that with the naked eye it is very difficult to find out the coating of waste plastics on the aggregate surface.

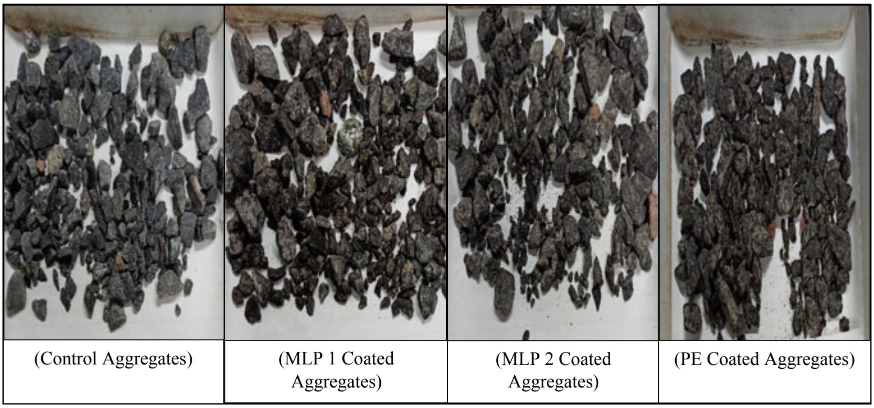

Fig. 1 Control aggregates and aggregates coated with different types of plastics

Fig. 2 DS1IAQ probe

3.3 *Emission Measurement*

Recycling and reusing of waste plastic in road construction can significantly contribute to saving the environment but there have been concerns across the globe about the release of harmful emissions when these waste plastics will be heated at a temperature of 160–170 °C to prepare hot asphalt mixes. To address these concerns in this study, an attempt has been made to study the emission release during the preparation of hot asphalt mixtures.

In this study, the emissions were recorded at two different stages: during the coating of waste plastics on the aggregates and during the mixing of bitumen with the plastic-coated aggregates. The emissions were recorded in the laboratory using the DS1IAQ probe (Fig. 2). The emissions recorded were total volatile organic compound (TVOC), formaldehyde (HCHO), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen dioxide (NO_2). At the same time, other gases such as nitric oxide (NO) and sulfur dioxide (SO_2) were recorded as zero concentration, thus not reported.

4 Results and Discussion

4.1 *Aggregate Characterization*

The aggregate impact value (AIV) significantly decreased with the addition of waste plastics. The brittleness of aggregates is measured through the impact value test; coating of waste plastics over the aggregates reduces the voids and air cavities present in the aggregate. The thin film of waste plastics formed over the aggregate surface

Table 2 Effect of waste plastic coating on aggregates' impact value

Mix type	Plastic content (in %/Weight of binder)	Specific gravity	Aggregate impact value
Control mix	0	2.80	8.95
MLP 1	6	2.78	7.530
	8	2.82	6.650
	10	2.80	6.210
MLP 2	6	2.75	5.030
	8	2.78	4.620
	10	2.81	3.890
PE-based	6	2.80	6.080
	8	2.83	5.350
	10	2.79	4.920

resists the cracking of aggregates. It can be observed from Table 2 that with the increase in the waste plastic content, the impact value reduces; it implies that with an increase in the thickness of the coating, the toughness of the aggregates increases. The AIV of control aggregates improves from 8.95 to 6.2 with 10% of MLP 1 waste plastic and to 3.89 with 10% of MLP 2, whereas with 10% of PE waste plastic it improves up to 4.9. MLP 1 waste showed the lowest effect on the AIV of aggregates.

Since MLP 1 primarily contains PET, its melting temperature is around 250 °C, and its glass transition temperature is around 70 °C [20, 21]. The aggregates are coated at 160 °C and at this temperature MLP 1 is in a semi-solid state; the liquid part partially coats the aggregate and gets absorbed into the voids of aggregates, and the solid part gets stuck to the irregular surface of the aggregate. During impact load, the MLP particles absorb some energy due to which the AIV value of MLP 1 coated aggregates is lower than the control aggregates.

4.1.1 Coatability Index

The coating of plastics fills the voids of aggregates due to which the porosity of the aggregates decreases [22]. With lesser voids on the aggregate surface, the absorption of moisture reduces. Table 3 shows that with the addition of waste plastic, the water absorption of the aggregates reduces. Figure 3 shows the trend of coatability index with varying types and percentages of waste plastic content. It was observed that with the increase in waste plastic content, the coatability index of aggregates increased. PE-based waste plastic provided the maximum coating followed by MLP 2 and then MLP 1 coated aggregates. Generally, the water absorption should be less than 2% for an aggregate to be used for asphalt road construction. Higher water absorption will

Table 3 Water absorption and coatability index of aggregates

Plastic type	Plastic content	Water absorption	Coatability Index
Control mix	0	1.597	0.00
MLP 1	6	1.300	18.59
	8	1.160	27.38
	10	0.864	45.89
MLP 2	6	1.062	33.50
	8	0.863	45.96
	10	0.729	54.35
PE-Based	6	0.788	50.68
	8	0.476	70.17
	10	0.233	85.42

result in the stripping of bitumen and will lead to pothole formation and moisture failure in the pavement. The presence of water is detrimental to the adhesion between the bitumen and aggregates.

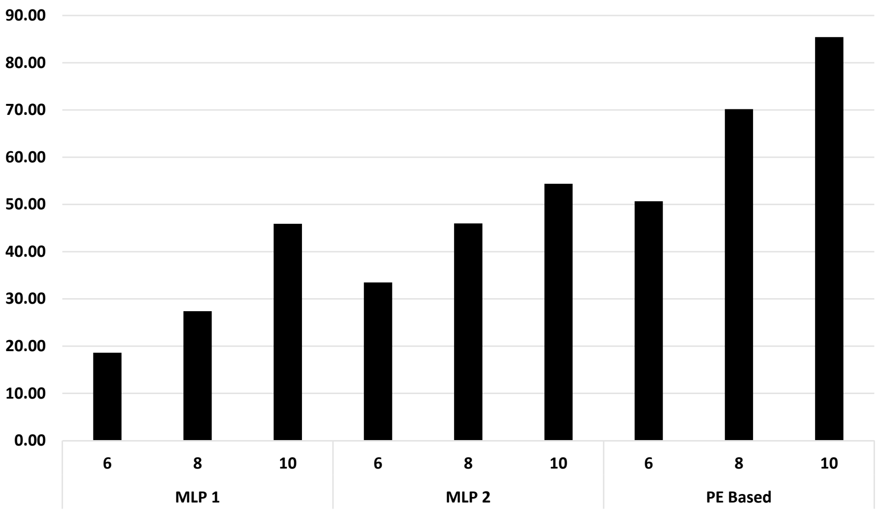

Fig. 3 Coatability index of plastic-coated aggregates

4.2 Marshall Test Results

4.2.1 Effect of Waste Plastic on Optimum Binder Content

It was observed from Table 4 that the optimum binder content decreases with the addition of waste plastic; this is because the plastic is coated over the aggregates, and the plastic gets absorbed by the aggregate and a thin film of plastic is formed. The film fills the pores of the aggregates, which are present at the surface of the aggregates; thus, there is lesser absorption of bitumen over the surface of plastic-coated aggregates, and the effective binder requirement reduces. Hence, a reduction in the optimum binder content of the mix was observed. Mixes prepared with PE-based waste plastic showed the least optimum binder content followed by MLP 2-based mix and then the mix prepared with MLP 1. With the addition of MLP 1 in the mix, there is nearly 2.5% reduction in optimum binder content when compared to the control mix, whereas this reduction increases with the addition of PE waste plastic in the mix to around 3% and with the addition of MLP 2 there is around 2.75% reduction in optimum bitumen content. The optimum bitumen content reduces further with the increase in the plastic content and by changing plastic type.

4.2.2 Marshall Stability and Flow Value

The Marshall stability value is the load required by the specimen to attain failure and it is the measure of cohesion. From Fig. 4, it was observed that the Marshall stability value increased with the addition of waste plastic. At higher waste plastic content, i.e., at 10% there was a reduction observed in the Marshall strength of the mixes. This happened due to the increased film thickness of the waste plastic over the rough surface of aggregates which lead to the reduction in the internal friction between the aggregates, thus the stability of the mix decreases. Also, the addition of very high dosages of waste plastics tends to make the bituminous mix very stiff and brittle. PE-based mixes showed the highest Marshall stability values in comparison to MLP-based mixes. For an effective asphalt pavement, the flow value should be in the range of 2–5 mm [23]; the flow value is the measure of deformation undergone by the sample; it is the vertical distortion at the time of failure. The results obtained from the waste plastic mixes are within the tolerance value.

4.2.3 Marshall Quotient

Marshall quotient is the pseudo stiffness that measures the resistance to permanent deformation of the mix. The Marshall quotient is defined as the ratio of the Marshall stability value and flow value. Its values are found within the tolerance limit at 8%

Table 4 Marshall mix design results

Mix properties	Control mix	MLP 1			MLP 2			PE-Based		
Waste plastic content	0%	6%	8%	10%	6%	8%	10%	6%	8%	10%
OBC%	5.545	5.440	5.408	5.385	5.412	5.375	5.376	5.410	5.288	5.315
Vv%	4.271	4.331	3.887	4.237	3.726	3.641	4.254	4.009	4.092	3.779
Stability (KN)	10.68	13.11	14.22	13.52	14.46	15.46	14.59	14.84	15.78	15.45
Flow (mm)	3.240	3.270	3.148	3.091	3.281	3.165	2.784	3.180	3.116	2.550
Marshall quotient	3.298	4.008	4.516	4.375	4.407	4.884	5.240	4.666	5.064	6.058

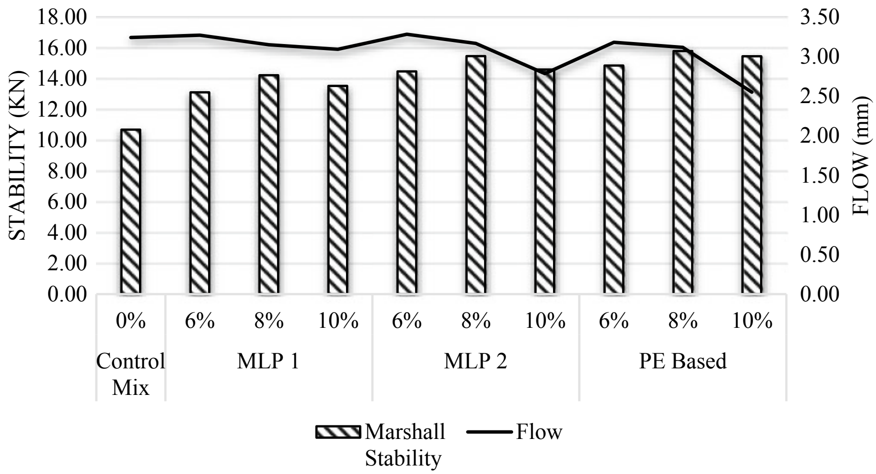

Fig. 4 Marshall stability and flow value

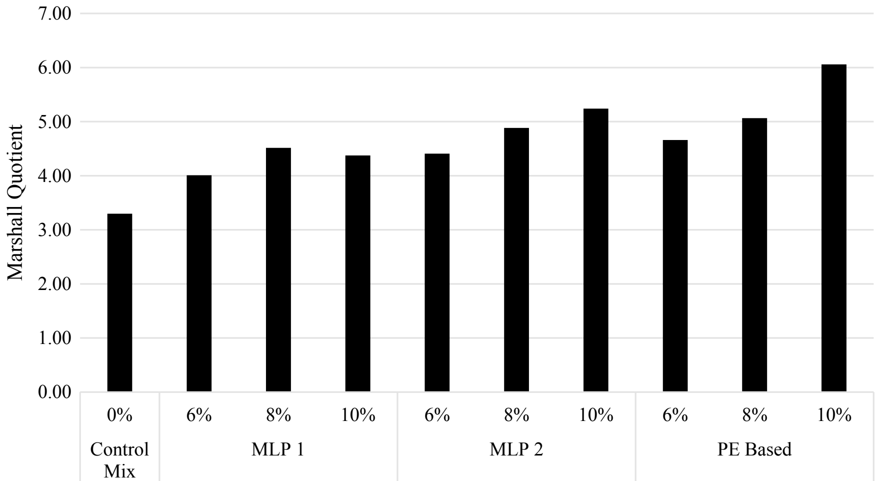

Fig. 5 Marshall quotient

dosage of waste plastic content. From Fig. 5, it was observed that the mix containing PE waste plastic is most stiff among other mixes, followed by MLP 2 mix and then MLP 1 mix. The results obtained from the study show that the mixes containing waste plastic have more resistance to permanent deformation when compared with the control mix; this is due to the coating of waste plastic on the aggregates which leads to a stronger bond between the aggregate and bitumen. It has been observed that with an increase in the percentage of waste plastic in the mix, the thickness of the coating also increases, which makes the mix stiffer; the chemical properties of the plastics also play an essential role in determining the stiffness of the mix. From the volumetric parameters of plastic waste-modified mixes, it can be concluded that a dose of 8% waste plastic by weight of bitumen should be considered as optimum plastic content.

4.3 Indirect Tensile Strength and Tensile Strength Ratio of the Mix

The indirect tensile strength test is appreciated in assessing the tensile properties of the asphalt mixes, which can be correlated with the cracking of the pavement. A high value of indirect tensile strength is an indication of higher resistance to low-temperature cracking. Moreover, a higher value of indirect tensile strength at failure would imply that the asphalt mix can withstand larger tensile strains prior to cracking. The tensile strength ratio of the mix is used to evaluate the susceptibility of the mix to moisture damage. Figure 6 shows the variation in indirect tensile strength and tensile strength ratio with respect to varying types and dosages of waste plastic. The indirect tensile strength of the mix increases with the increase in waste plastic content and at 10% dose of waste plastic, there is a slight decrease in the ITS value. This might be because with the increase in waste plastic content, the thickness of the coating of plastic over the aggregates increases, making the mix brittle, thus it reduces the resistance of the mix to tensile strain. From Fig. 6, it was observed that the mixes containing plastic waste showed more ITS value when compared with the control mix. Among the waste plastic mixes, the PE-based mix offers maximum ITS value followed by MLP 2 and then MLP 1.

The tensile strength ratio of the mixes containing waste plastic is found higher. The presence of waste plastic in the asphalt mix increases the resistance of the

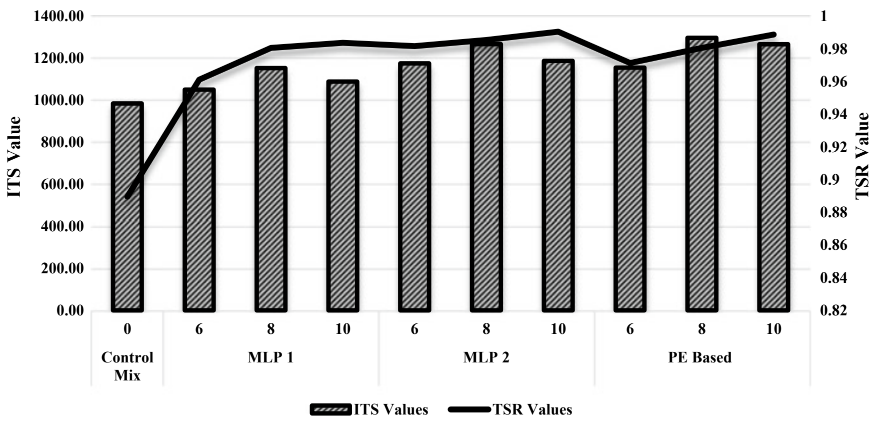

Fig. 6 ITS and TSR results

asphalt mix toward moisture damage. MLP 1, MLP 2, and PE are polymers with long-chain hydrocarbons, and bitumen is a complex mixture of saturates, aromatics, resins, and asphaltenes which are also hydrocarbons. When hot bitumen is added to waste plastic-coated aggregates to prepare asphalt mixture, some portion of bitumen diffuses through the plastic coating and makes a strong bond with the aggregate. This results in a stronger bonding between the bitumen and plastic-coated aggregates and hence imparts better resistance to moisture penetration into the mix.

4.4 Coating and TSR Correlation

From Fig. 7, it was observed that with the increase in the coating of waste plastics over the aggregates, the resistance to moisture damage has increased significantly. This shows that the coating of plastic has a positive correlation with the tensile strength ratio of the mix. The coating of plastic over the aggregates was evaluated using the coatability index. It was observed from Fig. 7 that the coatability index positively correlates with the TSR values of all three waste plastic mixes. As the coatability index can be directly calculated with the water absorption of the aggregates, thus, it can be easily calculated on-site in the field. In earlier studies, researchers have evaluated the coating of plastic by using X-ray diffractometry, which requires a dedicated instrumental setup and trained personnel to operate the instrument and which is also not available easily in civil engineering labs across the country. Thus, the coatability index test will find its usefulness for evaluating the coating of waste plastic in situ.

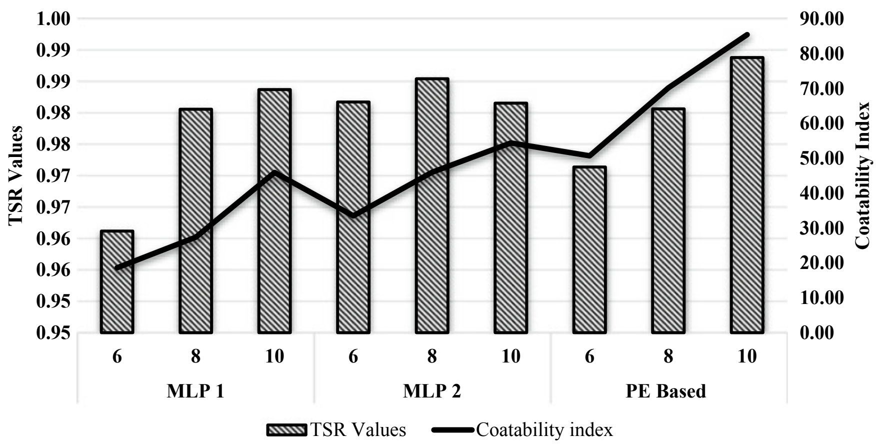

Fig. 7 TSR and coatability index correlation

4.5 Environmental Emissions Measurement

Table 5 shows the results of gaseous emissions during the coating of waste plastics over aggregates. It was observed that the concentration of total volatile organic compound (TVOC) during the mixing of MLP 1 was highest, followed by MLP 2 and then the PE-based mixture; due to the presence of PET and PP in MLPs, the concentration of TVOC was higher. The melting temperature of PET is around 250 °C; hence, the MLP 1 plastic was partially melted at a coating temperature of 160–165 °C; thus, the release of formaldehyde was lesser for MLP 1 mixtures. Carbon dioxide emission was observed highest for MLP 1 and least for MLP 2 mixtures.

Table 6 illustrates the results of the emission of gases during the mixing of bitumen with plastic-coated aggregates. It was observed that the emissions for the asphalt mixtures containing waste plastics were higher than the control mixture. Mixtures modified with MLP 1 showed the highest emissions of TVOC, CO_2, and the least emission of formaldehyde. In contrast, emissions of NO_2 and CO are nearly similar for all the mixtures.

4.6 Resilient Modulus

The resilient modulus of waste plastic-modified mixes was evaluated and compared with the resilient modulus of control asphalt mix at different temperatures. To understand the effect of the addition of different types of waste plastics on asphalt mix properties, it is imperative to understand the properties of basic polymers present in these waste plastics. MLP 1 contains Polyethylene Terephthalate (PET) polymer and MLP 2 is a combination of Polypropylene (PP) and PET, whereas PE-based waste is basically waste carry bags which is mainly LDPE. All three polymers PP, PE, and

Table 5 Emissions during coating of plastic

	TVOC (ppm)	HCHO (ppm)	CO (ppm)	CO_2 (ppm)	NO_2 (ppm)
MLP 1	1.26–1.33	0.09	011–024	590–650	0.25–0.29
MLP 2	1.18–1.21	0.11	05–017	523–580	0.23–0.28
PE-based mix	1.12–1.18	0.13	011–025	546–585	0.22–0.28

Table 6 Emissions during mixing

	TVOC (ppm)	HCHO (ppm)	CO (ppm)	CO_2 (ppm)	NO_2 (ppm)
Control mix	1.04–1.07	0.07	07–019	535–572	0.18–0.26
MLP 1	1.25–1.43	0.11	015–025	593–736	0.25–0.32
MLP 2	1.11–1.31	0.12	018–027	578–682	0.26–0.30
PE-based mix	1.15–1.23	0.13	018–028	568–597	0.26–0.32

PET have good moisture barrier properties; out of the three, PE is a more flexible polymer in comparison to PP and PET. PET is a long-chain thermoplastic resin made from ethylene glycol and terephthalic acid. During the manufacturing of food packaging material, PET is held in the stretched form at elevated temperatures, it slowly crystallizes and becomes more rigid and less flexible. PET is a semi-crystalline resin [24, 25]. When added to the asphalt mixture, it stiffens the mixture and increases the M_R value in comparison to the control mixture. However, due to its high melting point (250 °C), PET is not able to coat the aggregates completely and is present in the asphalt mix as inert material and hence it absorbs some energy resulting in larger recoverable deformation thus reduced resilient modulus values in case of MLP 1. MLP 1 has 100% PET content, whereas MLP 2 has both PP and PET due to which the MLP 1 modified mixture has lower M_R values when compared with MLP 2 and PE-based mixture.

The findings of this study reveal that the presence of waste plastics increases the rigidity of the mixture to a certain extent because the addition of these additives decreases the stresses caused by cyclic loading due to their elastic response. The increase in M_R values at 25 °C from the control mixtures are 19, 22.62, and 30.14% with the addition of MLP 1, MLP 2, and PE waste plastic respectively, whereas at 35^0C the increase observed was 41.45, 56.94, and 54% with the addition of MLP 1, MLP 2, and PE waste plastic respectively, and at 45 °C the increase observed was 22.29, 26.11, and 15.28% with the addition of MLP 1, MLP 2, and PE waste plastic, respectively. In the previous investigations carried out by other researchers, it was found that the stiffer asphalt mixes show lower permanent deformation under dynamic loading [26, 27]. Another study done by Tayfur et al. on different polymer modifiers showed that the stiffer mix undergoes higher permanent deformation under static loading and lesser permanent deformation under dynamic loading [28]. Since the stiffness of the mixture increases with the addition of waste plastic, the resistance to permanent deformation of the mixture's containing waste plastics as modifiers increases (Fig. 8).

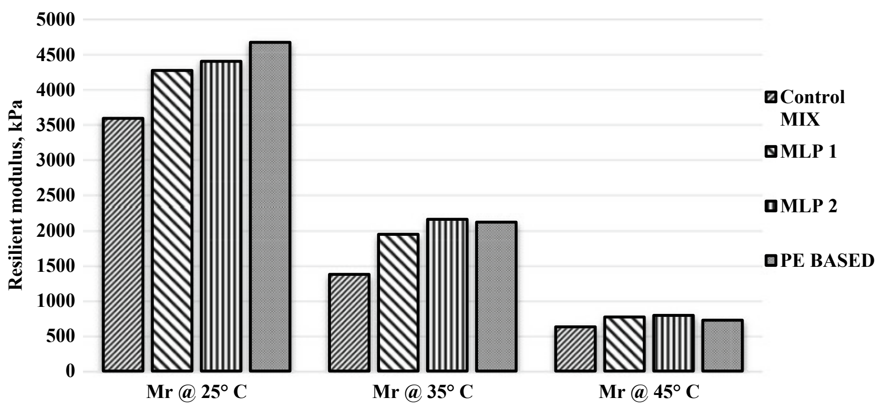

Fig. 8 Resilient modulus of the mixes

4.7 Dynamic Creep Test

Total permanent deformation of waste plastic asphalt mixes was found by doing a dynamic creep test, and results were compared with the control asphalt mixture. The specimens for the dynamic creep test were prepared at optimum waste plastic content (8% by weight of bitumen). It can be observed from Fig. 9 that with the addition of waste plastics, the rutting resistance of the asphalt mixtures has improved significantly. PE-modified mixes result in the lowest amount of permanent deformation, followed by MLP 2 modified mix and MLP 1 modified mix. MLP 2, which contains both PP and PET, showed more resistance to permanent deformation when compared with MLP 1 which is 100% PET. PP is referred to as amorphous and PET is referred to as a semi-crystalline substance. When the coating and mixing temperatures exceed the glass transition temperature of PET (75 °C), the amorphous portion of PET and PP transforms into a liquid; and due to PET's high melting point of roughly 250 °C, a crystalline region exists as a solid part. As a result, MLP 2 shows improvement in asphalt mixture properties in two ways: first, the liquid and molten part of MLP 2 increases the binding between the asphalt binder and aggregate, and second, the solid part of MLP 2 absorbs some of the cyclic load's energy.

From Fig. 9, it was observed that after 1000 loading cycles the deformation observed in the control mix was maximum, whereas the mixture modified by PE waste plastic was minimum and it is 63.33% lesser than the control mix followed by MLP 2 modified mixture which is nearly 40% lesser than control mix and mixture modified by MLP 1 shows 20% lesser deformation than control mix. MLP wastes due to their high melting point and rigid structure do not melt and coat the aggregates completely and hence showed more deformation in comparison to PE-based waste plastic mix. PE polymer is more flexible than PP and PET plastic.

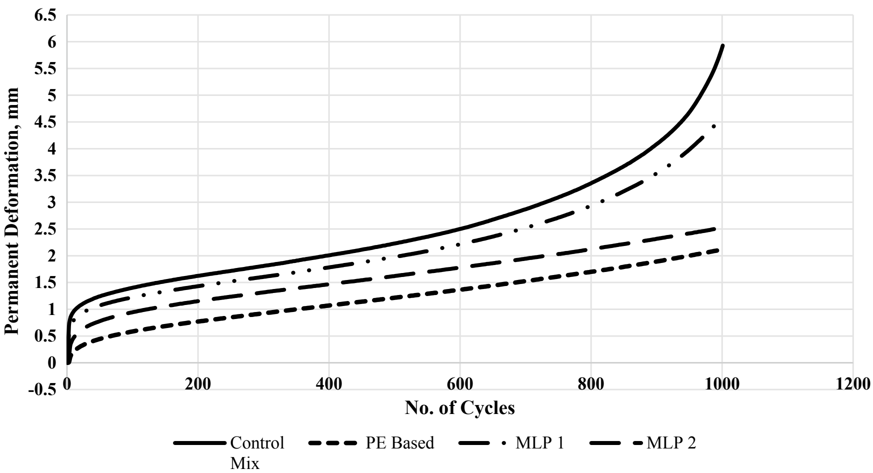

Fig. 9 Cumulative permanent deformation versus load cycles at 60 °C

5 Conclusion

Waste plastic can be blended with aggregate or mixed with bitumen to change its property. Most of the available studies are limited to the use of polyethylene (PE) and Polypropylene (PP)-based waste plastic. The laboratory investigation on multilayer plastics has been attempted in the present study, and the following conclusions can be drawn on the basis of the results achieved in this study:

1. Coating of waste plastics over aggregates improves the strength as well as water absorption of aggregates. PE-based waste plastic having a melting point of 122 °C gives the highest coating on aggregates when asphalt mixes are prepared at 155–160 °C.
2. With the addition of waste plastics, the optimum bitumen demand of the asphalt mixes decreases, which leads to the saving of natural resources of petroleum-based bitumen.
3. From the Marshall quotient values, it can be concluded that the stiffness of mixes increases with the addition of waste plastics. 8% dosage is found as the optimum waste plastic content. At higher dosages, the asphalt mix becomes very stiff which can lead to cracking failure.
4. MLP-based waste plastic has rigid polymer (PET), due to which mixes containing MLP waste plastic give higher resilient modulus since the stiffness in the mix has increased.
5. From dynamic creep results, it can be concluded that PE being a flexible polymer gives better resistance to permanent deformation as the flexible PE allows the recovery of the strain. In colder regions where cracking failure is of concern, PE-based waste plastic should be used.
6. The addition of waste plastics improves the resistance of asphalt mixes to moisture damage.
7. Coatability Index is a good parameter to evaluate the coating of waste plastic over the aggregates.
8. Emissions for mixtures containing waste plastics were observed higher than the control mixture; among them, the mixture containing MLP 2 and PE waste plastics have nearly similar emissions.

References

1. Mahapatra D (2013) Plastic time bomb: plastic waste time bomb ticking for India, SC says - Times of India. The Times of India. https://timesofindia.indiatimes.com/home/environment/pollution/Plastic-waste-time-bomb-ticking-for-India-SC-says/articleshow/19370833.cms. Accessed 17 May 2021.
2. Behl A, Sharma G, Kumar G (2014) A sustainable approach: utilization of waste PVC in asphalting of roads. Constr Build Mater 54:113–117. https://doi.org/10.1016/J.CONBUILDMAT.2013.12.050

3. Salter RJ, Rafati-Afshar F (1987) Effect of additives on bituminous highway pavement materials evaluated by the indirect tensile test. Transp Res Rec:183–195.
4. Vasudevan R, Velkennedy R, Ramalinga Chandra Sekar A, Sundarakannan B (2007) Utilization of waste polymers for flexible pavement and easy disposal of waste polymers. Int J Pavement Res Technol 3:105–111. https://doi.org/10.6135/ijprt.org.tw/2010.3(1).34.
5. Sridhar R, Bose S, Sharma G, Kumar G (2004) Performance characteristics of bituminous mixes modified by waste plastic bags. Highw Res Bull 71:1–10
6. Vasudevan R, Ramalinga Chandra Sekar A, Sundarakannan B, Velkennedy R (2012) A technique to dispose waste plastics in an ecofriendly way-application in construction of flexible pavements. Constr Build Mater 28:311–320. https://doi.org/10.1016/j.conbuildmat.2011.08.031.
7. Angelone S, Cauhapé Casaux M, Borghi M, Martinez FO (2016) Green pavements: reuse of plastic waste in asphalt mixtures. Mater. Struct/Mater. Constr. 49:1655–1665. https://doi.org/10.1617/s11527-015-0602-x.
8. IRC:SP:98–2013 (2013) Guidelines for the use of waste plastic in hot bituminous mixes (dry process) in wearing course.
9. Shbeeb L, Awwad MT (2007) The use of polyethylene in hot asphalt mixtures. Am J Appl Sci 4:390–396
10. Sarang G, Lekha BM, Shankar AUR (2014) Stone matrix asphalt using aggregates modified with waste plastics. ASCE 2014:9–18
11. Sarang G, Lekha BM, Krishna G, Ravi Shankar AU (2016) Comparison of stone matrix asphalt mixtures with polymer-modified bitumen and shredded waste plastics. Road Mater Pavement Des 17:933–945. https://doi.org/10.1080/14680629.2015.1124799.
12. Mitchell MR, Link RE, Punith VS, Raju S, Kumar K, Bose KS, Veeraragavan A (2011) Laboratory evaluation of stone matrix asphalt mixtures with polyethylene and cellulose stabilizers. J Test Eval 39:102919. https://doi.org/10.1520/JTE102919.
13. Vasudevan R, Saravanavel S, Rajesekaran S, Thirunakkarasu D (2006) Utilisation of waste plastics in construction of flexible pavement. Indian Highw 34:5–20. https://trid.trb.org/view/1156200. Accessed 17 May 2021.
14. Shankar AUR, Sarang G (2013) Performance studies on bituminous concrete mixes using waste plastics. Highw Res J: 1–11. https://www.researchgate.net/publication/285905618.
15. IS: 2386 Part-1 (1963) Indian method of test for aggregate for concrete – part I-Particle size and shape
16. IS: 73 (2013) Paving bitumen–specification.
17. EN 12697–25 (2005) Bituminous mixtures test methods for hot mix asphalt part 25: cyclic compression test.
18. Velasquez R, Cuciniello G, Swiertz D, Bonaquist R, Bahia H (2012) Methods to evaluate aggregate coating for asphalt mixtures produced at WMA temperatures. In: Proceedings of the Annual Conference of Canadian Technical Asphalt Association, vol 57, p 225. Canadian Technical Asphalt Association, Vancouver, Canada
19. Bairgi BK, Mannan UA, Tarefder RA (2019) Influence of foaming on tribological and rheological characteristics of foamed asphalt. Constr Build Mater 205(2019):186–195
20. Xue Y, Hou H, Zhu S, Zha J (2009) Utilization of municipal solid waste incineration ash in stone mastic asphalt mixture: pavement performance and environmental impact. Constr Build Mater 23:989–996. https://doi.org/10.1016/J.CONBUILDMAT.2008.05.009
21. Keating M, Malone L, Saunders W (2004) Annealing effect on semi-crystalline materials in creep behavior. J Therm Anal Calorim 69:37–52. https://doi.org/10.1023/A:1019925420733
22. Zoorob SE, Suparma LB (2000) Laboratory design and investigation of the properties of continuously graded asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt). Cem Concr Compos 22:233–242. https://doi.org/10.1016/S0958-9465(00)00026-3
23. Ministry of Road Transport & Highways (MoRTH) specification, specifications for road and bridge works for state road authorities, Fifth Revision (2013)

24. Gueguen O, Ahzi S, Makradi A, Belouettar S (2010) A new three-phase model to estimate the effective elastic properties of semi-crystalline polymers: application to PET. Mech Mater 42:1–10. https://doi.org/10.1016/J.MECHMAT.2009.04.012
25. Raabe D, Chen N (2004) Recrystallization in deformed and heat treated PET polymer sheets. Mater Sci Forum 467–470:551–556. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/MSF.467-470.551
26. Baghaee Moghaddam T, Soltani M, Karim MR (2014) Experimental characterization of rutting performance of polyethylene terephthalate modified asphalt mixtures under static and dynamic loads. Constr Build Mater 65:487–494. https://doi.org/10.1016/J.CONBUILDMAT.2014.05.006.
27. Mokhtari A, Moghadas Nejad F (2012) Mechanistic approach for fiber and polymer modified SMA mixtures. Constr Build Mater 36:381–390. https://doi.org/10.1016/J.CONBUILDMAT.2012.05.032.
28. Tayfur S, Ozen H, Aksoy A (2007) Investigation of rutting performance of asphalt mixtures containing polymer modifiers. Constr Build Mater 21:328–337. https://doi.org/10.1016/J.CONBUILDMAT.2005.08.014

Planning Strategies for the Improvement of Intermediate Public Transport in Walled City: Case Study of Walled City, Delhi

Hrishi Sharma, Sandeep Kumar, and Charu Nangia

Abstract Intermediate Public Transport (IPT) plays an important role in Indian cities as it helps in connecting the user to the Mass Transit modes and increases the accessibility to these modes. Walled City, Delhi, over a period of time has evolved as a major commercial and recreational area. Over the period of time, the need for IPT in the transport system of Delhi has increased quite rapidly. In 2000–01, the modal share of Cycle Rickshaw and Auto Rickshaw was 6.7%, while in 2007–08, the modal share increased to 11.5%, where cycle rickshaw completed almost 8% of the trips. Only Cycle Rickshaw trips have a share of approximately 34% of the total traffic volume entering the Walled City, which is roughly more than 1/3rd of the total incoming traffic. In this study, indicators such as Traffic Characteristics, Network Characteristics, Socio-Economic Profile, Travel Characteristics and IPT Infrastructure were used to study the IPT system in Walled City, Delhi, and identify the critical issues and gaps which act as hindrances to smooth mobility in the area. After studying and analyzing the IPT system in detail, the major issues identified include the absence of a formal policy framework for IPT which makes the system unorganized and is the major reason for the other issues relating to this sector. This paper discusses the existing situation of IPTs in the Walled City, Delhi, in particular and recommends proposals to improve the existing situation for the seamless operation of IPTs in this area.

Keywords Intermediate public transport (IPT) · Last mile connectivity · Public transport · IPT modes · Walled City · Non-motorized transport (NMT) · Intelligent transport system (ITS)

H. Sharma (✉) · S. Kumar · C. Nangia
Amity University, Noida, Uttar Pradesh 201301, India
e-mail: hrishisharma18@gmail.com

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1 Background

Zone-A (Walled City) or popularly known as Shahjahanabad/Old Delhi is known for its markets, bazaars, food, culture and vibrant nature. For planners, Shahjahanabad is a place with a complex street network, mixed land use and multifaceted spatial features. The area is known for its narrow streets and a variety of traffic modes moving on these streets simultaneously. Out of the numerous transportation modes, Intermediate Public Transport (IPT) is the mode that is responsible for the majority of passenger trips within the area. Intermediate para-transit (IPT) like auto rickshaws (three-wheeled motor vehicles), cycle rickshaws (three-wheeled cycles) and recently evolved e-rickshaws (battery-operated three-wheeled vehicles) serve most of the cases for first-last mile connectivity [1]. Due to the absence of rules and norms, it is largely being operated informally. The role of IPT becomes more crucial in Zone-A, because the streets become narrow as we move to the inner parts of the zone, which makes it difficult for mass transit modes to provide public transport services. Although IPT functions fairly well on these narrow streets and provides a cheaper and faster mode of transport, in the Walled City, cycle rickshaws are the most significant mode used for intra-zone movement, after walk trips. Comparing the trip length frequency distributions of the walk trips and cycle rickshaws, it is observed that after a distance of 750 m, the trend shifts from walk trips to cycle rickshaw trips. The usage of cycle rickshaws is predominantly over a radius of 1.5 km. Cycle rickshaws are being utilized for transporting people from the inner areas to the bus stops, three-wheeler stations, etc. on the major networks. Even those who own vehicles show a high dependence on cycle rickshaws, especially those who own cars [2]. The aim of the research is to analyze the impact and vitality of IPT in Walled City, Delhi, and provide suggestive measures to improve the IPT system and introduce Intelligent Transport System in the study area. The objectives of the research will be.

1. To analyze the existing IPT system in the study area;
2. To identify the issues and shortcomings in infrastructure and management in the existing IPT;
3. To deliver planning interventions for the shortcomings identified in the existing IPT system.

The methodology adopted for the completion of this research is adopted after going through a lot of literature and multiple projects. The methodology is as follows: Identification of the Problem; Study Area Selection; Formulation of Aims and Objectives; Literature Review and Case Study; Data Collection; Data Analysis and Inferences; SWOC analysis; and Planning Interventions and Recommendations.

2 Literature Review

The significance of IPT in Delhi can be witnessed at various places, but Walled City is one place where the significance becomes needed. Out of the numerous transportation modes, Intermediate Public Transport (IPT) is the mode that is responsible for the majority of passenger trips within the area. Due to the absence of rules and norms, it is largely being operated informally. The role of IPT becomes more crucial in Zone-A, because the streets become narrow as we move to the inner parts of the zone, which makes it difficult for mass transit modes to provide public transport services. IPT acts as the major feeder service to the major mass transit modes like the Metro and Buses in the Old Delhi area. IPT services are used for the movement of both goods and people. One can witness a variety of IPT options available in Old Delhi, like Auto Rickshaw, Cycle Rickshaw, Battery Powered Rickshaw, Motorbike Three-Wheeler Rickshaw, etc [3]. There are several different IPT modes available in the Walled City area which helps in working on a wider scope of work and studying the IPT modes in more depth. To study the role and impact of IPT in more depth, two case studies were done of Jaipur and Udaipur Walled Cities (Table 1).

Through all these literature studies, it was observed that all these different modes are available in huge amounts and are easy to ply. But the major problem observed was their incompetent management and informal operations. To resolve these issues,

Table 1 Summary of case studies

Case study: Udaipur Walled City	*Case study: Jaipur Walled City*
Identified issues	
Poor public convenience facilities; encroachment by local vendors and parked vehicles; Lack of designated pick-up and drop-off points; No dedicated infrastructure for IPT; No designated or planned routes for IPT	
Proposed intervention	
To solve these identified issues, the proposed interventions were as follows: Modernized IPT system that would cater to last mile connectivity needs through the introduction of GPS-enabled BS 3/BS 4 three/four wheelers that enable better control and monitoring and real-time information dissemination; this also includes CNG/battery operated shared vehicles (e-rickshaws) in Walled City on pre-defined routes; smart car parking outside walled city boundaries for the residents as well as the visitors	To solve these identified issues, the proposed interventions were as follows: sustainable mobility with corridors fitted for Non-motorized transport; Pedestrianization; Public bike sharing system; Universal access (barrier-free); Electric vehicles/IPT (rickshaws); Smart parking and smart signage; Smart Auto/Taxi stands; App for IPT; Taxis and car-pooling app
Parameters identified from the case studies	
Road network characteristics; Traffic characteristics; Travel Characteristics; IPT infrastructure; and traffic management	Socio-economic profile; Road network characteristics; Traffic characteristics; Travel characteristics; IPT infrastructure; and traffic management

it is important to study the sector in detail and identify all the possible parameters contributing to these issues. To identify these issues, various data collection and data analysis methods can be used. To analyze the IPT system in the Walled City, 5 parameters were studied in detail. The parameters studied were: Road Network Characteristics; Traffic Characteristics; Travel Characteristics; IPT Infrastructure; and Traffic Management. This mode has the potential to resolve the public transit issues as per the Zonal Development Plan of Walled City [4].

3 Literature Review

Zone-A (Walled City) or popularly known as Shahjahanabad/Old Delhi is the ancient Walled City existing since the Mughal period and has served as a center of attraction to Delhi since its independence. Walled City, Delhi, is located in Zone-A (Walled City) of Delhi. It is a part of the Special Area recognized under the Master Plan Delhi 2021 for having special heritage and cultural importance, along with areas like Sadar Bazaar, Paharganj and Karol Bagh. The total population of the Walled City is 2.5 Lakhs (as per the 2011 Census). The total geographical area of Zone-A after excluding the areas outside the Walled City is 569Ha. The overall population density of the area is 440ppHa. The female-to-male sex ratio of Zone-A is 864:1000 (Table 2).

The Walled City Area has been marked as a Special Area in MPD 2021. Land use of the surrounding areas is mainly in the form of Recreational Greens, Institutions, Public and Semi-public Facilities and Commercial. Within the core of the Walled City, residential areas have mixed-use development owing to the organic nature of its growth. Following older development patterns, major streets connecting landmarks have developed into commercial corridors for wholesale trade and warehousing [5]. Public/Semi-public facilities are a bare minimum. The data collection was done through both primary and secondary sources. Primary data collection included multiple surveys, namely Road Network Inventory Survey, Traffic Volume Count Survey, Origin Destination Survey, Speed and Delay, IPT Operator Survey, IPT User Survey and IPT Parking Survey.

Table 2 Basic Demographic Profile (*Source* Census 2011, ZDP-Walled City Delhi)

Total population (2011)	2.5 Lakhs
Total geographical area	569Ha
Population density	440 pp/Ha
Number of sub-zones	16
Number of wards	11

4 Analysis

For analysis, the 12 most congested streets identified by Zonal Development Plan were selected. On these 12 streets, speed 7 Delay survey was conducted. After analyzing the results, further 5 most congested streets were selected. The 5 selected streets were Nai Sarak, Swami Vivekananda Road, Chawri Bazaar Road, Urdu Bazaar Road and Ajmere Gate Road (Fig. 1 and Table 3).

Further, Traffic Volume Count survey was conducted on the selected 5 streets. Out of the 5 road stretches, 3 road stretches were found to have a Level of Service (LOS) of level F which is the worst followed by 1 each of LOS E and D. The maximum traffic volume was observed on Swami Vivekananda Marg because of the major share of slow-moving vehicles like Animal/Hand-Driven Carts. Nai Sarak has an LOS of level D which is the result of vehicles parked on both sides of the street

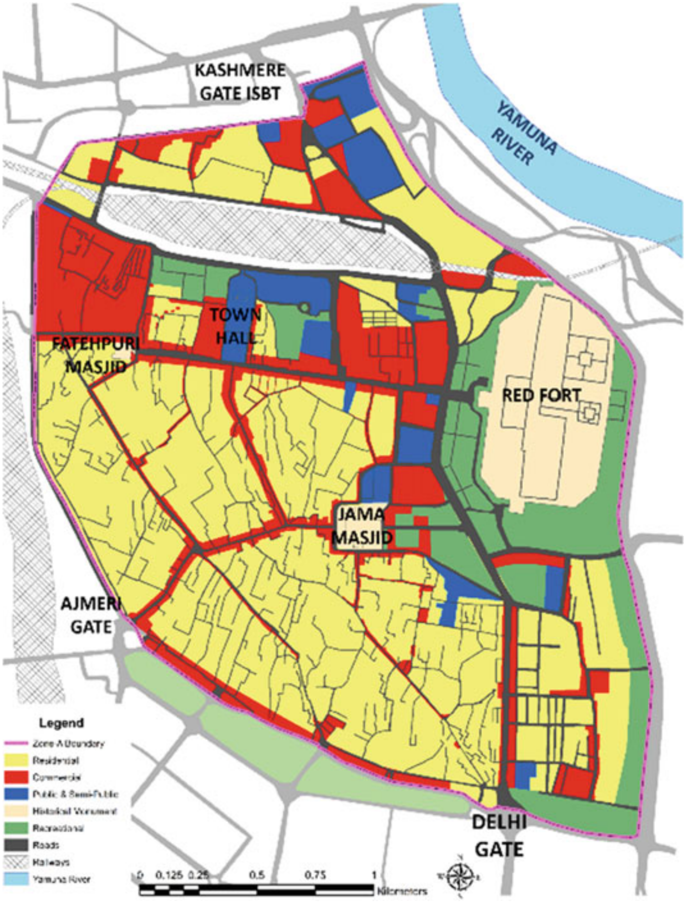

Fig. 1 Land use map of Walled City, Delhi (*Source* Author)

Table 3 Speed and delay survey results (*Source* Primary Survey, Author)

Road stretch name	Stretch distance (KM)	Direction	Total duration (In Minutes)	Average duration (non-peak hours)	Stoppage period (in minutes)	Delay (in minutes)	% difference B/W avg. duration and delay (%)
GB road	1.31	S–N	14	8	7	6	75
GB road	1.31	N-S	13	9	6	4	66.7
Lalkuan bazaar road	1	N-S	13	6	8	7	116.7
Lalkuan bazaar road	1	S–N	17	6	10	11	166.6
Ajmere gate road	0.43	E-W	19	2	16	17	850
Ajmere gate road	0.43	W-E	25	2	21	23	1150
Chawri bazaar road	0.57	E-W	23	2	18	21	1050
Chawri bazaar road	0.57	W-E	21	2	19	19	950
Nai sarak	0.68	N-S	12	3	7	9	300
Nai sarak	0.68	S–N	13	4	7	9	225
Sitaram bazaar road	0.96	S–N	10	5	6	5	100
Sitaram bazaar road	0.96	N-S	12	5	7	7	100
Chitli qabar road	0.91	S–N	14	13	4	1	7.69
Chitli qabar road	0.91	N-S	15	13	3	2	15.38
Urdu Bazaar Road	0.86	W-E	17	6	11	11	183.3
Urdu Bazaar Road	0.86	E-W	22	6	14	16	266.6
Swami Vivekananda Marg	0.41	E-W	10	2	6	8	400
Swami Vivekananda Marg	0.41	W-E	12	2	5	10	500
Shyam Lal Road	1	N-S	6	3	4	3	100

(continued)

Table 3 (continued)

Road stretch name	Stretch distance (KM)	Direction	Total duration (In Minutes)	Average duration (non-peak hours)	Stoppage period (in minutes)	Delay (in minutes)	% difference B/W avg. duration and delay (%)
Shyam Lal Road	1	S–N	8	3	5	5	166.6
Netaji Subash Marg	2.25	S–N	13	6	4	7	116.6
Netaji Subash Marg	2.25	N-S	13	7	3	6	85.71
Shyama Prasad Mukherjee Marg	1.73	E-W	8	5	2	3	60
Shyama Prasad Mukherjee Marg	1.73	W-E	10	5	4	5	100

and encroachment by local vendors and small food carts/stalls. Urdu Bazaar has an LOS of level F because of the haphazard on-street parking situation resulting in the reduction of the effective carriageway and causing congestions and slowing down the traffic movement (Fig. 2).

After analyzing the data, it was observed that the major reason for congestion along the streets is the encroachment by parked vehicles on both sides of the street on the shoulders. Other than the on-street vehicle encroachment, encroachment by local vendors or food stalls is also a contributing factor (which is highlighted by the orange block). Another reason observed in this figure is the mixing of slow- and fast-moving vehicles and the mixing of passenger vehicles with goods carrier vehicles (Fig. 3).

Further, travel characteristic surveys were conducted in which the results were then studied in order to understand the gaps and the issues. IPT was observed to be the most used mode to travel to/in Zone-a (Walled City). Followed by Metro and Private Vehicles, NMT options like Walking and Cycling are less preferred by users with only 10% and 6% share, respectively. 6% people also prefer buses (Fig. 4). Buses are majorly used to reach the zone and then change their mode for intra-zonal movement. The majority of IPT trip lengths are in a range of 500−1000 m because of the proximity of the major attractions and their location. For shorter trips, users prefer Cycle Rickshaws while for longer routes users ply E-Rickshaws or Auto Rickshaws. Trips longer than 2500 m are usually for inter-zonal movement (Fig. 5). Almost half of the IPT users prefer E-Rickshaws over the other two IPT modes, while 26.2% of users prefer using Cycle Rickshaws. Users prefer IPTs because of

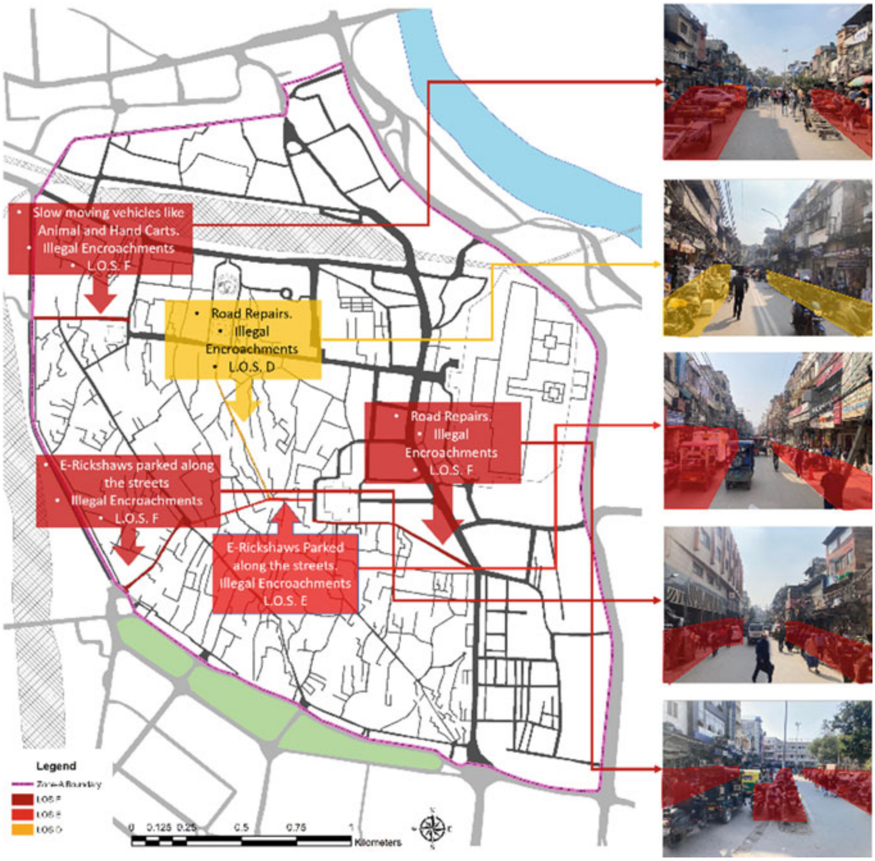

Fig. 2 LOS of road stretches with photographic evidences (*Source* Primary Survey)

their characteristics which help them in performing exceptionally in areas like Walled City. They are small in size, can carry 3–4 passengers and have less fuel consumption, adequate speed; all these factors together help IPTs in being the number one priority of users. As per the users, they chose IPT modes for these reasons: Accessibility, Comfort, Convenience and Affordability (Table 4).

Further, the Infrastructure of Zone-A was analyzed. The data was collected from secondary sources as well as primary surveys like the parking infrastructure survey. Zone-A lacks the IPT infrastructure like Parking, Authorized IPT stand, Government Workshops/Repair shops, Integration with Public Transportation (BRTS or MRTS), Access to Restrooms and Drinking Water Facilities. These basic infrastructure facilities should be there in Zone-A to facilitate a better IPT system to cater to more passengers more efficiently. Parking facilities in Zone-A are very less as compared to the number of IPT vehicles in the area.

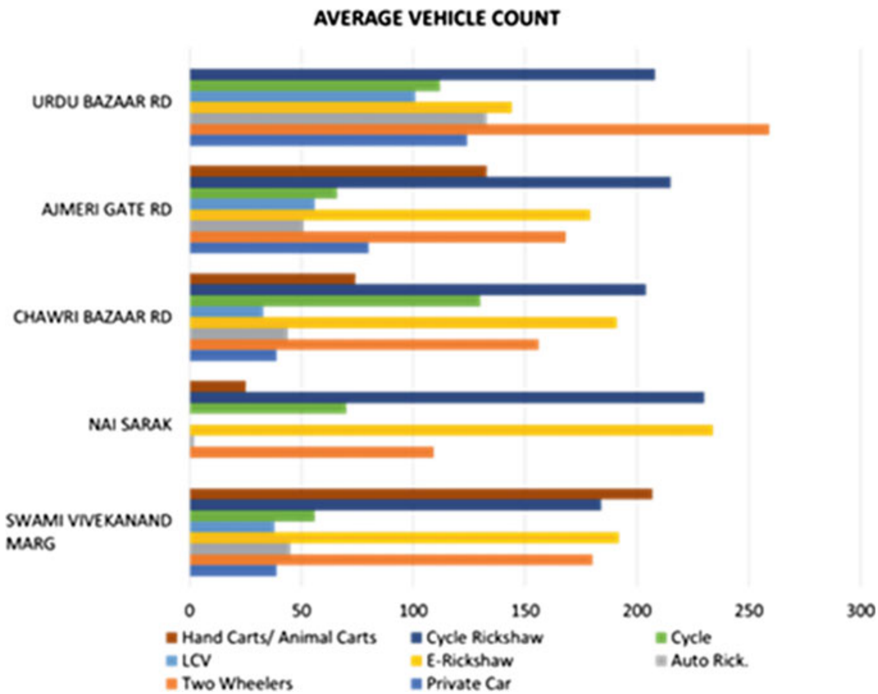

Fig. 3 Average vehicle count (*Source* Primary Survey)

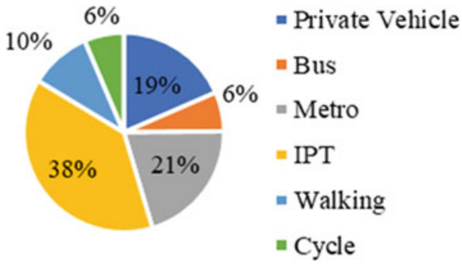

Fig. 4 Modal share (*Source* Primary Survey)

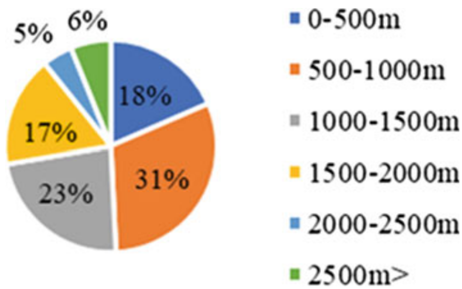

Fig. 5 Average Trip Length (*Source* Primary Survey)

Table 4 Trip characteristics—IPT operator survey (*Source* Primary Survey)

S. No	Attribute	Classification	Percentage Share
1	Average daily trips	10–20	41.70
		20–30	40
		30–40	15
		40–50	3.30
2	Average trip fare collected (Per Trip)	20–40	17
		40–60	24.60
		60–80	14.80
		80–100	40.20
		100 +	3
3	Average occupancy	1	1.70
		2	48.30
		3	13.30
		4	33.30
		4 +	3.30

5 Issues Identified

After analyzing all 5 parameters and the data collected from numerous surveys conducted, the below-mentioned issues were identified. There is no formal policy framework for IPT which makes the system unorganized and is the major reason for the other issues relating to this sector. Since there is no formal policy, there is zero economic stability or support for drivers which further impacts the socio-economic character of the drivers and demotivates them. There is no provision for any other social benefit for drivers like pensions, insurance or any other facility. In the modern world that we live in, technology and the usage of advanced sciences are common in pretty much any field. But still in the Walled City, we can hardly witness the usage of Intelligent Transport Systems. There is a lack of financial assistance.

The absence of a government institution for the IPT sector ensures the lack of a maintained system to control and manage the IPT in Walled City areas. There are almost zero infrastructure facilities for IPT drivers as there are no Stands, Parking, Drinking Facility or any other such facility which is a basic requirement. Poor traffic management systems can be witnessed throughout the study area as there is a minimal arrangement from the government within Walled City, Delhi. Like any other commercial area, carriageway encroachment by vendors, store owners and parked vehicles is very common. Thus, it can be said that though IPT is an important mode in the walled city, this sector being unorganized and not recognized by the government is facing one of the biggest challenges in the times to come. Therefore, in order to upgrade the service and IPT vehicles, there is a need for improvement that must be brought to the sector before it is too late and their importance is lost.

6 Proposals and Recommendation

Multiple proposals and recommendations are provided since there are a lot of issues that need to be tackled in order to improve the IPT system in Walled City, Delhi. The proposal provided are.

1. A special purpose vehicle is to be formed between private companies to build the required IPT infrastructure and then operate and manage the IPT system in Walled City.
2. The SPV will work in coordination with respective authorities GNCTD-Transport Department, NDMC, SRDC, DDA, PWD, ASI and Traffic Police while providing the required Infrastructure in the Walled City.
3. Route Management by introducing new routes with designated time slots and vehicle typologies for efficient and smooth traffic movement. Junction Redesign proposal for Hauz Qazi Chowk.
4. Usage of Intelligent Transport System for traffic management throughout the study area (Fig. 6).

To improve the IPT system in Walled City, Delhi, it is important to provide infrastructure facilities to assist the IPT system which is currently absent. To resolve the existing issues, the following infrastructure facilities have been proposed:

1. IPT Parking
2. IPT Stand Facilities
3. Halt and Go Stands
4. Restrooms and other facilities.

Fig. 6 Junction redesign-Hauz Qazi Chowk (*Source* Author)

A mix of commercial and residential activity in the core of the Old City has led to a complex composition of vehicles with commercial as well as passenger vehicles accessing the main commercial streets throughout the day (Delhi Urban Arts Commission, 2017). Activities such as loading and unloading of goods cannot be stopped. Drop-off or pick-up by inter-para transit vehicles too cannot be hindered. Hence, the situation calls for a traffic regulation plan which has been designed as a unidirectional time-based circulation system. Emergency vehicles should be allowed free passage at all times.

To improve the existing traffic circulation within the Walled City, two types of traffic circulation is provided, so that cargo movement and passenger movement do not mix up and effect the smooth flow of traffic. This can be achieved by restricting the movement of goods when passenger traffic movement is more prominent and vice versa. This can be achieved by restricting the movement one type of movement during its non-peak hours as the traffic volume coming is exceptionally high and such measures should be adopted. After analyzing the IPT system, it was observed that the commuter peak hours are 08:00–22:00 from Monday to Saturday, and on Sunday markets are closed so comparatively less traffic enters the area. New Traffic Circulation Routes can be designed for both Passengers as well as goods movement (Fig. 7).

The following different measures can be taken up in order to introduce ITS in the existing IPT system: Traffic Management Centre and Control Centre, GPS, Surveillance, ANPR for E-Challan, Smart App and Smart Card. The Traffic Management and Information Control Centre (TMICC) are control rooms having requisite IT infrastructure, applications, video walls, operator consoles and other visualization tools that support the monitoring and management of traffic on the road network (Source: TMICCs & NUTH, DIMITS). To manage the IPT traffic network, a Traffic Management Centre is established, in which activities like surveillance, data management, E-challan and route information will be provided.

GPS continuously transmits coded information, which precisely identifies the locations of the vehicles on the ground. This information is then sent to the Control Centre (TMC) through a wireless communication link. Installation of GPS and GPRS in IPT vehicles could solve many problems related to IPT. The GPS will be assisting in the following tasks which will eventually help in better traffic management and control:

1. Monitoring and Tracking.
2. Data Collection: Real-time information of vehicle details and speed will provide a real-time route map on a point-to-point basis.
3. Automatic Bill Generation on the basis of Distance Traveled, Stoppage Period, etc.
4. Traffic Management through real-time information.
5. It will ensure a secure and reliable IPT service.
6. GPS would be an essential tool to formalize the sector and organize it under an SPV.

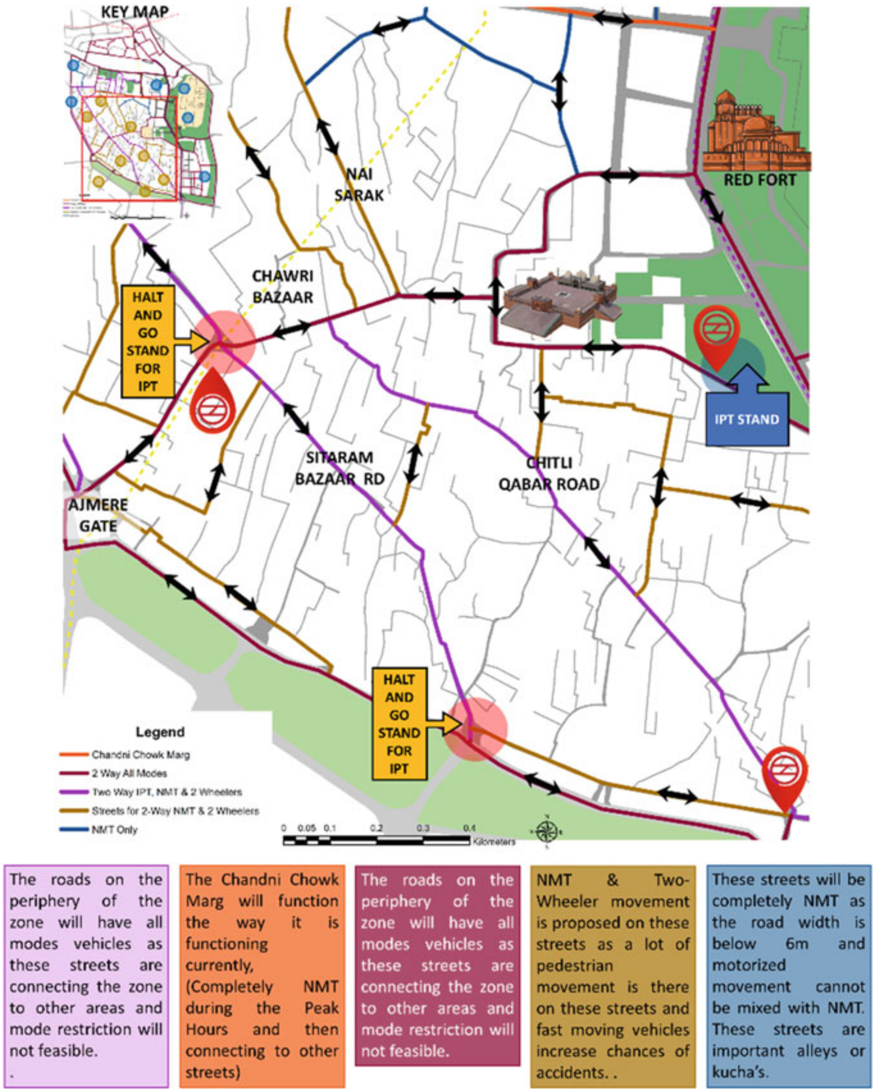

Fig. 7 Proposed passenger & goods circulation (*Source* Author)

Surveillance is important for any transportation system nowadays. Surveillance is important for both safety and also efficient management of traffic; surveillance can be done through CCTVs and Sensors which can help us understand the on-ground situation and identify the problems immediately and those elements can be improved and obstructions can be removed. Also, such measures promote safety and assurance to vulnerable groups.

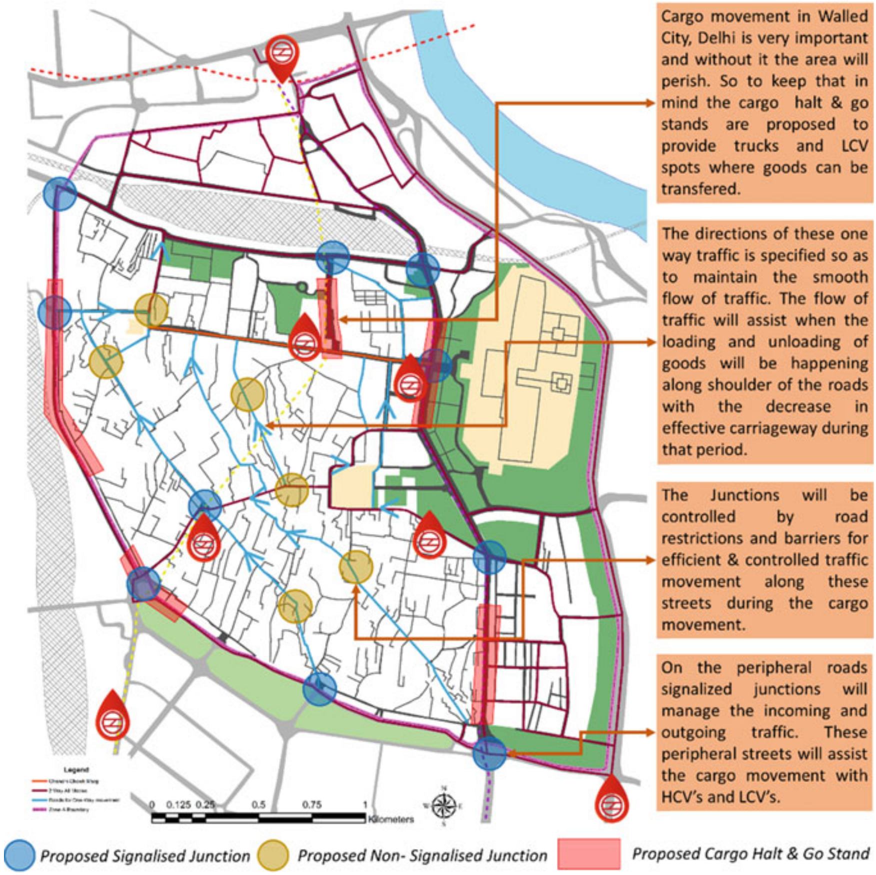

Fig. 7 (continued)

Automatic number plate recognition (ANPR) is a surveillance system that allows users to track, identify and monitor moving vehicles. License plates of vehicles passing by are scanned and saved by mounted cameras. ANPR system is simple to install and operate. To manage the traffic movement, it is important to install an ANPR system. Online challans will be issued using this system. Link this system with the ISTA app for issuing challan. Collecting data about traffic movement and real-time traffic situations. It works along with the GPS system to provide cumulative data which is easier to process.

An app will be developed that will manage the IPT system in Walled City, Delhi. A simple interface will be developed so as to make sure it is user-friendly. The app will connect all the IPT modes with GPS which will help in managing the transit and also give real-time data. The app can be linked to the DMRC app and smart card for user ease. The app will be available in all formats, Android/IOS/Windows. The process of boarding an IPT is shown below.

1. Open the IPT App
2. Open the code scanner
3. Scan the code on the IPT
4. Select payment mode
5. Do the payment
6. Select "Start Ride"
7. After completion of the ride, select "End Ride".

Through this system, the user can pay an auto-generated bill through any payment mode. The user can board the IPT easily. The user gets all the information about the driver, vehicle, route, speed and other details which gives assurance to the user. A rating system can also be introduced to make it more accountable and responsive.

7 Conclusion

Through this research, I wanted to establish the role of IPT in the existing public transport system and how it has been an integral part of the system even though it is not formally recognized. This mode not only serves as a transport mode for millions but also is a source of employment for hundreds of thousands of people. In a developing country like India where there is a huge population to cater to with people from different socio-economic backgrounds, IPT can be the key link in encouraging people to use public transport by providing them that last mile connectivity. IPT is not a formally recognized mode of public transport in the majority areas of India, yet it serves such a large number of populations every day throughout our country. But urban planners can help in formulating a guiding framework where this mode can be formally recognized and promoted; this mode can serve a larger number of populations more efficiently and effectively. Efforts are made in this thesis to establish the importance and need for IPT in Zone-A (Walled City), Delhi, and analyze the gaps in the existing IPT system in order to understand the problematic areas. Further recommendations and proposals were provided in order to uplift the IPT system in the area so that it can serve in a better way and a new efficient way so that visitors, operators and everyone gets benefitted from this. Such recommendations can also be implemented in similar Walled Cities in India since they have a similar character and moreover similar issues.

References

1. Kumar A, Roy UK (2019) E-rickshaws as sustainable last mile connectivity in an Urban dilemma: case of Delhi. In: International Conference on Transportation and Development 2019: Innovation and Sustainability in Smart Mobility and Smart Cities-Selected Papers from the International Conference on Transportation and Development 2019. pp 184–195. https://doi.org/10.1061/9780784482582.016
2. Bose R, Sarkar PK (n.d.) The role of cycle rickshaws-low cost means of transport in old part of a city. http://www.codatu.org/ Codatu.Org.
3. Bromley R (2016) The streets of old Delhi: order in a seemingly-chaotic public realm. Middle East Institute. MEI@75. https://www.mei.edu/publications/streets-old-delhi-order-seemingly-chaotic-public-realm
4. Delhi Development Authority (1999) Zonal development plan A & C. https://www.dda.org.in/planning/docs/Zone%20A&C.pdf
5. Delhi Urban Art Commission (2017) Rejuvenation of Shahjahanabad, Delhi

Assessment of Sustainable Public Transportation Provisions in Himachal Pradesh, India

Arunava Poddar, Akhilesh Kumar, Akhilesh Nautiyal, and Amit Kumar Yadav

Abstract With the increase in population in hilly areas, the importance of public transportation increases which requires appropriate management. Safe mobility of PT provides sustainable, accessible, affordable, and multimodal transportation for all, including people who don't prefer driving due to age, disability, or lower income. The current study describes the present scenario of PT in the state of Himachal Pradesh (HP). The state of HP holds high PT utilization for deliveries of goods and tourism which causes congestion in traffic movement mostly leading to accidents. The people of HP primarily use PT to fulfill their need for transportation for both shorter and longer distances. The main aim of this study is to interview people using public transportation with the help of a questionnaire and analyze their responses to improve safety measures. 5000 person's feedback has been considered for the analysis in the study. The present study concluded that safety for people traveling on public transportation is essential for all groups of people. Providing safe and cheap PT is a massive challenge in Himachal Pradesh, which may be simplified by adopting the results of the present study.

Keywords Public transportation · Traffic · Accident · Safety · Questionnaire · Himachal Pradesh

A. Poddar
Department of Civil Engineering, Shoolini University, Himachal Pradesh, Solan, India

A. Kumar (✉)
Department of Civil Engineering, Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab, India
e-mail: akhileshsharma54@gmail.com

A. Nautiyal
Civil Engineering Department, Chandigarh University, Punjab, India

A. K. Yadav
Department of Civil Engineering, Central University of Jharkhand, Ranchi, Jharkhand, India

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1 Introduction

India probably has the highest road fatality rates and out of 1.25 million deaths worldwide every year; 8–10% of all road-based deaths occur in India [1]. Road safety is supposed to be built into the traffic system by appropriate traffic engineering practices, but its due importance in road system development and operation in India is yet to be established. The giant road development program being undertaken in India is grossly deficient in traffic engineering. Traffic engineering aims to provide the most scientific design to make the roadway safe for all users and to provide a forgiving road [2]. The other critical dimension of the road safety problem in India is poor public education regarding road safety. The population of hilly terrain is increasing day by day [3]. Hence, it's a challenge for the government and private transport corporations to provide an efficient transportation network that is safe for wildlife and people.

Transport management in Himachal Pradesh is mostly found congested at main tourist places, having a lack of parking facilities, with a high rate of accidents and pollution due to increasing vehicular movement. It is claimed that most of the issues could be solved with the introduction of economic instruments like taxation on old polluting vehicles, incentives that discourage private ownership and use of vehicles, subsidizing the use of public transportation (PT), and integrating transport with urban planning [4]. One of the solutions mentioned is the use of PT; however, the safety of people using PT remains a concern. Hence, the present study focuses on the assessment of safety measures required particularly for PT in the state H.P. The scheduled services of buses, taxis, private hire buses, and even the provision of school services were included in the category of PT [5]. The highway networks are accelerating at a fast rate, and the safety of PT becomes a concern for everybody as most of the people living in the hilly regions use PT to fulfill their daily needs of transportation [6]. PT is preferred for longer and shorter distances because of their affordable cost but less attention is given to the accidents which lead to loss of lives, properties causing fatal injuries, and periodical obstruction of traffic flow [7]. Geographical information systems (GIS) can improve public safety hazards with many available tools and methodologies [8–12]. Pavement condition also plays a vital role in the safety concerns of the people using PT [13, 14]. Effective pavement maintenance planning is very crucial to provide pavement in good and serviceable condition [15]. Timely application of pavement maintenance activities improves road user safety [16, 17]. In addition, there are many reasons why people do not use PT to its full potential, and safety is the leading cause among them. In states like HP, people of all ages use these facilities provided by the Himachal Road Transportation Corporation (HRTC), but their safety is a genuine concern. Due to the mixed traffic pattern of the state, narrow streets, encroachment around roads, and the recent construction of elevated roads around the state, the safe movement of PT has become very difficult. The risk of accidents also increases in drunken driving, and the rate of liquor consumption by PT drivers is high in H.P. So, safety assessment can, to some extent, protect the PT from potential hazards. This study attempts to assess the safety issues of PT in

Table 1 The severity of accidents in Himachal Pradesh

Year	Road accident	Person killed	Injured person	Year	Road accident	Person killed	Injured person
2002–03	2,830	695	3,917	2011–12	3063	1051	5260
2003–04	2,607	867	4,188	2012–13	2867	1057	5422
2004–05	2758	920	4674	2013–14	3008	1116	4961
2005–06	2807	863	4833	2014–15	3012	1179	5522
2006–07	2756	886	4688	2015–16	3168	1271	5764
2007–08	2953	921	5272	2016–17	3114	1203	5452
2008–09	2840	898	4837	2017–18	3110	1208	5551
2009–10	3023	1173	5630	2018–19	2873	1146	4904
2010–11	3104	1105	5350	2019–20	1791	671	2520

Source Police Department, HP/Deptt. Road Tpt. And Highways, GOI/Newspapers

detail in the state of H.P. and identify the essential factors responsible for accidents and their relative contribution.

2 Methods

2.1 Case Study of Himachal Pradesh

Himachal Pradesh, a state located in the northern part of the country having a major part of the road transportation in hilly terrain, with a 7.51 million population (in 2021) [16] is considered the place for the case study. Table 1 shows that people killed in road accidents in Himachal Pradesh [17] is higher. Thus, there is a need to study the safety issues that can prevent or decrease the rate of accidents. PT is involved in a few of the accidents happening in hilly terrains [18]. As PT is the most trusted and regularly used transportation by the common people, hence, a proper safety assessment in consultation with experts and people using the PT can somewhat help the state.

2.2 Data Collection

Research scholars visited Himachal Pradesh to perform a one-to-one questionnaire survey based on some basic questions enlisted in Table 2.

Table 2 Questions to understand the PT safety-based perception of people in Himachal Pradesh

S. no	Questions
1	How old are you and the other members of your household?
2	Are you a caregiver for a person over age 60 or with a disability while traveling on a bus?
3	Do you have a disability or other health concern that prevents you from using the bus facility?
4	If MRTS (Mass Rapid Transit System) will be introduced in the city, then which facility will you prefer?
5	What type of bus (private/public) do you prefer safe and why?
6	Which category of the bus (old[a]/new/AC) do you prefer safe and why?
7	If you do not use the bus, why not?
8	How would you rank the facilities on bus stops? (1—worst, 2—bad, 3—good, 4—excellent)
9	Do you feel safe on public transport? Why is sometimes traveling in buses unsafe?

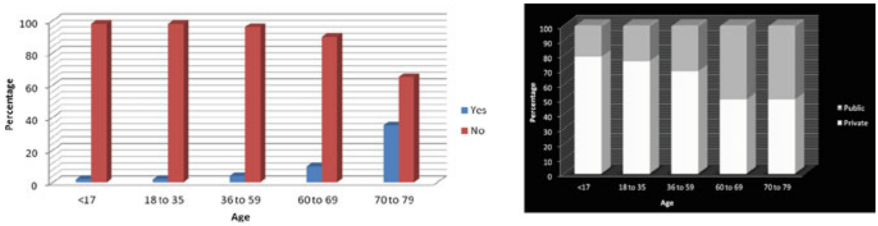
[a] Old Bus: Buses with more than 3 years of service [19]; New Bus: Buses with less than 3 years of service; AC bus: Air-conditioned buses from the origin of the journey to destination (e.g.: Volvo)

3 Results and Discussion

The present study aims to obtain more explorative and qualitative information on how PT influences the actual behavior of people living in Himachal Pradesh. It was used to review the experiences of people based on the questions mentioned in Table 2. The questionnaire was distributed to the different age groups of people near bus stands and taxi stands. 5000 person's feedback was considered for the analysis.

People were of different age groups, i.e., the percentage of people interviewed was based on their age groups. 7% of people were of age group less than 17, 56% of people were of age group 18 to 35, 27% people were of age group 36 to 59, 5% from 60 to 69, 3% people from the age group 70 to 79, and 2% people were above 80 ages. Opinions of people varied mostly according to their age groups. The percentage of caregivers to people aged above 60 were having some disabilities. Answers are described in the form of positive or negative. Disability or other health concerns are significant issues that prevent many people from using the bus facility. Figure 1a shows the percentage of people who do not use the PT facility due to disability or health concerns. Most people do not have a disability, but the percentage of people having a problem using PT due to their disability is to be considered.

The transportation system is to be designed so that disabled persons can also use the transportation facility within the city. Two types of bus facilities exist in Himachal Pradesh, and those are either public or private buses. People have their own opinion on using public or private buses. Figure 1b shows the percentage of people using private buses and public buses depending on safety. Public buses are safer than private buses, but people prefer private buses as private buses travel faster because security is compromised. Table 3 provides people's preferences for using



(a) (b)

Fig. 1 **a** Percentage of people who do not use or use public transportation due to disability. **b** Percentage of people preferring public and private buses

old, new, or AC PT buses for traveling. Maximum people preferred new buses as they are well maintained. This contributes to safety, and the number of old buses that exist should be eliminated one by one so that the whole system becomes perfect and safe. According to the survey, the number of AC buses should also be increased. According to the responses presented in Fig. 2a, Mass Rapid Transit System (MRTS) is preferred by higher income people, and lower income people can also use the system if it is cheap and user-friendly. However, according to Fig. 2b, people in Himachal Pradesh ranked their bus stop facilities as good. People preferred reasons for unsafe traveling. The reasons are the terrible condition of the bus, uncomfortable seats, and overcrowded bus. Public behavior is the most critical aspect, and driver behavior makes a huge difference in the safety of traveling. During the night and in bad climate conditions, the driver is solely responsible for safe driving.

People in Himachal Pradesh do not have better options other than PT. The mass rapid transport system is very much necessary to increase the safety and ease of the traffic system in Himachal Pradesh. People while traveling in buses face difficulties, and those difficulties should be reduced to increase safety.

Table 4 show the different reasons why people feel unsafe while traveling in buses and trains. 62% of people preferred that they want more bus facilities during morning and evening peak hours, whereas 9% of people wanted a safe bus facility during late night hours and 29% of people were comfortable with the type of bus facility they have in the city; 56% people preferred that if they get door-to-door service and safe service at night time, their trip will also increase and that will be the comfortable type of transportation in the city. People suggested that the Police are responsible

Table 3 Type of bus usage information of people in percentage

Age	Old (%)	New (%)	AC (%)
Less than 17	1	92	7
18 to 35	2	89	9
36 to 59	2	70	28
60 to 69	0	50	50
70 to 79	0	50	50

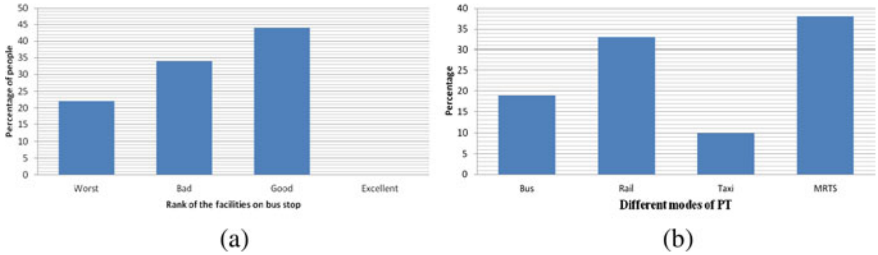


Fig. 2 **a** Comparison of a different mode of public transportation based on safety. **b** Ranking of the facilities of bus stops

for enforcing the rules and regulations and providing a safe transportation system for the town. 68% of people prefer that they have a proper police facility in the city, whereas 32% of people prefer that police facilities increase at night as shown in Fig. 3. Himachal Pradesh's share has been highest in the total population in hilly terrain states. The city experienced unprecedented growth in its people. Although Himachal Pradesh was at the bottom among the 23 metropolitan places in terms of its population, its growth rate (71.77%) had been recorded. Himachal Pradesh contains heterogeneous traffic consisting of people of different classes. The annual income of people traveling varies from person to person. The survey in this study consists of 41% of females and 59% of males, and they are further classified based on income. People of different income groups have other priorities. Higher income people preferred safety, comfort, and less traveling time. Lower income people liked less traveling costs, less traveling time, and safety. Lower income people compromise with comfort, so they ranked the HRTC facility as an excellent facility.

Table 4 Reasons for unsafe traveling on a bus

Reasons for unsafe traveling in a bus	% of people supporting the reasons
Rash driving	27
Pickpocketing	5
The bad condition of the road	8
Improper timing of buses	2
Lack of safety aides on buses	5
Lack of drinking water during the journey	1
Traffic jams	12
Others	40

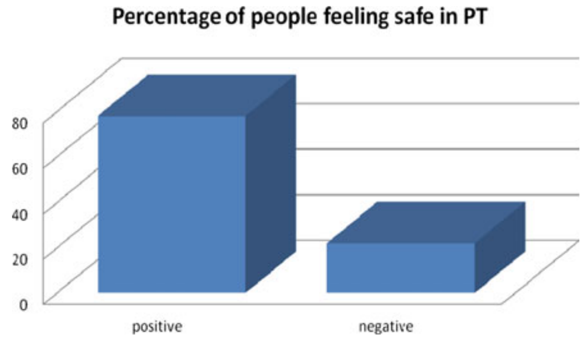


Fig. 3 Percentage of people feeling safe in PT

4 Conclusion

The present study concludes that transport management in the Himachal Pradesh state is out of gear with high congestion in major tourist areas, a lack of parking facilities, a high rate of accidents, and pollution due to vehicular movement. It is argued that most of the problems could be solved with the introduction of economic instruments like taxation on old polluting vehicles, incentives that discourage private ownership and use of vehicles, subsidizing the use of public transport, and integrating transport with urban planning. Further, it was concluded from people's responses that the most critical supply appreciation sub-aspects are safety, travel time, and punctuality. People's satisfaction is explained weakly by supply, travel, and traveler characteristics. Therefore, the main conclusion is that much interpersonal bias occurs, which means that different travelers show different satisfaction. The results show that higher people's dignity can be obtained if the following points are implemented in the PT management system. The offered PT can be better, and the appreciation may be higher with the improvement of travel time, frequency, punctuality, people's friendliness, and driving style. Thus, the needs concerning speed and comfort are most important. The whole transportation system should be made safe by preventing crowding and increasing traveler satisfaction of frequent travelers.

References

1. Sikdar PK, Bhavsar JN (2009) Road safety scenario in India and proposed action plan. Transp Commun Bull Asia Pac 79:1–16
2. Tettamanti T, Varga I, Szalay Z (2016) Impacts of autonomous cars from a traffic engineering perspective. Period Polytech Transp Eng 44(4):244–250
3. Spehia RS (2015) Status and impact of protected cultivation in Himachal Pradesh, India. Curr Sci: 2254–2257.
4. Batta RN, Pathak RD, Smith RFI (2008) Road transport in Himachal Pradesh: policy options for sustainable transportation. South Asian J Manag 15(1).

5. Manetti G, Bellucci M, Bagnoli L (2017) Stakeholder engagement and public information through social media: a study of Canadian and American public transportation agencies. Am Rev Public Adm 47(8):991–1009
6. Mohan D, Tiwari G, Mukherjee S (2016) Urban traffic safety assessment: a case study of six Indian cities. IATSS Res 39(2):95–101
7. Lakhotia S, Lassarre S, Rao KR, Tiwari G (2020) Pedestrian accessibility and safety around bus stops in Delhi. IATSS Res 44(1):55–66
8. Kumar A, Sharma RK, Bansal VK (2019) GIS-based comparative study of information value and frequency ratio method for landslide hazard zonation in a part of mid-Himalaya in Himachal Pradesh. Innov Infrastruct Solut 4:28. https://doi.org/10.1007/s41062-019-0215-2
9. Kumari S, Poddar A, Kumar N (2021) Delineation of groundwater recharge potential zones using the modeling based on remote sensing, GIS and MIF techniques: a study of Hamirpur district, Himachal Pradesh, India. Model Earth Syst Environ. https://doi.org/10.1007/s40808-021-01181-w
10. Kumar A, Sharma RK, Bansal VK (2018) Landslide hazard zonation using analytical hierarchy process along national highway-3 in mid Himalayas of Himachal Pradesh, India. Environ Earth Sci 77:719. https://doi.org/10.1007/s12665-018-7896-2
11. Kumar A, Sharma RK, Mehta BS (2020) Slope stability analysis and mitigation measures for selected landslide sites along NH-205 in Himachal Pradesh, India. J Earth Syst Sci 129:135. https://doi.org/10.1007/s12040-020-01396-y
12. Kumar A, Sharma RK, Bansal VK (2019) GIS-based landslide hazard mapping along NH-3 in mountainous terrain of Himachal Pradesh, India using weighted overlay analysis. In: Lecture Notes in Civil Engineering, vol 21. Springer, Cham. https://doi.org/10.1007/978-3-030-02707-0_9
13. Nautiyal A, Sharma S (2021) Scientific approach using AHP to prioritize low volume rural roads for pavement maintenance. J Qual Maint Eng. https://doi.org/10.1108/JQME-12-2019-0111
14. Nautiyal A, Sharma S (2019) A model to compute service life of rural roads using present pavement condition and pavement age. Compusoft 8(7): 3261–3268. https://ijact.joae.org/index.php/ijact/article/view/981.
15. Nautiyal A, Sharma S (2021) Condition based maintenance planning of low volume rural 568 roads using GIS. J Clean Prod 312(127649):569. https://doi.org/10.1016/J.JCLEPRO.2021.127649
16. Nautiyal A, Kumar A, Poddar A, Parajuli N (2021) Optimum transportation of relief materials aftermath the disaster. J Achiev Mater Manuf Eng 109(1).
17. Kumar A, Poddar A, Nautiyal A (2021) Urban transportation system problems in context of the Indian conditions. In: Belt and Road Webinar Series on Geotechnics, Energy and Environment. Springer, Singapore, pp 300–314. https://doi.org/10.1007/978-981-16-9963-4_24
18. Awasthi B, Raina SK, Verma L (2019) Epidemiological determinants of road traffic accidents in a largely rural hilly population. J Sci Soc 46(3):79
19. Gramsch E, Le Nir G, Araya M, Rubio MA, Moreno F, Oyola P (2013) Influence of large changes in public transportation (Transantiago) on the black carbon pollution near streets. Atmos Environ 65:153–163

Impact of Runway Configuration on Flight Delays

Dhanachand Thokchom and Aditya Kumar Tiwary

Abstract Flight delays have become a major complication for many airlines around the world. In order to reduce the complications like economic loss and customer satisfaction, analyzing the data and causes of flight delays is a must. This study focuses on runway configuration as a factor for flight delays. The paper will also briefly analyze the different types of runway configurations. The study will conduct a statistical two-way ANOVA test to test flight delay data of selected airports in the United States. Runway configuration and hub types are taken as independent variables and flight delay data as the dependent variable for the analysis. The two-way ANOVA result fallouts to reject all the null hypotheses meaning there is no significant level of interaction between runway configuration types, hub types, and the interaction between runway configuration and hub types. This research concludes that there is no need for any specific runway configuration in order to reduce flight delays. The study will also help in the development of new airports according to the findings of the study.

Keywords Flight delay · Runway configuration · ANOVA

1 Introduction

Runway configuration is the number of runways and their relative orientation on an airfield [1–3]. There may be one or more runways in an airfield, and they can be a combination of various basic runway configurations. There are four basic runway configurations. They are single runways, parallel runways, intersecting runways, and Open-V runways.

Flight delay is one of the most important indicators of the performance of any airline or transportation system [4, 5]. It is a global challenge in the aviation sector. As per the report of the US Bureau of Transportation (BTS), the ratio of flight delays

D. Thokchom (✉) · A. K. Tiwary
Department of Civil Engineering, Chandigarh University, Mohali, India
e-mail: dhanachandth@gmail.com

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increases from 14.69 to 20.8%. Some of the major known causes of flight delays are weather conditions, aircraft technical problems, disasters like a bird strike, etc. [6–8].

Delays in flight have many negative impacts on the airline, passengers, airports, and also on the whole transportation system. Huge economic loss is there when a flight is delayed. Penalties, fines, and restrictions can also be imposed if the airline is not punctual. Moreover, it also gives a bad impression to the passengers especially frequent flyers impacting the airline marketing strategies [5].

There is an increase in the number of flight delays globally. An airline passenger is presumed to arrive at their destination on time, and delays in flights account for most of the complaints by customers [1]. Aircraft can be late even if they touch down in time if they didn't arrive at the gate in time. This research is done to conduct research on whether runway configuration has any significant impact on flight delays. Data on flight delays of selected airports will be analyzed with respect to their runway configuration. It will help in bringing a better understanding of the relationship between runway configuration to flight delays.

1.1 Scope of Study

Passengers and airlines assume to depart and arrive at airports on time. Delayed flights cause a huge problem for airlines as well as for passengers. Bad weather conditions that cause most of the delays are unavoidable, but we need to see other factors as well. Although much past research has developed many algorithms and techniques for the Optimization of Runways and Optimal selection of runway configuration considering the total Traffic volume in Airport design, very little research has been done to find out whether there is any relation between the different types of runway configuration design and the actual flight delay data statistics. Using the ANOVA test, the study will help in finding out whether there is a need for any specific runway configuration in order to reduce flight delays.

2 Literature Review

Singh [9], express to find some architectural system to prevent runway incursion and conflicts. After analyzing the factor for flight delays due to incursion or collision on the runway, the paper proposes a combination of Ground Based Guidance System (GBGS) and Runway Automated Guidance System (RAGS) for better efficiency. This system will secure the runway for any runway configuration before clearance is issued for takeoff, landing, or crossing operations.

Staggered Approach Procedure (SGAP) and Steeper Approach Procedure (SAP) are two analytical models offered by [10] for calculating the maximum arrival departure and mix operation capacity for closely spaced parallel runways (SEAP). Frankfurt Airport (UK) and San Francisco International Airport (CA) are used as closely spaced runway examples for the two models (US).

Baranishyn [1], examine customer service and satisfaction in case of flight delays. The study concluded that flight delays give a negative impression to the customers. It also states that the authority fails to convey the reason for flight delays to the customer in a reasonable time. Airlines should always be vigilant of possible flight delays to reduce inconvenience to passengers.

Stiverson and Rathinam [11], study ways for optimal selection of runway configuration while designing an airport. As runway configuration greatly influences the capacity of the airport, the study presents a Mix of Integer Programming (MIP) to help in selecting optimal airport runway configuration and keeps a balance of arrival and departure. The Mix Integer Programming model is found to be very effective for single airports.

Stiverson and Rathinam [11], proposed a heuristics approach for managing runway queue problems. The paper addresses the problem of bottlenecks and queuing on the runway resulting in total delays of the aircraft. This paper proposed a Runway Quinces Management Problem (RQMP) for scheduling departing aircraft. It concluded that 3-opt and 4-opt heuristics outperformed 2-opt heuristics.

Oktal [12], developed a fresh numerical model for optimizing runway alignment. In contrast to the FAA's wind rise technique, the new Calculation of Optimum Runway Orientation (CORO) model uses the number of wind observations directly without grouping the wind velocities. The major purpose of the CORO model is to configure three different runway directions.

Haider et al. [13] discuss the idea of endless runway configuration. While the idea is not yet put into practical use, the test was conducted by US Navy and General Motors in the nineteenth century. The papers point out that the problem of increasing air traffic can be solved through circular runway configuration. The paper analyzes the possibility of having a circular runway at Jewar Airport Noida.

Carvalho et al [5], conducted a thorough study of data science's applicability to research on aircraft delays. The report highlights a thorough evaluation of the literature on several methods for looking at aircraft delays. It lists six key factors to consider while analyzing aircraft delays in the conclusion: arrival, departure, propagation, airline, airport, and air system.

Sternberg et al. [5], suggested a taxonomy to address problems related to flight delays. The taxonomy includes the domain (scope and problem) and data science (data and method) branches. The paper suggested various statistical analyses like regression analysis, correlation analysis, econometric models, etc. The paper concluded that delay prediction is a very important step in the process of decision-making for air transportation systems.

Cheung et al. [14], suggested using a dynamic slot allocation method as opposed to the fixed slots given to airlines, which frequently result in the slot over-or underutilization. The paper analyzes the airport performance for scheduling both segregated

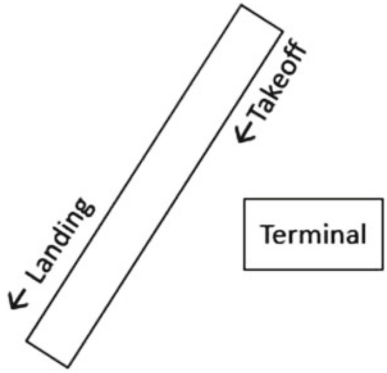

Fig. 1 Single runway configuration

and mixed-mode runway configuration operations. According to the study, multiple runway configurations with separated modes of operation can manage 20% more traffic.

Tan et al. [8], have thoroughly examined the spread of flight delays in China. According to the study, a 10-min arrival delay can result in a 7.49-min departure delay for the next flight. The study discovers that the Chinese Hub airport typically has smaller delay propagation when compared to the US market.

2.1 Runway Configuration

The four most common runway configurations are as follows. These include Single Runways, Parallel Runways, Intersecting Runways, and Open-V Runways [5, 15, 16]. According to their design, a lot of large airports combine the standard runway configuration.

2.1.1 Single Runway

A single runway is the simplest type of runway. They are mainly used for the non-Hub airport. It consists of only one runway, and it is used both for takeoff and landing. In ideal conditions, they can handle up to 100 flights in an hour [3]. A figure of a Single runway configuration is shown in Fig. 1.

2.1.2 Parallel Runway

A parallel runway consists of at least two or more runways configured in a parallel way. Generally, one runway is used for takeoff and another for landing [17, 18]. But both the runways can be used for takeoff and landing according to the conditions [3].

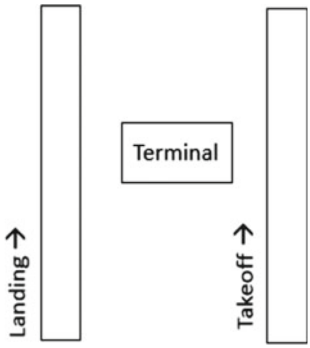

Fig. 2 Parallel runway configuration

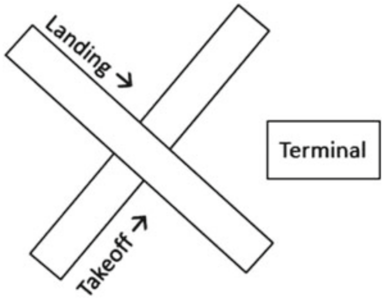

Fig. 3 Intersecting runway configuration

The runway capacity will increase greatly from a single runway, but there may be some negative impacts like the NAS delays. Researchers from the Netherlands are observing issues related to queueing for closely spaced runways [10]. A figure of a Parallel runway design is shown in Fig. 2.

2.1.3 Intersecting Runway

Intersecting runways are those runways that intersect each other at a point. The main reason for designing an intersecting runway is to tackle the challenges of strong winds [3]. It is also seen that runways that intersect near the end have higher capacity than those that intersect in the middle [19, 20]. A pictorial representation of Intersecting runway configuration is shown in Fig. 3.

2.1.4 Open V

Generally, Open-V runways consist of two runways that do not intersect each other but are oriented in different directions. They can be classified as Converging and Diverging Runways according to their use [3]. A pictorial view of how converging and diverging an Open-V runway works is shown in Fig. 4.

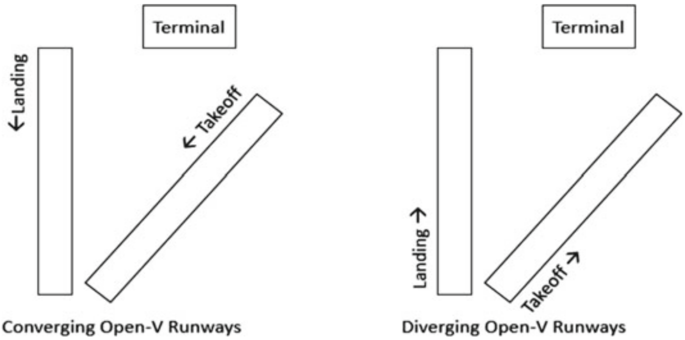

Fig. 4 Open-V runway configuration

2.2 *Analysis of Variance (ANOVA)*

By assessing a few populous approaches for commonly assigned records, analysis of variance (ANOVA) determines whether or not found variations across pattern approaches of quantitative records are statistically significant [21]. ANOVA can assist establish whether or not the means of numerous independent samples are statistically different. ANOVA tests come in a variety of forms, including one-way and two-way ANOVA.

A two-way ANOVA is used to examine the impact of two independent factors on a single dependent variable. There are three separate pairs of null and alternative hypotheses in this test. The effects of the first independent variable, the effects of the second independent variable, and the presence or absence of an interaction between the two independent variables are tested in turn in the first, second, and third analyses, respectively.

In contrast to a one-way ANOVA, a two-way ANOVA requires a second computation of the interaction between the two independent variables. Similar to one-way ANOVA, testing software is recommended. The p-value for each hypothesis is provided by the statistical analysis. Each p-value needs to be compared to an established alpha level, and the corresponding null hypothesis needs to be accepted or rejected, just as in a one-way ANOVA. Following the rejection of the null hypothesis, post hoc analysis can be used to identify the nature of the mean differences [21].

3 Methodology

The methodology used in this study consisted of the following steps:

(1) Survey and Data Collection
(2) Data Analysis.

3.1 Survey and Data Collection

A survey was done to determine the runway configuration of various airports in the USA. Airports will be selected having different runway configurations. 40 airports are selected having different runway configurations. After the selection of the airport, flight delay data for 2021 of the respective airport will be retrieved from the database of the Bureau of Transportation Statistics (BTS).

Runway Classification—As Airport design the runway configuration by combining the four basic types of runway configuration. We classify them as Single, Intersecting, Non-intersecting, and Combination. There is only one runway at a single-runway airport. Whenever there are two runways at an airport, it's crucial to make sure they don't intersect with one another. Runways at an airport are considered to be either "intersecting" or "non-intersecting" depending on whether or not they cross each other. Because of their similarity in layout and take-off/landing procedures, this research classified both Parallel and Open-V runways as non-intersecting. If the airport has more than two intersecting runways, then they are either classed as Intersecting or Combination Runways. In airports with more than two runways, if each and every runway crosses one another, they are classed as intersecting runways. The airport is referred to as a combined runway if one runway does not contact all other runways. This category includes airports that have both intersecting and non-intersecting runways because it is possible to operate in either classification if one or more runways are not in use at any given moment.

Hub Classification—Airports are divided into two categories: hub airports and non-hub airports. Hub airports consist of the airports that the FAA has categorized as primary, intermediate, and secondary hubs. Non-hub airports are still considered non-hub airports for the study. In order to distinguish delays at airports with varying traffic levels, each runway configuration is further divided into hub and non-hub airports.

Flight Delay Data of Selected Airports (from Bureau of Transportation Statistics—BTS)

The flight delay data of selected 40 airports of the year 2021 are tabulated below (Table 1).

The final airport category counts between subject factors are shown in Table 2. There are ten airports each for single, intersecting, non-intersecting, and combination runway configurations. When the data are classified according to their hub type, there are twenty airports under the hub and twenty airports under the non-hub category.

Table 1 Flight delay data

Airport	Runway Configuration	Hub type	Delay % (2021)
BLI/Bellingham International	Single	Hub	11.42
MDT/Harrisburg International	Single	Hub	15.47
SAN/San Diego International	Single	Hub	16.64
GSP/Greenville-Spartanburg International	Single	Hub	17.39
RSW/Southwest Florida international	Single	Hub	18.12
MFR/Rougue Valley International	Single	Non-hub	15.3
SAW/Sawer International	Single	Non-hub	17.75
BGR/Bangor International	Single	Non-hub	17.74
JAC/Jackson Hole	Single	Non-hub	17.42
CRW/Yeager	Single	Non-hub	13.94
LGA/LaGuardia	Intersecting	Hub	14.01
ALB/Albany International	Intersecting	Hub	20.32
PWM/Portland International Jetport	Intersecting	Hub	17.76
ORF/Norflok International	Intersecting	Hub	18.27
FNT/Bishop International	Intersecting	Hub	19.28
SGF/Springfield-Branson National	Intersecting	Non-hub	15.23
ABE/Lehigh Valley International	Intersecting	Non-hub	16.26
PIA/General Downing-Peoria International	Intersecting	Non-hub	20.97
SWF/Stewart International	Intersecting	Non-hub	27.49
GRB/Austin Straubel International	Intersecting	Non-hub	12.21
LAX/Los Angeles International	Non-intersecting	Hub	16.44
CLE/Cleaveland Hopkins International	Non-intersecting	Hub	19.38
IAH/George Bush Intercontinental	Non-intersecting	Hub	16.66
IAD/Washington Dulles International	Non-intersecting	Hub	15.89
SLC/Salt Lake City International	Non-intersecting	Hub	13.42
GPT/Gulfport-Biloxi International	Non-intersecting	Non-hub	13.31
MFE/McAllen Miller International	Non-intersecting	Non-hub	26.36
ROW/Roswell International Air Center	Non-intersecting	Non-hub	17.36
MLB/Melbourne International	Non-intersecting	Non-hub	11.09
BFL/Meadows Field	Non-intersecting	Non-hub	16.93
BNA/Nashville International	Combination	Hub	12.43
JFK/John F. Kennedy International	Combination	Hub	18.35
MIA/Miami International	Combination	Hub	18.15
CVG/Cincinnati International	Combination	Hub	18.67
ABQ/Albuquerque International Sunport	Combination	Hub	21.45

(continued)

Table 1 (continued)

Airport	Runway Configuration	Hub type	Delay % (2021)
HRL/Valley International	Combination	Non-hub	22.35
SBN/South Bend International	Combination	Non-hub	17.04
LAN/Capital Region International	Combination	non-hub	12.96
FWA/Fort Wayne International	Combination	Non-hub	16.73
SBA/Santa Barbara Municipal	Combination	Non-hub	18.01

Table 2 Final airport category count between subject factors

Details	Number	Value label	N
Runway configuration	1	Single	10
	2	Intersecting	10
	3	Non-Intersecting	10
	4	Combination	10
Hub type	1	Hub	20
	2	Non-Hub	20

3.2 Data Analysis

Statistical data analysis will be done for the data collected from the Bureau of Transportation Statistics. Two-Way ANOVA test will be done by taking Runway Configuration and Hub Classification as independent variables, and Flight delay data as the dependent variable. SPSS software is used for the analysis.

3.2.1 Hypothesis

H01: μ single = μ intersecting = μ non-intersecting = μ combination

Hα1: not all μ are equal.

H02: μ hub = μ non-hub

Hα2: not all μ are equal.

H03: There is no significant interaction between configuration and hub classification

Hα3: There is a significant interaction between configuration and hub classification.

3.2.2 Two-Way ANOVA Output

After the data were categorized, they were transferred into SPSS for statistical analysis. The two-way ANOVA test generated the descriptive data for the input and is shown in Table 3. The mean and standard deviations for each runway configuration and hub type are displayed in the descriptive statistics. The analysis of variance was conducted at 0.05 alpha levels.

The estimated marginal means of the delayed data were plotted in Fig. 5. They were plotted for each runway configuration with respect to their runway configuration. One line represents one runway configuration. If the lines are parallel or nearly parallel to each other, then they are assumed to have no significant interaction with one another. Although it is expected that lines that cross each other interact, further evidence is required to determine whether or not the interaction is meaningful. Since the lines are roughly parallel to one another, it can be seen from the graph that there is little interaction between the runway configurations. It is also seen that no lines cross each other meaning there is no significant interaction between the different types of runway configurations.

We plot the descriptive data in a bar graph with standard errors which are shown in Fig. 6. The graph is plotted for each runway configuration with blue bars representing the hub and orange bars representing the non-hub type. It is to observe whether the standard error bars overlap each other or not. If there is a huge difference between the standard error bars, then it is assumed to have significantly different data. In the graph shown below, it is seen that the data do not have significant differences from one another.

Table 3 Descriptive statistics for delay data

Runway configuration	Hub type	Mean	Std. deviation	N
Single	Hub	15.808	2.64145	5
	Non-Hub	16.43	1.72595	5
	Total	16.119	2.12895	10
Intersecting	Hub	17.928	2.40029	5
	Non-Hub	18.432	5.96181	5
	Total	18.18	4.2928	10
Non-intersecting	Hub	16.358	2.1261	5
	Non-Hub	17.01	5.83712	5
	Total	16.684	4.15574	10
Combination	Hub	17.81	3.29169	5
	Non-Hub	17.418	3.36025	5
	Total	17.614	3.14272	10
Total	Hub	16.4945	2.63172	20
	Non-Hub	17.1705	4.29695	20
	Total	16.8325	3.53363	40

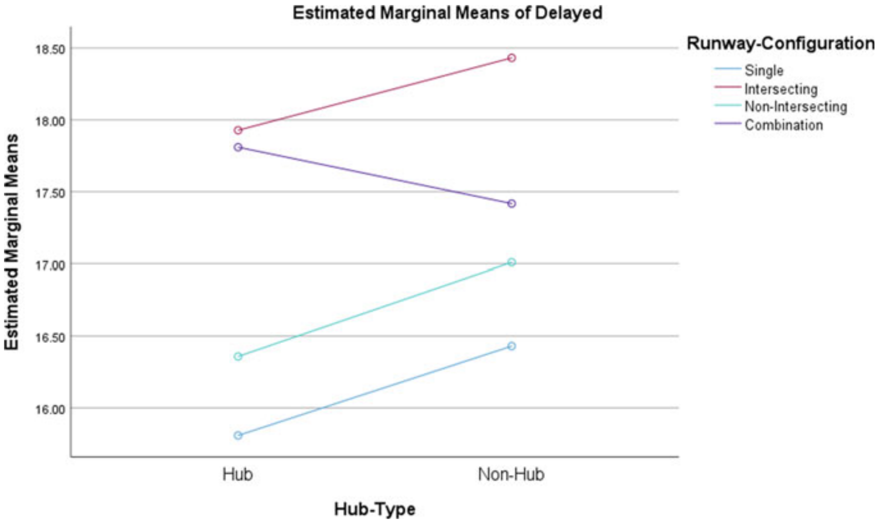

Fig. 5 Estimated marginal means plot of delayed data

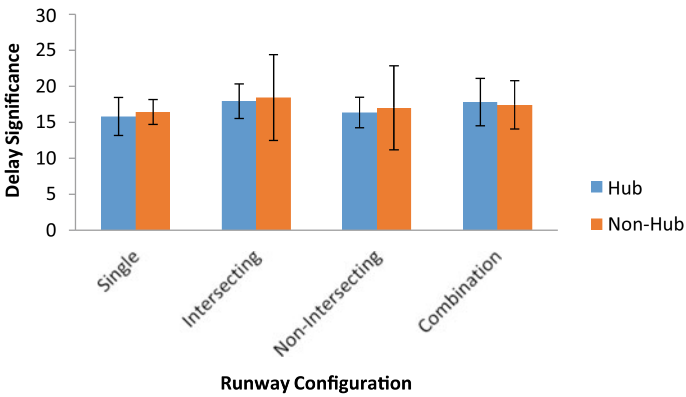

Fig. 6 Descriptive data chart

The two-way ANOVA results showing the significance level are tabulated in Table 4. While considering the first hypothesis, we get the significance level of $p = 0.614$. Considering the interaction between the Hub classification, we get the significance level of $p = 0.772$. Lastly, when we see the interaction between the different types of runway configuration and hub classification, we get a significance level of $p = 0.987$. The Analysis of Variance was conducted at 0.05 alpha level.

Table 4 Two-Way ANOVA output

Source	SS (sum of squares)	Df (degree of freedom)	MSE (mean square)	F	p-value (significance)
Runway	25.563	3	8.521	0.609	0.614
Hub	1.201	1	1.201	0.086	0.772
Runway*hub	1.849	3	0.616	0.044	0.987
Error	447.918	32	13.997		
Total	12,240.401	40			

4 Results and Discussions

The different possible runway layouts are the primary focus of the first set of null and alternate hypotheses. They look at how Single Runways, Intersecting Runways, Non-Intersecting Runways, and Combination Runways fare in terms of having roughly equal or unequal resources. The two-way ANOVA result had a p-value higher than the 0.05 alpha level, $F(3,32) = 0.609$, $p = 0.614$.

The hub kinds are the focus of the second set of null and alternative hypotheses. It examines whether or not the means between the hub and non-hub airports were equal. The two-way ANOVA result had a p-value higher than the 0.05 alpha level, $F(1,32) = 0.086$, $p = 0.772$.

The final set of null and alternative hypotheses is used to test the significance of a relationship between runway configuration and hub type. The two-way ANOVA had a p-value that was higher above the alpha level of 0.05, $F(3,40) = 0.044$, $p = 0.987$ (Table 5).

The three null hypotheses cannot be rejected because the two-way ANOVA for all three tests yielded p-values higher than the 0.05 alpha level. It is found that the two-way ANOVA at 0.05 alpha level has no significance between the runway configuration and flight delay percentage, $F(3,32) = 0.609$, $p = 0.614$. Additionally, neither the hub type interaction ($F(1,32) = 0.086$, $p = 0.772$) nor the hub type and runway classification interaction ($F(3,40) = 0.044$, $p = 0.987$) are statistically significant. No post hoc test was required because none of the three evaluated sources show significance at the 0.05 alpha level.

Table 5 Summary of two-way ANOVA results

Source	*Significance level (p-value)*	*Alpha level*	*Null hypothesis*	*Status*
Runway configuration	0.614	0.05	H01	Fail to reject
Hub Type	0.772	0.05	H02	Fail to reject
*Runway*Hub*	0.987	0.05	H03	Fail to reject

5 Conclusion

The study concluded that for constructing a new airport that is estimated to accommodate more than 10,000 passengers annually, no specific runway configuration plays a significant role in delays of flight. For reducing the number of flight delays as a whole, this research concludes that no further studies among the four types of runway configurations are needed as they all have an equal statistical mean. However, doing the same analysis by including data from various countries all over the world will give a better and more precise conclusion.

The concept of Circular runway configuration design may be adopted on a trial basis to see if it can reduce the number of aircraft delays. Delay as a whole needs to be further investigated across industries as there is a global increase in aircraft delays. It will help in finding out the causes and the solution to the problem.

References

1. Baranishyn M, Cudmore B, Fletcher T (2010) Customer service in the face of flight delays. J Vacat Mark 201–215
2. Bertsimas D, Frankovich M, Odoni A (2011) Optimal selection of airport runway configurations. Oper Res 59(6):1407–1419. https://doi.org/10.1287/opre.1110.0956
3. Horonjeff R, McKelvey F, Sproule W, Young S (2010) Planning and design of airports, 5th edn. McGraw Hill Professional
4. Bednarek JR (2001) America's airports: airfield development 1918–1947. Texas A&M University Press, College Station, TX
5. Carvalho L, Sternberg A, Maia Gonçalves L, Beatriz Cruz A, Soares JA, Brandão D, Carvalho D, Ogasawara E (2020) On the relevance of data science for flight delay research: a systematic review. Transp Rev 41(4):499–528. https://doi.org/10.1080/01441647.2020.1861123
6. Garber PE (1963) The history of flight. Ann N Y Acad Sci 107:464–469
7. Jia X, Chung D, Huang J, Petrilli M, The L (2004) ARO: Geographic information systems-based system for optimizing airport runway orientation. J Transp Eng 130(5):555–559. https://doi.org/10.1061/(asce)0733-947x(2004)130:5(555)
8. Tan X, Jia R, Yan J, Wang K, Bian L (2021) An exploratory analysis of flight delay propagation in China. J Air Transp Manag 92:102025. https://doi.org/10.1016/j.jairtraman.2021.102025
9. Singh G, Meier C (2004) Preventing runway incursions and conflicts. Aerosp Sci Technol 8(7):653–670. https://doi.org/10.1016/j.ast.2004.08.001
10. Janic M (2008) Modelling the capacity of closely-spaced parallel runways using innovative approach procedures. Transp Res Part C: Emerg Technol 16:704–730
11. Stiverson P, Rathinam S (2011) Heuristics for a runway-queue management problem. Proc Inst Mech Eng, Part G: J Aerosp Eng 225(5):481–499. https://doi.org/10.1177/09544100jaero871
12. Oktal H, Yildirim N (2014) New model for the optimization of runway orientation. J Transp Eng 140(3):04013020. https://doi.org/10.1061/(asce)te.1943-5436.0000637
13. Haider H, Rawat D, Jaysawal D (2018) Endless runway-orientation, design and calculations. Int J Res Eng Appl & Manag 04(03). https://doi.org/10.18231/2454-9150.2018.0336
14. Cheung W, Piplani R, Alam S, Bernard-Peyre L (2021) Dynamic capacity and variable runway configurations in airport slot allocation. Comput Ind Eng 159:107480. https://doi.org/10.1016/j.cie.2021.107480
15. Kazda T, Caves B (2010) Airport site selection and runway system orientation. Airpt Des Oper 45–68. https://doi.org/10.1108/9780080546438-003

16. Kennedy RJ (2015) Four runway configuration types and their relation to arrival delays. Open Access Theses 489. https://docs.lib.purdue.edu/open_access_theses/489
17. Yazdi MF, Kamel SR., Chabok SJ, Kheirabadi M (2020) Flight delay prediction based on deep learning and Levenberg-Marquart algorithm. J Big Data 7(1). https://doi.org/10.1186/s40537-020-00380-z
18. United States Department of Transportation (2019a) Air travel consumer report. Office of Aviation Enforcement and Proceedings, Washington D.C.
19. United States Department of Transportation (2019b) Bureau of transportation statistics. Understanding the Reporting of Causes of Flight Delays and Cancellations. http://www.rita.dot.gov/bts/help/aviation/html/understanding.html
20. United States Department of Transportation (2019c) Data and statistics. Office of the Assistant Secretary for Research and Technology. http://www.rita.dot.gov/bts/
21. Moore DS, McCabe GP, Craig BA (2014) Introduction to the practice of statistics, 8th edn. W.H. Freeman and Company, New York

Effects of Adding Polyethylene Terephthalate (PET) to Dense Bituminous Macadam Mixes Using the Dry Process

Mukesh Saini, Praveen Aggarwal, and Sunil Chouhan

Abstract This study looked at the mechanical characteristics of dense bituminous macadam mixtures that have been amended using waste plastic bottles (PET). Bitumen content was taken as 4.1–4.9% (with a 0.2% increment), and the amount of PET content was taken as 4–14% (with a 2% increment) of bitumen content. The quantity of bitumen content required for traditional mixes was 4.82%, whereas modified mixes require 4.50%. Reduction in optimum bitumen content and better rutting performance indicates that dense bituminous macadam mixes improve with the addition of PET. This technology is beneficial in an environmentally friendly way.

Keywords Dense bituminous macadam · PET · Mechanical properties

1 Introduction

Economic challenges and productivity constraints have been major issues for both developed and developing countries during the last two decades. To maintain economic competitiveness, manufacturers began to produce large trucks for delivering products, which increased the axle load on the pavement. Heavy vehicles are rising dramatically on roads as a result of regulations, and pavement life expectancy is decreasing. This main issue may be solved by utilising high-quality materials or employing more efficient construction techniques. With an increase in population,

M. Saini · S. Chouhan (✉)
Maharishi Markandeshwar Engineering College, Mullana, India
e-mail: chauhan954@gmail.com

M. Saini
e-mail: mukeshsaini512@mmumullana.org

P. Aggarwal
National Institute of Technology, Kurukshetra, India

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there will be an increase in the production of various waste items. Plastics, a daily used material, cause environmental problems after their usage.

Plastic trash has been identified as a severe concern and is being tackled in solid waste management. Waste plastics have a long life due to their non-biodegradable characteristics. Depending on the kind of waste plastic, an uncontrolled burning process produces a variety of dangerous air pollutants. Thermal treatment recycled the plastic in the second application, and each thermal treatment degrades the quality of the plastic to some extent [1–3]. The wet and dry methods are the two most common ways to utilise discarded plastic in road construction. Waste plastic is mixed with bitumen in the wet process, whereas aggregates are coated with waste plastic before being used in bituminous mixes in the dry process [4]. The kind and dosage of plastic used to impact the behaviour of asphalt mixes, and these attributes can be enhanced by employing the dry process. More intermolecular interaction behaviour of bitumen and plastic-coated aggregate improve strength, resulting in considerable improvement in bituminous mix quality [5–7]. The use of PET-coated aggregates in asphalt mixes improves fatigue resistance, which helps to improve the durability of pavements under severe loading conditions [8–10].

2 Experimental Work

2.1 Materials

2.1.1 Asphalt

Asphalt material of Grade VG30 was utilised in this investigation, which was procured from the IOCL Panipat Refinery (Haryana, India). Various engineering properties were determined as per Indian Standards as given below in Table 1.

Table 1 Asphalt properties

S. no	Properties	Measured value	Required as per IS:73-2013 [11]
1	Penetration value, mm [12]	53	Min. 45
2	Softening point °C [13]	49	Min. 47
3	Ductility value, mm [14]	58	Min. 40
4	Flash point, °C [15]	260	Min. 220
5	Specific gravity, °C [16]	1.01	–
6	Absolute viscosity, poises [17]	2980	2400–3600

Table 2 Characteristics of aggregates

S. no	Properties	Tests	Measured values	Specification
1	Cleanliness [18]	Grain size	0.60	Max. 5
2	Particle shape [18]	Flakiness and elongation indices	21.56%	Max. 35%
3	Strength [19]	Los Angeles Abrasion	23.45%	Max. 30%
		Aggregate impact	19.65%	Max. 24%
4	Durability [20]	Soundness: sodium sulphate	7.24%	Max. 12%
5	Water absorption [21]	Aggregate size		
		19.0 mm	0.74%	Max. 2%
		13.2 mm	0.87%	
		6.0 mm	0.97%	
6	Stripping [22]	Stripping test	Retained coating 96%	Retained coating 95% Min.
7	Density [21]	Specific gravity		
		19.0 mm	2.702	–
		13.2 mm	2.701	
		6.0 mm	2.680	
		Stone dust	2.596	

2.1.2 Aggregates

Characteristics of aggregate play an important role in the durability of roads. The study employed locally accessible aggregates from the Yamunanagar quarry of Haryana, India. Table 2 lists the aggregate characteristics as per the requirement of MoRT&H, 2013, specification.

2.1.3 Mineral Filler

According to the MoRT&H, 2013 standards [23], limestone of specific gravity 2.25 was used as mineral filler and grading as listed in Table 3 [24].

2.1.4 Modifier

The used waste plastic bottles (PET) were shredded into sizes 600 μ to 2.36 mm before being added to the mixture. The physical characteristics of PET are displayed in Table 4 [24].

Table 3 Grading of filler material

S. no	Sieve size (mm)	Cumulative percentage passing	
		Required	Adopted
1	0.6	100	100
2	0.3	95–100	97
3	0.075	85–100	88

Table 4 Physical characteristics of PET

S. no	Property	Value
1	Size	600 μ–2.36 mm
2	Density (gm/cc)	1.24
3	Melting temperature (°C)	170–180

3 Methods

3.1 Mould Preparation

The proportioning of materials affects the mechanical and volumetric properties of bituminous mixtures. As demonstrated in Table 5 and Fig. 1, the material proportioning for dense bituminous macadam (Grade-II) was carried out analytically in accordance with the MoRT&H, 2013, guidelines. A total of 1200 gm of material was used to cast the Marshall Specimens. Bitumen concentrations varied from 4.1 to 4.9% (with a 0.2% increment). Bitumen and aggregates were heated separately to 150 and 170 °C for conventional mixes, and modified mix coating of waste plastic was done on aggregates. Once the bitumen was suitably covered over the aggregates, filler material was added after the materials had been well mixed to create a homogenous mixture. Hydrated lime was added at the end of mixing to control the voids in the mixture. When the mixture was uniform and ready to be put into the Marshall mould, mixing continued at 160 °C. Seventy-five hammer blows were used to compact the mould in the Marshall Compaction pedestal. The sample was inverted after being compacted with the same number of blows on the opposite side. The collar and base plate were removed after compaction. The specimen was extruded using a sample extractor after cooling to room temperature. Figure 2 displays the prepared samples.

3.2 Marshall Stability Test

The Marshall Stability Test [25] is a widely used method for determining optimum bitumen content. The stability value is determined by the specimen's maximum load at 60 °C. Prior to being submerged for 30 min in a 60 °C water bath, Marshall Mould

Table 5 Aggregate proportioning for dense bituminous macadam (grade-II) mix

Sieve size (mm)	Cumulative percentage passing by weight of total aggregate passing					Gradation		
	Designation					Specifications for GRADing, MoRT&H, 2013		Observed grading (30:23:10:35:02)
	Aggregates			Stone dust	Lime			
	19 mm	13.2 mm	6.0 mm			Range	Mean	
37.5	100.0	100.0	100.0	100.0	100.0	100	100	100.0
26.5	100.0	100.0	100.0	100.0	100.0	90–100	95	100
19.0	80.4	100.0	100.0	100.0	100.0	71–95	83	94
13.2	8.6	97.4	100.0	100.0	100.0	56–80	68	72
4.75	0.0	11.9	92.3	95.4	100.0	38–54	46	47
2.36	0.0	1.4	8.1	82.1	100.0	28–42	35	32
0.300	0.0	0.0	1.8	46.4	100.0	7–21	14	18
0.075	0.0	0.0	0.6	7.8	88.0	2–8	5	3

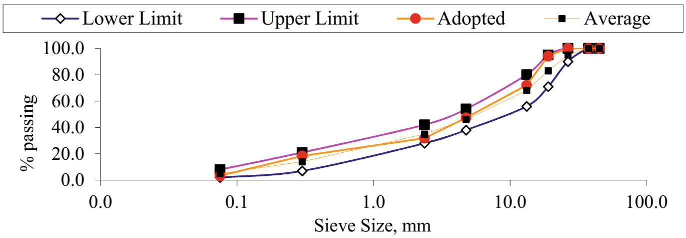

Fig. 1 Dense bituminous macadam mix gradation

Fig. 2 Prepared Marshall mould

was weighed in both air and water. Strain control loading was applied to the specimen as shown in Fig. 3, and the data collection system noted the stability value.

Fig. 3 Marshall loading frame for stability test

3.3 Retained Stability Test

The effect of water on bituminous mixes may be evaluated by knowing its retained stability value. Retained stability values of conventional and modified mixes were determined as per the given formula:

$$\text{Retained Stability (\%)} = \frac{\text{Marshall Stability for Condition Specimen (24 h at 60°C)}}{\text{Marshall Stability un-condition Specimen (30 min at 60°C)}} \times 100$$

3.4 Indirect Tensile Strength Test

Bituminous mixes are evaluated for their tensile qualities using their ITS value. Unconditioned samples were cast in accordance with the AASHTO T283 specification [26] and evaluated using Eq. 1:

$$ITS = \frac{2Pmax}{\pi td} \tag{1}$$

Pmax = Max. Load (N), t = Specimen thickness (cm), d = Specimen Diameter (cm).

3.5 Wheel Tracking Test

The ability of asphalt mixes to resist rutting is crucial in determining how long a pavement will last. Casting was done on slabs that were 300 × 300 × 50 mm in size at optimum bitumen content for rutting performance. The wheel rut shaper was used to manage the voids with eight passes applied at 6.5 kg/cm^2 pressure, and the wheel rut tester equipment was employed to maintain 0.7 MPa pressure. Using AASHTO T324 [27] specifications for 20,000 passes/repetitions, the rutting performance of conventional and modified bituminous macadam mixes in wet and dry circumstances at 50 °C was evaluated.

4 Results

4.1 Marshall Stability, Flow, and Marshall Quotient Properties

Marshall Stability value of modified mixtures increases up to 10% PET concentration and thereafter drops (Fig. 4). Up to 10% PET content, modified mixtures resulted in greater adhesion between the components. Modified mixes are attributed to fatigue cracking owing to increased stiffness up to 10% PET content, according to the flow value indicated in Fig. 5. Modified bituminous mixes with a higher Marshall Quotient (Fig. 6) satisfy the requirement of the stiff bituminous mix.

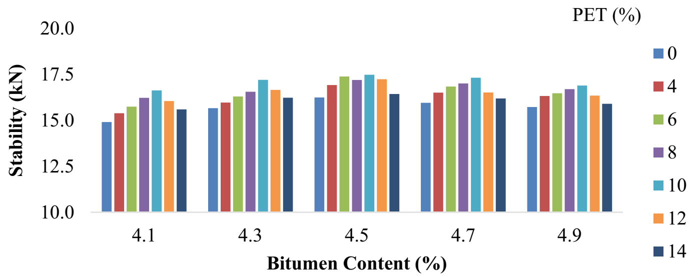

Fig. 4 Marshall stability versus PET content

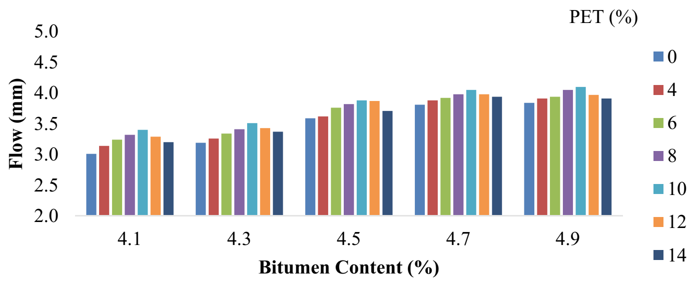

Fig. 5 Flow value versus PET content

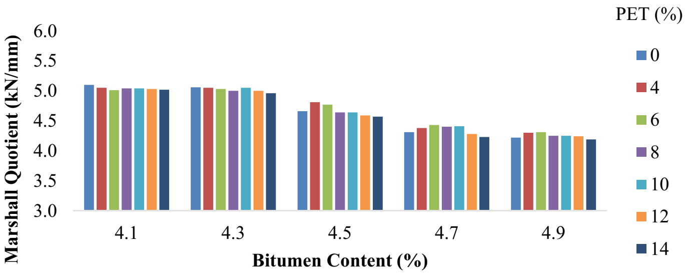

Fig. 6 Marshall quotient versus PET content

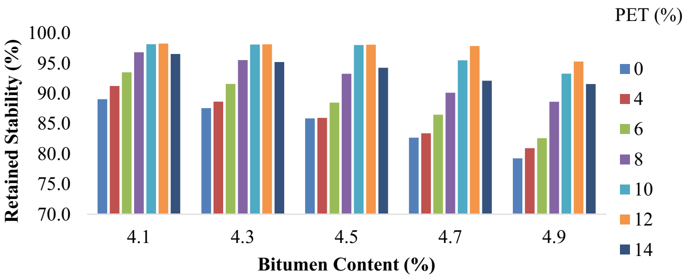

Fig. 7 Retained stability versus PET content

4.2 Retained Stability

An increase in retained stability up to 12% PET content as shown in Fig. 7 indicates that PET content improves the adhesion between aggregate and bitumen. Dense bituminous macadam mixes coated with PET improve the durability of pavement in water-logged areas due to more water resistance properties.

4.3 Indirect Tensile Strength

Tensile strain behaviour of dense bituminous macadam mixes improves up to 10% PET content (Fig. 8). As a result, these improved mixtures may tolerate substantially higher tensile loads before cracking.

4.4 Optimum Bitumen Content

The properties of a bituminous mix are met when the bitumen content is optimal. Optimum bitumen content for conventional mixes was found to be 4.82%, whereas

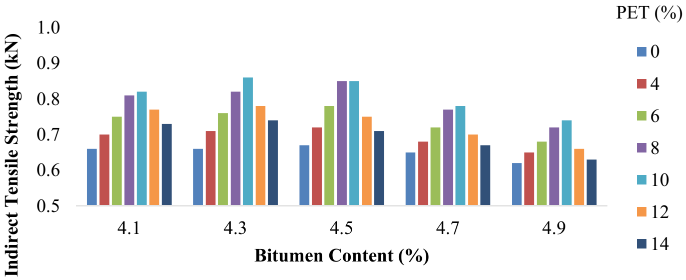

Fig. 8 Indirect tensile strength versus PET content

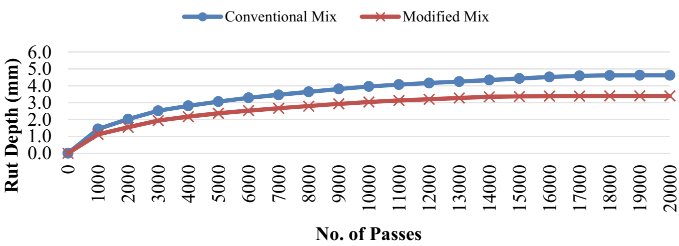

Fig. 9 Rutting (dry condition)

4.50% at 10% PET content for modified mixes. Thus, a 6.64% reduction in optimum bitumen content shows improvement in the volumetric and mechanical properties of modified dense bituminous macadam mixes.

4.5 Rutting Performance

Rutting occurs in flexible pavements due to over consolidation. It is caused by a build-up of irreversible deformations caused by repeatedly applying enormous loads, lateral displacement due to shear failure of the layer, or a combination of the two. Rutting behaviours of conventional and modified mixes at optimum bitumen content as shown in Figs. 9 and 10 indicate that resistance against rutting of conventional mixes improves with the addition of PET.

5 Conclusions

The goal of this study was to see how dense bituminous macadam mixtures (G-II) would react when polyethylene terephthalate was added using a dry process. The mechanical properties required for an ideal bituminous mix were assessed. Marshall

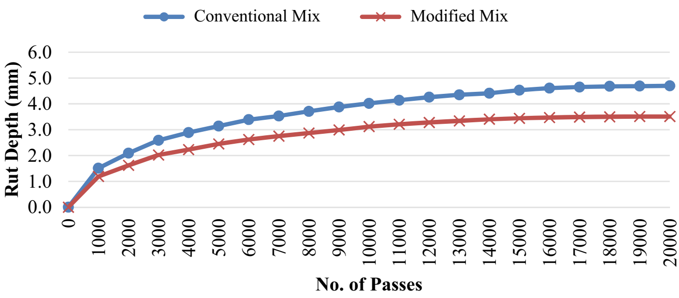

Fig. 10 Rutting (wet condition)

Stability has improved up to 10% PET concentration, and the stability of modified mixtures demonstrates higher adherence. The flow value of modified mixes increased up to a dose of PET 10% and decreases after that due to improvement in stiffness. Marshall Quotient of the modified mixture is higher which fulfils the condition of stiff bituminous mixes. Higher retained stability of modified mixes increases the durability of flexible pavement, especially in water-logged areas. With the addition of PET to DBM mixes, the quantity of optimum bitumen content was lowered to 6.64 per cent. When compared to traditional mixes, the rutting performance of modified DBM mixes is superior. Hence, for safe disposal of non-biodegradable waste plastic, this technique is helpful for better durability of pavement along with an environmentally friendly solution.

References

1. Prasad KVR, Mahendra SP, Kumar NS, Rakesh SG, Vijay V, Likith T, Yogesh BP (2013) Study on utilization of waste plastic in bituminous mixes for road construction. In: Proceedings of the international conference on futuristic innovations and developments in civil engineering, pp 198–203
2. Ranadive MS, Hadole HP, Padamwar SV (2018) Performance of stone matrix asphalt and asphaltic concrete using modifiers. J Mater Civ Eng 30(1):1–9
3. IRC: SP: 98 (2013) Guidelines for the use of waste plastic in hot bituminous mixes (dry process) in wearing courses, 1st ed. Indian Road Congress, New Delhi, India
4. Sangita, KhanTA, Sabina, Sharma DK (2011) Effect of waste polymer modifier on the properties of bituminous concrete mixes. Constr Build Mater 25:3841–3848
5. Ahmadinia E, Zargar M, Karim MR, Abdelaziz M, Shafig P (2011) Using waste plastic bottles as additive for stone mastic asphalt. Constr Build Mater 32:4844–4849
6. Ahmadinia E, Zargar M, Karim MR, Abdelaziz M, Ahmadinia E (2012) Performance evaluation of utilization of waste polyethylene terephthalate (PET) in stone mastic asphalt. Constr Build Mater 36:984–989
7. Bindu CS, Beena KS (2010) Waste plastic as a stabilizing additive in stone mastic asphalt. Int J Eng Technol 2(6):379–387
8. Modarres A, Hamidreza HH (2014) Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes. Constr Build Mater 61:8–15

9. Rahman WMNWA, Wahab AFAW (2013) Green pavement using recycled polyethylene terephthalate (PET) as partial fine aggregate replacement in modified asphalt. Constr Build Mater 53:124–128
10. Shankar AUR, Lekha BM, Sarang G, Abhishek P (2014) Performance and fatigue behaviour of semi dense bituminous concrete using waste plastics as modifier. Indian Highways 42(7):17–26
11. IS: 73 (1992) Paving bitumen specification, 2nd ed. Bureau of Indian Standards, New Delhi, India
12. IS: 1203 (1978) Determination of penetration, 1st revision. Bureau of Indian Standards, New Delhi, India
13. IS: 1205 (1978) Determination of softening point, 1st revision. Bureau of Indian Standards, New Delhi, India
14. IS: 1208 (1978) Determination of ductility, 1st revision. Bureau of Indian Standards, New Delhi, India
15. IS: 1209 (1978) Determination of flash point and fire point, 1st revision. Bureau of Indian Standards, New Delhi, India
16. IS: 1202 (1978) Determination of specific gravity, 1st revision. Bureau of Indian Standards, New Delhi, India
17. IS: 1206 (1978) Determination of viscosity, 1st revision. Bureau of Indian Standards, New Delhi, India
18. IS: 2386 (1963) Methods of test of aggregates for concrete, Part-1, particle size and shape, 1st ed. Bureau of Indian Standards, New Delhi, India
19. IS: 2386 (1963) Methods of test of aggregates for concrete, Part-4, Los Angles Abrasion value and aggregate impact value, 1st ed. Bureau of Indian Standards, New Delhi, India
20. IS: 2386 (1963) Methods of test of aggregates for concrete, Part-5, soundness, 1st ed. Bureau of Indian Standards, New Delhi, India
21. IS: 2386 (1963) Methods of test of aggregates for concrete, Part-3, water absorption, 1st ed. Bureau of Indian Standards, New Delhi, India
22. IS: 6241 (1971) Method of test for determination of stripping value of road aggregates. Bureau of Indian Standards, New Delhi, India
23. MoRT&H: (Ministry of Road Transport and Highways) (2013) Specification for road and bridge works. Indian Roads Congress, V - Revision, New Delhi, India
24. Saini M, Aggarwal P, Chauhan S (2019) Behaviour of bituminous concrete mixes with addition of waste plastic bottle via dry process. Int J Innov Technol Explor Eng (IJITEE) (2):732–736, ISSN: 2278-3075
25. ASTM D-1559 (2004) Test for resistance to plastic flow of bituminous mixture using Marshall apparatus. American Society for Testing Materials
26. AASHTO: T283 (2014) Resistance of compacted bituminous mixture to moisture induced damage. American Association of State Highway and Transportation Officials, Washington, USA
27. AASHTO T324 (2017) Standard method of test for Hamburg wheel-track testing of compacted asphalt mixtures. American Association of State Highway and Transportation Officials, Washington, USA

Numerical Parametric Study on Time-Dependent Response of Geocell-Reinforced Flexible Pavements

Anjana R. Menon and Anjana Bhasi

Abstract Flexible pavements on weak soil are prone to longitudinal cracking and rut formation on the surface. Geocell-reinforced granular layers offer enhanced load distribution and restrict settlement on the pavement under regular vehicular traffic. An intensive parametric study was done to assess the degree of impact of various factors on the time-dependent behavior of flexible pavement with a geocell-reinforced granular base. Parameters analyzed include stiffness and aspect ratio of geocell, frictional characteristics of the granular layer, and subgrade shear strength. The independent effect of each influential parameter on the mechanism of load transfer was analyzed using three-dimensional modeling incorporating the actual honeycomb shape of the geocell. The load transfer mechanism in a geocell is most affected by the tensile stiffness of geosynthetic material and the aspect ratio of the cellular pocket. While the effect of the wide slab mechanism is affected by the strength characteristics of all pavement layers, including fill friction, subgrade cohesion, and geosynthetic stiffness, the membrane effect is dependent purely on the strength and aspect ratio of the geocell. The aspect ratio close to unity is desirable for efficient and uniform stress transfer through Geocell walls.

Keywords Geocell · Honeycomb shape · Repetitive loading · Parametric study · Load transfer mechanism

1 Introduction

Geocells are becoming increasingly popular among civil engineers worldwide due to their versatile applications and ease of installation. Some of the significant fields of application of geocell reinforcement include foundations, embankments, retaining

A. R. Menon (✉) · A. Bhasi
NIT, Calicut, Kerala, India
e-mail: anjana5193@gmail.com

A. Bhasi
e-mail: anjanabhasi@nitc.ac.in

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walls, pavements, and slope stability [1–3]. The load transfer mechanism of geocell involves two principles: membrane action and wide slab mechanism. The membrane action of the geocell is contributed by the vertical component of shear strength mobilized by the geocell walls upon external loading, owing to the resistance of the membrane to bending action [2, 4]. The wide slab mechanism, also called the vertical stress dispersion effect, arises due to the increased rigidity of the geocell-soil composite. The rigid slab-like structure formed by the geocell-infill composite increases the load dispersion angle through the geocell layer, thus increasing the effective stress distribution area on the underlying subgrade [2, 5]. Gedela et al. [6] studied the load dispersion mechanism of geocell-reinforced foundations and analyzed the influence of various factors on the degree of improvement using digital imaging techniques. The significant factors influential in geocell-reinforced systems' behavior include the geocell's strength, geometry, and characteristics of the host soil material in which the geocell is embedded [7–9]. Flexible pavements on soft subgrades demand a reinforcement mechanism to reduce the imbibed stress on the subgrade. Geocell-reinforced granular layer helps in subgrade stress reduction and provides a rigid undulating platform that mitigates settlement-induced cracking on the surface, thus increasing the pavement's service life [10]. The conventional design based on Burmister's layer theory can be modified to incorporate the effect of geocell reinforcement. It is assumed that the geocell reinforcement improves the elastic modulus of the granular layer by a factor that is quantified based on infill strength, subgrade strength, and position of the geocell [11]. In the last few decades, natural geotextiles are gaining popularity in several applications including pavements [12]. But the long-term feasibility can be assured only by using suitable surface treatment to enhance the durability of the fibers [13, 14]. It is to be noted that the initial cost of geosynthetic reinforced pavements is inevitably higher than the unreinforced case due to the additional material cost. However, the reduced maintenance cost owing to increased durability and possible reduction in design layer thickness can compensate for this, in the life cycle assessment. However, there are minimal studies on the time-dependent response of Geocell-reinforced flexible pavements. Since pavements are designed for 5–10 years, and the load is dynamic, the time-dependent response of pavement is significant. Considering various influential factors, the dependence rate on each factor is vital in optimizing the design to suit the field conditions. In the present study, the degree of impact of several influential factors on the Time-dependent behavior of geocell-reinforced flexible pavement is assessed using three-dimensional modeling. The actual curvature of honeycomb-shaped pockets is traced from the scaled-down specimen for accurate simulation of the load transfer mechanism [15]. The effect on wide slab mechanism and membrane effect is analyzed separately about time to provide guidelines for geocell-reinforced flexible pavement design.

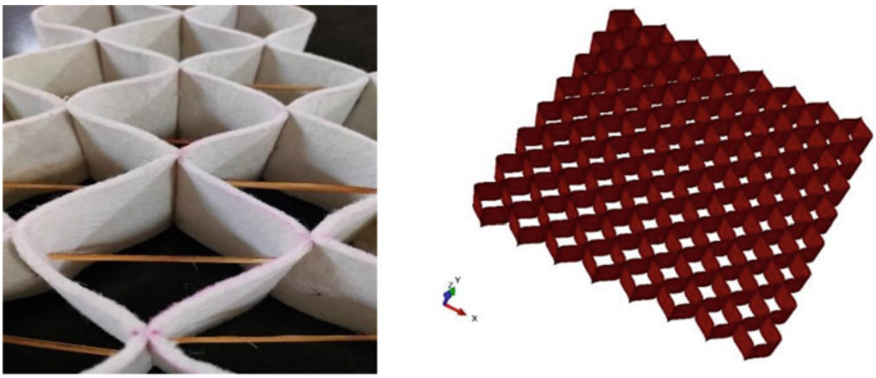
2 Materials and Methods

A three-dimensional model of a hypothetical pavement section is developed using the finite element package ABAQUS [16]. The model details and analysis procedure are explained in the subsequent sections.

2.1 Model Geometry and Loading

Basic model geometry: The analysis is performed on a 5 m wide stretch of pavement laid on a soft subgrade overlain by a granular base layer of 0.7 m thickness and surface asphalt course 0.1 m thick. The base is reinforced using Geocell, having a pocket opening size of 0.5 m. To trace the geocell dimensions, a scaled-down specimen was manufactured using a polypropylene-based non-woven geotextile procured from Geodukan [17]. The honeycomb-shaped pockets were developed by stitching the geotextile material in a transverse direction at regular intervals. The coordinates of a single pocket were carefully traced and replicated using ABAQUS to generate the model of the geocell network. Figure 1 shows the laboratory prototype and numerical model of the geocell adopted in the study. The properties of materials used in the basic model are listed in Table 1.

Loading and boundary conditions: Repetitive wheel loads are the most frequent loads on flexible pavement, and pavement response depends on the wheel configuration and traffic intensity. For the present study, cumulative traffic of 100 MSA is considered, and the pavement thickness is based on respective guidelines by IRC [18]. Table 2 shows the wheel configurations and loading characteristics adopted for



(a) (b)

Fig. 1 Geocell used in the study: **a** laboratory prototype and **b** numerical model

Table 1 Material properties used in the basic model

Parameter	Infill material (B)	Subgrade (S)	Geocell (G)
Density (kg/m^3)	1470	1450	200
Friction angle (°)	39	5	–
Elastic modulus (kPa)	57,900	10,600	3.3×10^7
Cohesion (kPa)	–	120	–
Height (m)	0.7	–	0.2

the model analysis. The tire configuration and contact pressure were adopted from Continental Tires [19].

Figure 2 shows the actual elliptical contact area of a wheel and the equivalent rectangular contact area adopted in the model [21]. Each wheel load was applied for a time of 0.01 s and repeated for 1000 continuous cycles. The subgrade bottom was restrained against all movements, whereas the lateral boundaries of the section were assigned roller boundaries to permit vertical deformation alone.

Mesh characteristics: The subgrade and granular base were assumed to behave in a linearly elastic-perfectly plastic manner adopting the Mohr–Coulomb failure criterion. In contrast, the behavior of the asphalt layer and geosynthetic reinforcement

Table 2 Loading characteristics used in the analysis [20]

Characteristic	Value
Traffic (MSA)	100
Wheel load (kN)	40
Contact pressure (kPa)	595
Tire dimensions (length × width) (m)	0.22 × 0.15
Axle distance (m)	1.5

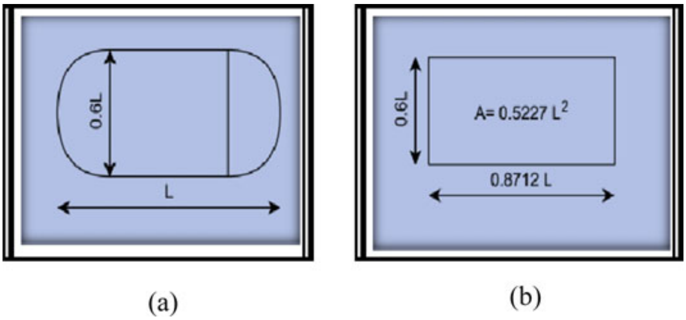


Fig. 2 Wheel contact area: **a** actual elliptical area and **b** equivalent rectangular area [15]

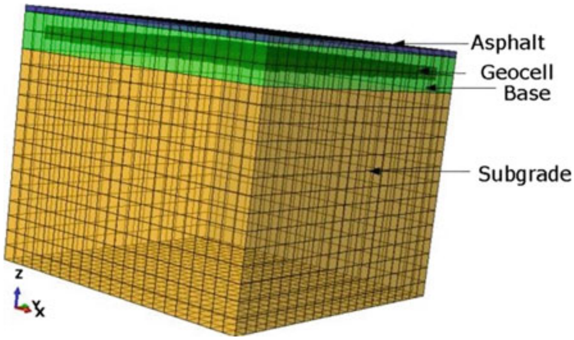


Fig. 3 Numerical model used in the analysis

were assumed to be linear elastic. The pavement layers were modeled as three-dimensional 8-noded linear brick elements with reduced integration (C3D8R). The continuum stress elements are chosen to depict the continuous stress deformation response under loading. The Geocell was modeled using three-dimensional 4-noded membrane elements with reduced integration. (M3D4R). Membrane elements offer zero resistance to bending, thus ideal for simulating the behavior of geosynthetic material. While the geocell, embedded in the granular layer, was assigned hard contact without separation, the different pavement layers were connected using general contact with zero slip and zero separation conditions. Figure 3 shows the profile of the model.

2.2 Parametric Study

Geocell-reinforced soil is a complex system dependent on many factors like subgrade characteristics, base material, and the strength and geometry of geocell. In the present study, the time-dependent response of geocell-reinforced flexible pavement is analyzed by varying the properties of infill material, subgrade, and geocell. The basic model is developed using the material attributes listed in Table 1. For the parametric studies, each parameter was varied at a time to assess the independent effect of individual factors. It is to be mentioned that while varying a fundamental property like the density of fill material, the associated properties like friction angle and elastic modulus vary. Hence, the complete set of properties of the material was varied in each trial for accurate simulation of the modified material characteristics, as summarized in Table 3. It is to be noted that, unlike the conventional studies on reinforced pavements, reduction in thickness is not analyzed in the study because a minimum thickness of 0.7 m is required for embedding the geocell of height 0.5 m. Instead, the study presents the variation in the degree of improvement in stress transfer and deformation under various geocell configurations and material characteristics. The material characteristics are assumed to be constant throughout the analysis. However, the effect of each parameter on the response of the material is analyzed in terms of the stress deformation response of individual layers.

The height of the geocell varied from 0.5 m to 0.4 m and 0.2 m, mentioned as High (H), Medium (M), and Low (L), respectively. For each height, the influence of each material—Subgrade, Geocell, and Base—was studied by varying one factor at a time, as indicated by the trial name in Table 4.

The material properties of infill material and subgrade are based on laboratory tests. The whole set of analyses was repeated for different geocell heights, 0.2 m, 0.4 m, and 0.5 m (Fig. 4) for a comprehensive assessment of the impact of the aspect ratio of the geocell.

Table 3 Summary of parameters analyzed in the study

Parameter	Infill material			Subgrade			Geocell		
Trial	B_1	B_2	B_3	S_1	S_2	S_3	G_1	G_2	G_3
Density (kg/m$^{3)}$	1470	1296	415	1200	1450	1980	80	200	250
Friction angle (°)	42	39	20	–	–	–	–	–	–
Elastic modulus (MPa)	59	37	83.3	9.6	10.6	14.5	1×10^4	3×10^4	5×10^4
Cohesion (kPa)	–	–	–	80	120	240	–	–	–

Table 4 Summary of model analysis

Geocell height (m)	Low (L) h = 0.2	Medium (M) h = 0.4	High (H) h = 0.5
Trial name	LB_1SG	MB_1SG	HB_1SG
	LB_2SG	MB_2SG	HB_2SG
	LB_3SG	MB_3SG	HB_3SG
	$LBSG_1$	$MBSG_1$	$HBSG_1$
	$LBSG_2$	$MBSG_2$	$HBSG_2$
	$LBSG_3$	$MBSG_3$	$HBSG_3$
	LBS_1G	MBS_1G	HBS_1G
	LBS_2G	MBS_2G	HBS_2G
	LBS_3G	MBS_3G	HBS_3G

L—Low; M—Medium; H—High; B—Base; S—Subgrade; G—Geocell

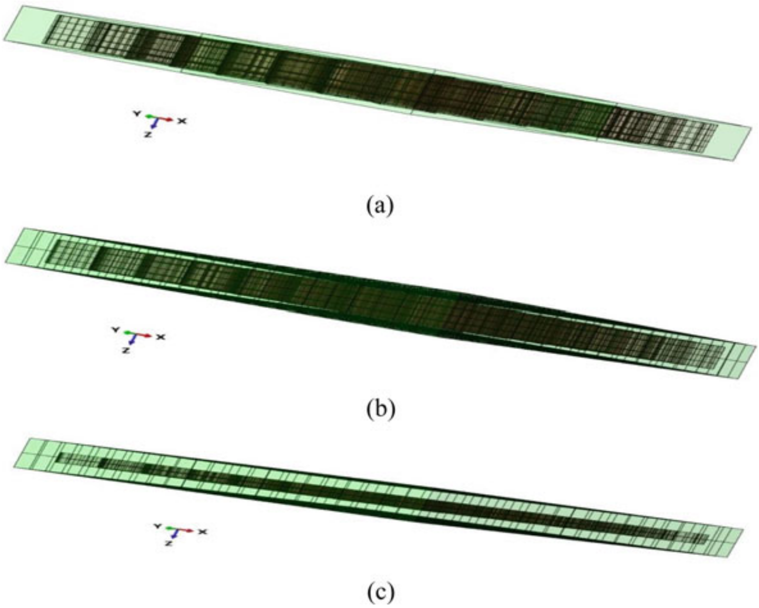


Fig. 4 Geocell of height: **a** 0.5 m-H, **b** 0.4 m-M, and **c** 0.2 m-L

3 Results and Discussion

The time-dependent behavior of flexible pavement is analyzed concerning the two primary mechanisms of load transfer in geocell-wide slab effect and membrane action. The wide slab effect refers to the rigid slab-like action of soil-geocell composite that widens the load dispersion angle, which is reflected in the stress on the underlying subgrade. The membrane action pertains to the tensile stress mobilized on the surface, enabling the membrane to take up a proportion of the imposed load. Each performance aspect is assessed under three different aspect ratios of geocell for the effect of various influential factors like base material properties, stiffness of reinforcement, the strength of subgrade, and height of geocell. In addition, the deformation at the wearing surface and geocell walls after 1000 cycles of loading are also portrayed for geocell reinforcement of various heights.

3.1 Deformation of Subgrade

The deformation characteristics of the subgrade are depicted using maximum vertical strain developed at the surface of the subgrade over time.

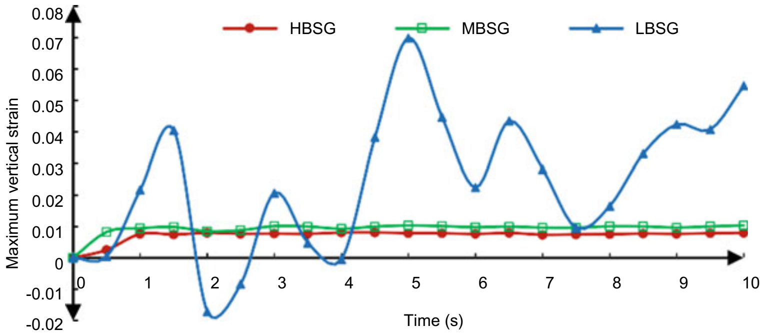


Fig. 5 Effect of the height of geocell on subgrade deformation

Effect of the height of geocell: Fig. 5 presents the effect of the height of the geocell on the time-dependent variation of maximum vertical strain developed at the subgrade. At medium and high wall heights, the maximum vertical strain developed remains nearly constant over time, slightly increasing with a decrease in wall height. However, for a low wall height of 0.2 m, there is a severe fluctuation of vertical strain, and the average strain value is much higher. With an aspect ratio as low as 0.4, the wide slab mechanism is not much efficient since the low walls fail to form a rigid mat. Hence, the efficiency of the geocell is insignificant. The slab action comes into effect at an aspect ratio of 0.8, with the strain almost uniform after the initial loading cycles. The strain further decreases when the aspect ratio becomes unity and remains stable after about 100 cycles of loading. However, considering the meager variation in strain levels, an optimum aspect ratio of 0.8 can be adopted in practice.

Effect of base material characteristics: Fig. 6a–c shows the effect of base material characteristics on maximum vertical strain developed at the subgrade surface over time for the pavement section with High, Medium, and Low-height geocell, respectively. It can be seen that for denser base material with high friction angle, the maximum strain is less. With an increase in friction, the interface friction characteristics also improve, leading to a rigid soil-geocell composite compared to the loose fill with low friction angle. Notably, the deformation profile is undulating in the case of low-height geocell. When the height of the geocell is too low compared to the depth of the embedded layer, the slab action is negligible. As a result, there is less uniformity in the magnitude of stress transferred to the subgrade and the resultant deformation.

Effect of stiffness of geocell: Fig. 7a–c shows the effect of geosynthetic stiffness on maximum vertical strain developed at the subgrade surface over time for the pavement section with High, Medium, and Low-height geocell, respectively. In all cases, the vertical strain on the subgrade is the minimum for the stiffest reinforcement and vice versa. The shear stress mobilized on the reinforcement is proportional to the axial stiffness of the material, thus reflected in the stress transferred to the subgrade and the resultant deformation. The trend aligns with the fact that the immediate settlement

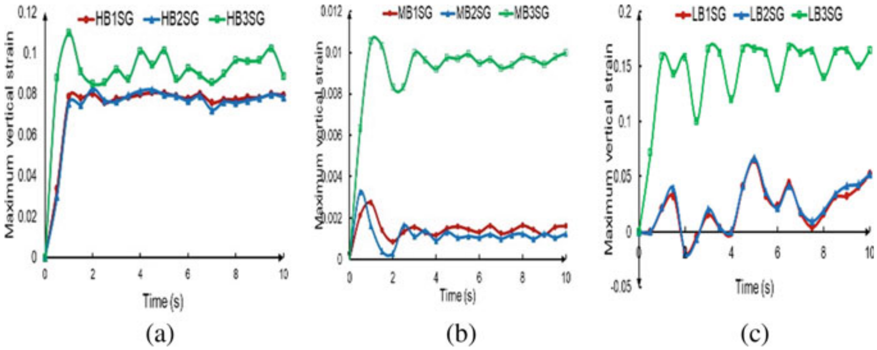


Fig. 6 Effect of granular base properties on subgrade deformation for **a** high, **b** medium, and **c** low geocell heights

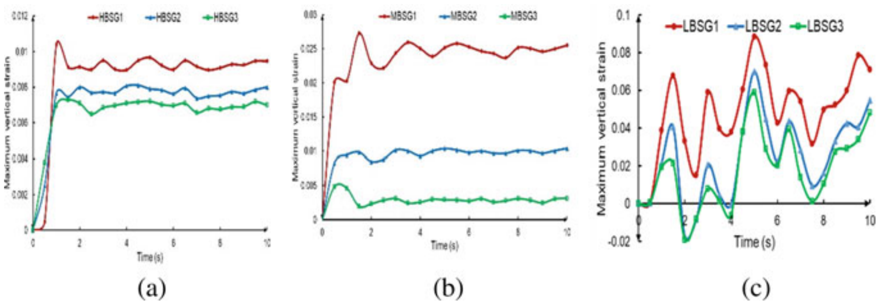


Fig. 7 Effect of stiffness of geocell on subgrade deformation for **a** high, **b** medium, and **c** low geocell heights

of cohesive soil is inversely proportional to the Elastic modulus, an indicator of the material's frictional characteristics. The undulations in the case of Low geocell again reflect the inefficiency of low wall height in the stress transfer.

Effect of subgrade strength: The effect of subgrade strength on maximum vertical strain developed at the subgrade surface over time for the pavement section with High, Medium, and Low-height geocell is shown in Fig. 8a–c, respectively. The magnitude of deformation is inversely proportional to subgrade cohesion, but the pattern is seen to be unaffected. The deformation pattern indicates that the subgrade settles at the first load cycle and remains uniform.

3.2 Surface Deformation

Figure 9 shows the surface deformation after 1000 cycles of loading for various types of geocell reinforcement. Though the pattern is similar, the improved performance

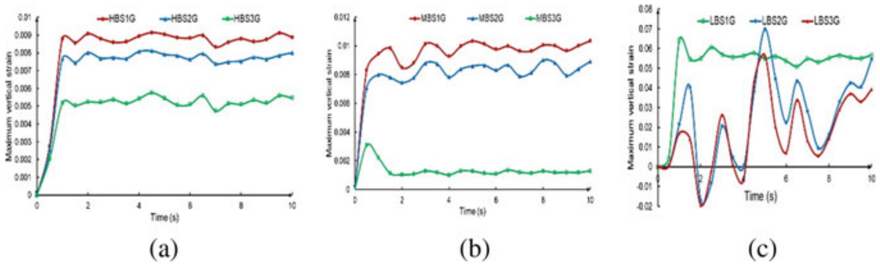


Fig. 8 Effect of subgrade strength on subgrade deformation for **a** high, **b** medium, and **c** low geocell heights

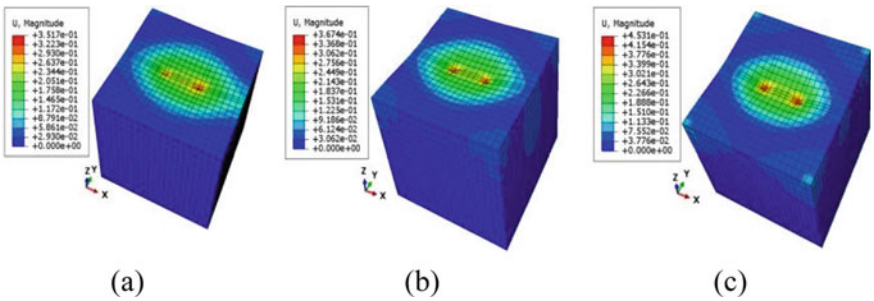


Fig. 9 Surface deformation after 1000 cycles of loading for **a** high, **b** medium, and **c** low geocell heights

of the High wall geocell is reflected in the magnitude of deformation at the wearing surface.

3.3 Membrane Action of Geocell

Membrane action is one of the major load transfer mechanisms in a geosynthetic reinforcement. It refers to the shear strength mobilized on the surface of the geosynthetic upon loading. The membrane develops tensile stress, which helps it to take up the imposed stress. In this study, the influence of various parameters on membrane action is analyzed in terms of the shear stress mobilized on the geocell walls.

Effect of height of geocell: Fig. 10 presents the effect of the wall height of the geocell on the maximum shear stress developed on the geocell.

The membrane action is found to be directly related to the geometry. The increase in the wall height of the geocell elevates the effective area contributing to the tensioned membrane action, which is reflected as higher shear stress on the membrane. However, the pattern of stress remains unaffected.

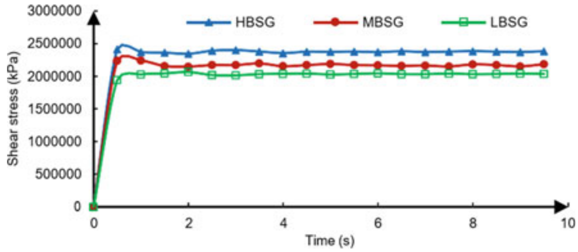


Fig. 10 Effect of the height of geocell on shear strength mobilized on geosynthetic

Effect of the base material characteristics: The influence of granular base material characteristics on the shear stress mobilized in the geocell is shown in Fig. 11a–c for High, Medium, and Low-height geocells, respectively. It is noted that the membrane action is not much affected by the frictional characteristics of base material, albeit with a slight increase in shear stress. Similar observations have been cited by previous studies indicating the insignificant effect of infill material on the behavior of geocell-reinforced soil [5]. The shear strength mobilized is higher when the wall height is 0.5 m, as summarized in Fig. 12.

Effect of stiffness of geocell: The axial stiffness of the material is a factor that directly impacts the membrane action. The higher the stiffness, the higher the shear stress mobilized on the material's surface, as shown in Fig. 12a–c. The increase in stiffness of the material indicates higher resistance to load-induced deformation. In other words, shear stress developed on the material against induced deformation is higher for a stiffer material.

Effect of subgrade strength: Subgrade characteristics significantly impact geocell membrane action, as indicated by Fig. 13a–c. The geosynthetic reinforcement is placed in the overlying granular layer. Hence, the stress developed on the membrane due to external load is unaffected by the underlying soil characteristics.

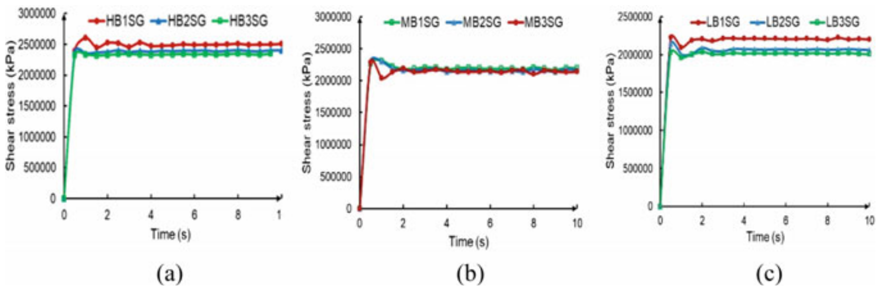


Fig. 11 Effect of properties of the granular base on shear strength mobilized on geosynthetic for **a** high, **b** medium, and **c** low geocell heights

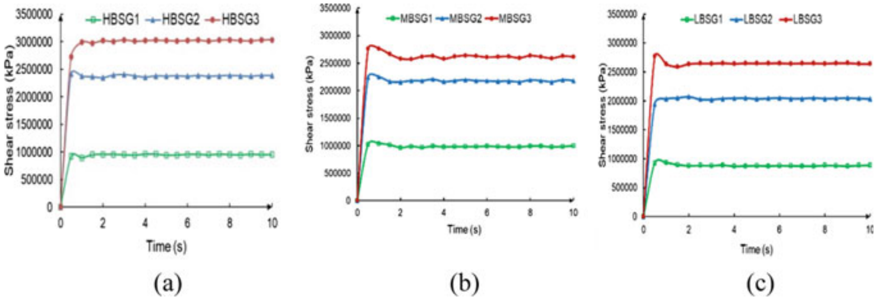


Fig. 12 Effect of stiffness of reinforcement on shear strength mobilized on geosynthetic for **a** high, **b** medium, and **c** low geocell heights

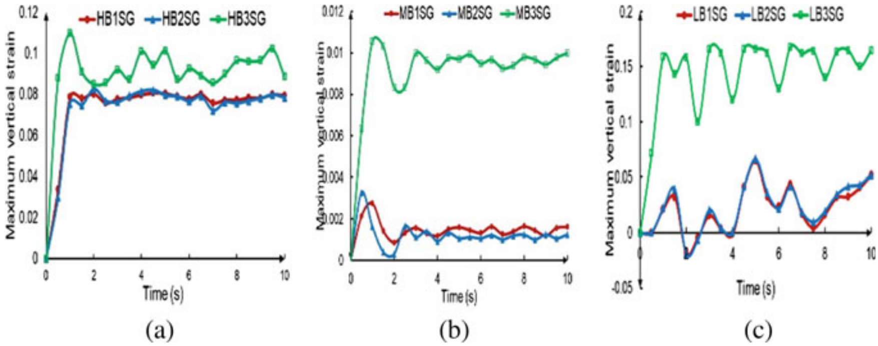


Fig. 13 Effect of subgrade strength on shear strength mobilized on geosynthetic for **a** high, **b** medium, and **c** low geocell heights

3.4 Deformation of Geocell Walls

The deformation pattern of geocell walls indicates the extent of membrane stress developed on the walls. It can be seen that even if the stiffness of the geosynthetic is the same, the deformation magnitude is higher for the low-height geocell, indicating the significance of the aspect ratio of the geocell, which refers to the height-to-diameter ratio of the pockets. For a wall height of 0.2 m, the aspect ratio is as low as 0.4. The overall rigidity of the walls is less in this case, which is reflected as excessive deformation (Fig. 14).

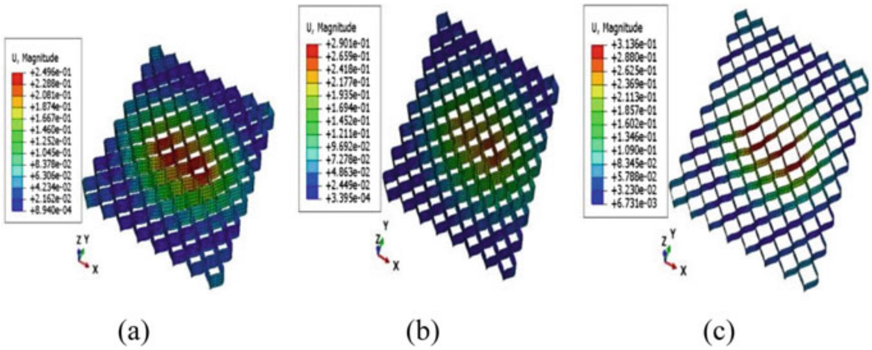


Fig. 14 Deformation of geocell after 1000 cycles of loading for **a** high, **b** medium, and **c** low geocell heights

4 Conclusions

Three-dimensional models of a flexible pavement section with geocell-reinforced granular base were assessed for time-dependent response under a standard repetitive wheel load. The effect of material characteristics and geocell geometry on the geocell-reinforced layer's two primary load transfer mechanisms, namely the wide slab action and the membrane effect, was analyzed over time. The observations lead to the following conclusions:

- The wide slab mechanism of geocell reinforcement helps the uniform load transfer to a broader area toward the subgrade, reflected in the subgrade deformation pattern. The maximum vertical strain in the subgrade varies inversely with friction angle and density of granular base material.
- The strain fluctuation with time is high for geocell with a low aspect ratio. As the aspect ratio approaches unity, the strain variation over time is negligible. Considering economy and efficiency, a minimum aspect ratio of 0.8 can be adopted in practice. Furthermore, the load transfer mechanism is not much affected by the characteristics of the infill material.
- The increase in geosynthetic stiffness and subgrade cohesion improves the stress response of the subgrade, the degree of impact being proportional to the height of the geocell wall. A soft subgrade suffers a higher immediate settlement, with the elastic expansion being lower than that of a stiff subgrade.
- The membrane action is observed to be purely a function of the stiffness and geometry of the geosynthetic material. It is independent of the characteristics of pavement layers, either the subbase or the subgrade. The maximum shear stress developed is low for the low axial stiffness of the geocell and is unaffected by the aspect ratio of the geocell. As the geosynthetic stiffness increases, the slab action is more effective, and the performance is a function of the aspect ratio of the geocell.

- The deformation of geocell walls and the surface deformation are a function of the aspect ratio of the geocell. An optimum height-to-diameter ratio of 0.8 is desirable for uniform deformation and stress transfer.

5 Scope for Future Studies

- The present study is focused on the effect of various internal factors, mainly material characteristics and geometry, on the time-dependent response of geocell-reinforced pavements. Considering the minimum thickness of the granular layer for embedding the geocell, the reduction in design thickness is not included. Thus, a cost analysis is irrelevant in this research and hence excluded. However, the study's findings can be used for a comprehensive analysis of the life cycle assessment of geocell-reinforced pavements in the future.
- The study's findings can be incorporated into the design methodology considering the effect of various parameters analyzed in this article. The modified design extended to field studies is vital in assessing the practical implications of geocell-reinforced pavements.

References

1. Vibhoosha MP, Bhasi A, Nayak S (2021) A review on the design, applications, and numerical modeling of geocell reinforced soil. Geotech Geol Eng 39(6):4035–4057. https://doi.org/10.1007/s10706-021-01774-3
2. Hegde A (2017) Geocell reinforced foundation beds-past findings, present trends, and future prospects: a state-of-the-art review. Constr Build Mater 154:658–674. https://doi.org/10.1016/j.conbuildmat.2017.07.230
3. Mamatha KH, Dinesh SV (2019) Performance evaluation of geocell-reinforced pavements. Int J Geotech 13(3):277–286. https://doi.org/10.1080/19386362.2017.1343988
4. Zhang L, Zhao M, Shi C, Zhao H (2010) Bearing capacity of geocell reinforcement in embankment engineering. Geotext Geomembr 28(5):475–482. https://doi.org/10.1016/j.geotexmem.2009.12.011
5. Menon AR, Konnur S, Bhasi A (2021) Model tests on coir geotextile-encased stone columns with tyre crumb-infilled basal coir geocell. Int J Geosynth Ground Eng 7(2):1–13. https://doi.org/10.1007/s40891-021-00274-x
6. Gedela R, Kalla S, Sudarsanan N, Karpurapu R (2021) Assessment of load distribution mechanism in geocell reinforced foundation beds using digital imaging correlation techniques. Transp Geotech 31:100664. https://doi.org/10.1016/j.trgeo.2021.100664
7. Choudhary AK, Dash SK (2021) Influence of soil density on performance of geocell-reinforced vertical anchor in sand. Geosynth Int 28(4):338–349. https://doi.org/10.1680/jgein.20.00047
8. Kabiri Kouchaksaraei M, Bagherzadeh Khalkhali A (2020) The effect of geocell dimensions and layout on the strength properties of reinforced soil. SN Appl Sci 2(10):1–13. https://doi.org/10.1007/s42452-020-03480-w
9. Jayamohan J, Aparna S, Sasikumar A (2019) Influence of properties of infill material on the behaviour of geocells. In: Ground improvement techniques and geosynthetics. Springer, Singapore, pp 57–66. https://doi.org/10.1007/978-981-13-0559-7_7

10. George AM, Banerjee A, Puppala AJ, Saladhi M (2021) Performance evaluation of geocell-reinforced reclaimed asphalt pavement (RAP) bases in flexible pavements. Int J Pavement Eng 22(2):181–191. https://doi.org/10.1080/10298436.2019.1587437
11. Saride S, Baadiga R, Balunaini U, Madhira MR (2022) Modulus improvement factor-based design coefficients for geogrid-and geocell-reinforced bases. J Transp Eng Part B: Pavements 148(3):04022037. https://doi.org/10.1061/JPEODX.0000380
12. Kumar N, Kandasami RK, Singh S (2022) Effective utilization of natural fibres (coir and jute) for sustainable low-volume rural road construction–a critical review. Constr Build Mater 347:128606. https://doi.org/10.1016/j.conbuildmat.2022.128606
13. Ghosh M, Saha R, Das M (2021) Application of jute-polypropylene blended geotextile in black cotton soil subgrade for low volume road construction. Int J Geosynth Ground Eng 7(3):1–8. https://doi.org/10.1007/s40891-021-00316-4
14. Jiniraj RB, Jayasree PK, Anusha SP (2022) Effect of surface modification on the performance of natural fibres—a review. Ground Improv Reinf Soil Struct 609–615. https://doi.org/10.1007/978-981-16-1831-4_54
15. Hegde AM, Sitharam TG (2015) Three-dimensional numerical analysis of geocell-reinforced soft clay beds by considering the actual geometry of geocell pockets. Can Geotech J 52(9):1396–1407. https://doi.org/10.1139/cgj-2014-0387
16. Simulia (2016) Abaqus/CAE user's manual. Version 6.14
17. http://geodukan.in/
18. IRC:37 (2018) Guidelines for the design of flexible pavements, Indian roads congress, New Delhi pp, pp 19–37
19. https://www.continental-tires.com
20. Arvin MR, Rezaei E, Bahmani Shoorijeh M (2018) Numerical evaluation of geocell-reinforced flexible pavements under traffic loads. Sci Iran 25(2):493–504. https://doi.org/10.24200/sci.2017.4191
21. Huang YH (2004) Pavement analysis and design. Pearson Prentice Hall, Inc. Upper Saddle River, NJ 07458, pp 8–530

Intelligent Accident Rescue System

Vishant Kumar, Sandesh Tyagi, Sakshi Garg, and Deepti Mehrotra

Abstract Vehicles on roads are increasing day by at a very fast pace. This increase in vehicles has also increased the number of road accidents. Every year, an average of 150,000 people die due to accidents in India. Therefore, it is necessary to evaluate such scenarios where first aid and rescue can be provided at the accident site or the breakdown site at the earliest. In this paper, we have proposed a solution for situations where rescue is needed. We have taken the scenario of school buses as nowadays school buses get late in reaching school due to traffic jams, road accidents, etc. A network of school buses has been created in which if the drivers or the passengers get to know about the traffic jams ahead on the road, then the driver can take another path and reach on time or in case of bus breakdown, the driver or the passengers can send the signal to the other nearby bus drivers for rescue. This has been established using the OMNet++ tool using the SIoV concept. The results obtained are promising with a fully deployed functional network that is capable of providing help to the victim node at the earliest.

Keywords V2V · SIoV · Intelligent rescue system · RSU · OBU

1 Introduction

As the world is changing day by day, people are focusing more and more on Internet of Things (IoT). Today, we see everything is getting smarter. We see smart homes, smart cities [1], and many smart devices which make things easier and smarter. Vehicles are also getting smarter day by day with the help of Internet of Vehicles (IoV) [2]. IoV vehicles are equipped with sensors and other technologies which help connect with other vehicles to transfer or receive data. We see many accidents occurring on roads due to a lack of concentration of drivers; the cars get off the roads and crash. If a vehicle has an early warning system, these types of crashes can be avoided. There

V. Kumar (✉) · S. Tyagi · S. Garg · D. Mehrotra
Amity University, Noida, India
e-mail: vishant683@gmail.com

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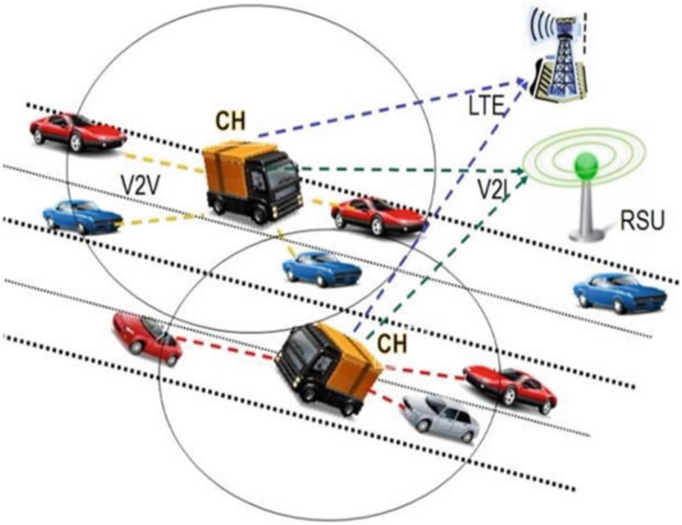


Fig. 1 SIoV

could be a situation in which one vehicle is stuck in traffic. In such cases with the assistance of V2V communication, the vehicle which is stuck in traffic can inform other vehicles to go for a different route as in Fig. 1.

From IoV, SIoV [1] came into the picture. In SIoV [3], the vehicles that are having common interests are socially connected with each other. In SIoV, vehicles connected with each other share information of common interest like vacant parking places, weather conditions, traffic information, etc. An instance of SIoV [4] considers a scenario where an ambulance carrying a patient is moving towards a hospital. Now while moving, it connects with other ambulances to know the traffic condition on the way to the hospital so if traffic is there the ambulance gets notified earlier and then it can change the route. SIoV does not just socialize or connect vehicles, it also connects the driver or passengers. Sensors are also attached to the vehicles which show information about the vehicles like whether the vehicle is working fine or not to the driver or the passengers. Our major contributions to this study are as follows: first, to provide a system which can effectively rescue an accidental vehicle. Second, a system which is multipurpose or can be used in many domains like ambulance, defence, school buses management, etc., and last, to get real-time traffic information and inform other connected vehicles.

The paper is further organized as Sect. 2 which is the literature review, and Sect. 3 is the methodology applied in the paper. Section 4 is the data analysis and results, and Sect. 5 is the conclusion.

2 Literature Review

SIoV is a new technology and the recent work done in this field was explored to identify the gap. It is given in Table 1.

Table 1 SIoV overview

S. No	Author	Application	Tools and Protocol used	Differences	Year
1.	Atzor et al. [5]	This paper tells us about the implementation of social internet of vehicles using cloud and virtualization techniques	Utilizes Intelligent Transportation System Station engineering (ITS SA) using Bluetooth 802.11p and Wi-Fi	It is different from our paper in a way that it does not make use of any simulator such as SUMO or NS3. It primarily focuses on implementing Social Internet of Vehicles using cloud and virtualization techniques	2018
2.	Abbas et al. [6]	Gives another street-mindful steering plan for Internet of vehicles by computing the assessed way ter	Used SUMO and NS3 simulator with IARAR protocol	This is different from our paper in a way that it emphasizes factors affecting the Internet of Vehicles (IoV) but we have focused on energy consumption. It also makes use of the IARAR protocol but in our paper, we have used TCP/IP and UDP protocol	2019
3.	Zia et al. [7]	This paper gives a specialist-based model of a suggested framework with cutting-edge SIOV	Uses the NetLogo which is created in an agent-based environment	It basically focuses more on an agent-based model. It does not even talk about the security of the model. Here, we discussed more of the security issues and the ways in which one can tackle them to prevent any piece of information from being exploited	2019

(continued)

Table 1 (continued)

S. No	Author	Application	Tools and Protocol used	Differences	Year
4.	Zang et al. [8]	MDTCS data transmission algorithm was given in this paper which is based on single-to-noise ratio	Uses MDTCS algorithm and the ISing model	This paper is different from our paper in a way as it focuses more on the data transmission. It highlights the challenges to guarantee the steadiness of information transmission because of quick organization geography changes, high information transmission deferrals and a few different reasons	2020
5.	Vershinin and Zhan [9]	The following paper mentions the security consciousness of the vehicle-to-vehicle dedicated short-range communication	Uses the MATLAB tool for simulation and works on RSA algorithm	This paper does talk about the security issues in vehicle-to-vehicle to communication but in our paper, we have attempted to involve better recreation programming for fostering the security execution of the DSRC	2020
6.	Arooj et al. [10]	In this review, they proposed the cross space, incorporated and examined the key elements to address different related viewpoints to diminish the intricacy among heterogeneous information sources	Makes use of OMNeT++ and the SUMO tool	This paper focuses more on the Internet of Vehicles, but we have focused more on SIOV, a subdomain of IOV	2020

3 Methodology

It is studied that there are very few studies that have discussed SIoV concerning emergency situations. Since no system is available which can provide rescue in emergency situations, our basic idea is to develop an artificial environment to test such situations and develop a system using SIoV which can provide emergency support and can be useful in many domains like Defence, Ambulance, and school buses. To develop an artificial environment, we have used SUMO and OMNet++ and we have analysed data collected from OMNet++. Also, Python script has been used to filter the data and generate graphs for further data analysis. Fig. 2 also gives a flow of the methodology.

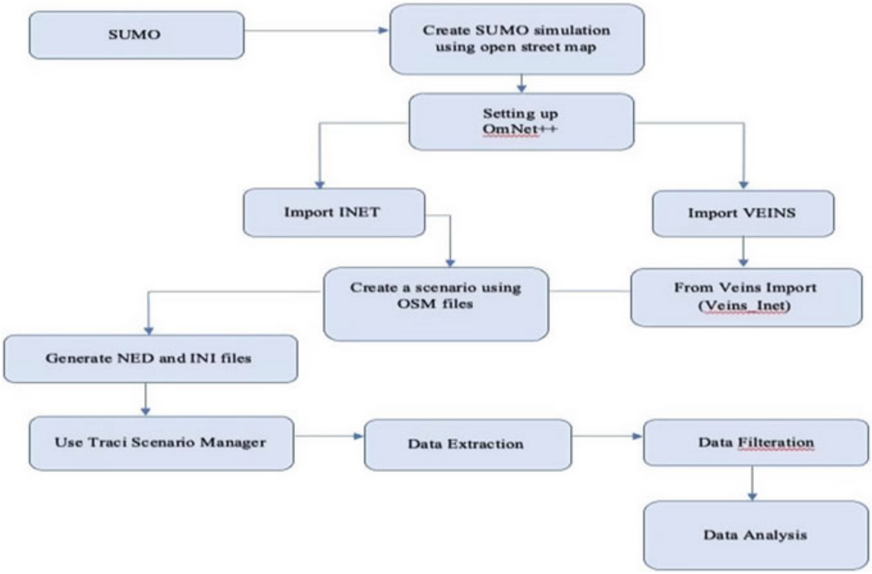


Fig. 2 Flowchart for this work

3.1 Sumo Simulation Details

For making connectivity between school buses and vehicles, Simulation of Urban Mobility (SUMO) is used. SUMO permits displaying of intermodal traffic frameworks including street vehicles, public vehicles, and people on foot. In this, we have created a real-time traffic scenario. For the network scenario, we have to use SUMO open street map (OSM) feature to create a real-time network scenario of Noida Sec 125 near Amity University Noida.

Setting up OMNet++: We imported the SUMO OSM file in OMNet++ to display a real-life situation. For making a V2V interface simulation and for a better picture of the network, Veins is used which is an open-source network simulation framework for running vehicular-based projects which can offer unrestricted extensibility. OMNeT++, an extensible modular and compound-based C++ simulation library and framework for building network simulators, supports a variety of frameworks such as INET and Veins for vehicle-to-vehicle communication (V2V). It supports TCP/UDP protocol.

3.2 Data Extraction

Below here, it can be seen that in OMNeT++ simulation, the map that we've fetched from SUMO is working perfectly fine and vehicles are moving on roads. The portion

Table 2 Dataset parameters

Parameters	Definition
Total distance	The total distance refers to the actual distance between the origin and destination locations of the substance
Total CO_2 emission	Total CO_2 emission is basically the data of total CO_2 emitted by vehicles. Stop time: stop time is the time at which the vehicle stopped. Start time: start time is basically the time the vehicles have started moving
Total lost packet	The total distance refers to the actual distance between the origin and destination locations of the substance
SNIR lost packets	Total CO_2 emission is basically the data of total CO_2 emitted by vehicles. Stop time: stop time is the time at which the vehicle stopped. Start time: start time is basically the time the vehicles have started moving

below the map shows the data like which vehicle is moving in which lane, etc. Time is also previously set for vehicles moving on the road. As we can see in the data shown below the map, the vehicles move every 124 ms.

Datasets. The dataset below shows us the following details as explained in Table 2.

The formula for the same is given below

$$\text{SNIR} = \text{Signal Power}/(\text{Noise} + \text{Interference power}) \tag{1}$$

3.3 Data Filtration

Data filtration is done to remove the multiple fields and any null values in the dataset that weren't necessary for the study like CO_2 emissions, etc. For this, a Python script is created to filter out the data and a code is written and implemented based on Python inbuilt libraries to create various graphs using Python script.

4 Data Analysis and Results

Data analysis is used to extract meaningful information from data and make decisions based on that knowledge. Analysing our past or future and making judgments based on it is what this is all about. After the deployment of the network over the simulation tool, we could establish a socially connected network where in case of an accident the nearby accessible active nodes can provide aid. So, during simulation we observed that nodes 68 and 70 had an accident. So, they reached out for help to other nodes in the network. We can see from the simulation that an accident took place between node 70 and node 67. Now if we see below that, node 70 is sending a signal to all other nodes that are there within seconds. Similarly, if two accidents occur then the nodes are capable to send a signal to other nodes or vehicles simultaneously.

After doing the analysis of nodes, we've created a graph which shows the SNIR packet loss for different nodes for node 70 and node 68 as in Figs. 3 and 4, respectively. The broadcast messages for node 68 and node 70 are shown in Figs. 5 and 6, respectively. These figures show a graph for node 68 and node 70 SNIR lost packet for different datasets like 130 nodes, 145 nodes, 160 nodes, 180 nodes, and 200 nodes.

Broadcast devices are simple messages from other apps or the system itself. These signals are referred to as events or intents on occasion. For example, applications can send out broadcasts to inform other apps that data has been downloaded to the device and is ready for them to use; the broadcast receiver will intercept this communication and take the required action.

Fig. 3 Node 70 SNIR packet loss

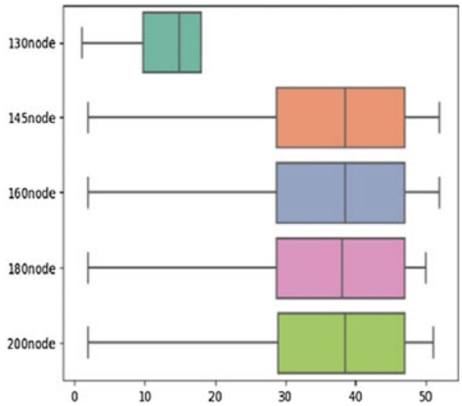
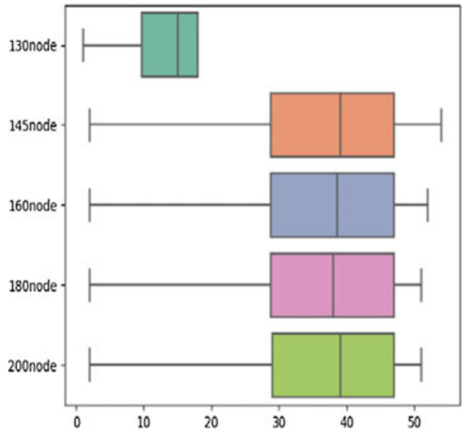


Fig. 4 Node 68 SNIR packet loss



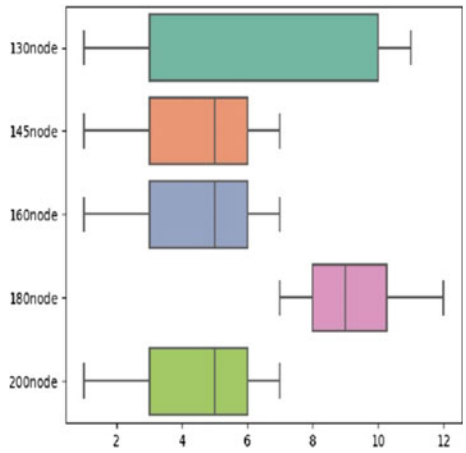


Fig. 5 Node 68 broadcast receiver

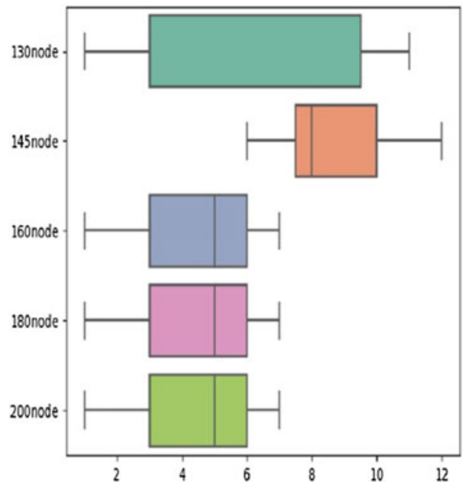


Fig. 6 Node70 broadcast receiver

The aim was to build a simulation to manage the connectivity between school buses in OMNet++. In the simulation, we could see that the vehicles are moving on roads and are perfectly visible with the time set at 113 ms.

5 Conclusion

In this study, a simulation has been developed by using OMNeT++, Veins, and INET. In this work, we varied the number of vehicles and did 5 simulations as 130, 145, 160, 180, and 200 vehicles or nodes to create connections and make them communicate with each other. As shown above, when the first node meets with an accident, it sends a packet named accident first to the radio manager and then sends it to the nearby other two nodes. In the paper, there is a brief explanation of the concepts used to achieve our goal. In the paper, we were able to gather datasets for 4 different node network for better results. Those numbers are 130, 145, 160, 180, and 200. In this paper, we showed communication between the vehicles. This is very helpful and if used in the real world, it could solve many problems like the problem of a school bus when stuck somewhere or it could be very helpful in emergency vehicles. The solution is not just helpful for school buses but is also helpful for emergency vehicles. We see many deaths in ambulances that take place daily in India because of not reaching on time, so with this, the vehicles could reach on time and lives can be saved.

References

1. Alam KM, Saini M, Saddik AE (2015) Toward social internet of vehicles: concept, architecture, and applications. IEEE Access 3:343–357. https://doi.org/10.1109/ACCESS.2015.2416657
2. Contreras-Castillo J, Zeadally S, Guerrero-Ibañez JA (2018) Internet of vehicles: architecture, protocols, and security. IEEE Internet Things J 5(5):3701–3709
3. Atzori L, Iera A, Morabito G, Nitti M (2012) The social internet of things (SIoT)–when social networks meet the internet of things: concept, architecture and network characterization. Comput Netw 56(16):3594–3608
4. Butt TA, Iqbal R, Shah SC, Umar T (2018) Social internet of vehicles: architecture and enabling technologies. Comput Electr Eng 69:68–84
5. Arooj A, Farooq MS, Umer T, Rasool G, Wang B (2020) Cyber physical and social networks in IoV (CPSN-IoV): a multimodal architecture in edge-based networks for optimal route selection using 5G technologies. IEEE Access 8:3360933630. https://doi.org/10.1109/ACCESS.2020.2973461
6. Abbas MT, Muhammad A, Song WC (2019) Road-aware estimation model for path duration in internet of vehicles (IoV). Wirel Pers Commun 109:715–738. https://doi.org/10.1007/s11277-019-06587-5
7. Zia K, Muhammad A, Khalid A, Din A, Ferscha A (2019) Towards exploration of social in social internet of vehicles using an agent-based simulation. Complexity 2019:13 pages. Article ID 8201396. https://doi.org/10.1155/2019/8201396
8. Zhang B, Yuan B, Bi X, Wei Z, Zhang M (2020) An adaptive multi-channel cooperative data transmission scheduling in VANETs. Sensors 20:5612. https://doi.org/10.3390/s20195612
9. Vershinin YA, Zhan Y (2020) Vehicle to vehicle communication: dedicated short-range communication and safety awareness. In: 2020 systems of signals generating and processing in the field of on-board communications, pp 1–6. https://doi.org/10.1109/IEEECONF48371.2020.9078660
10. Atzori L, Floris A, Girau R, Nitti M, Pau G (2018) Towards the implementation of the social internet of vehicles. Comput Netw 147. https://doi.org/10.1016/j.comnet.2018.10.00

A Critical Review on Transitopia of Tomorrow as a Solution of the Transit System to Stimulate the Use of Public Transportation to Make Cities Liveable

Snigdha, Charu Nangia, and Manoj Kumar

Abstract Urbanization has caused cities to grow horizontally, leading to issues with urban sprawl, longer commutes, and a rise in the demand for private vehicles, all of which have a negative impact on the environment. Adding new mass rapid transit systems (MRTS), such as metro railways and bus rapid transit systems, has boosted public transportation in many cities in order to address issues and fill in gaps (BRTS) [1]. However, in order to create liveable, healthy, and intelligent cities, it is crucial to utilize these systems effectively. Urban transportation is a serious concern in today's megacities. The transportation network extended and evolved to cover the new urban fabrics and connect them to the rest of the city because of considerable urban expansion and population growth. It is quite challenging to achieve growth and development, especially in developing cities. Urban transportation is facing a new issue due to the ever-increasing population of urban regions. The difficulty with which these options can be used to meet the current requirements as well as the constraints on the options' availability, space, and relationships with one another increase the complexity of the issue. The need for speedier communication, travel, and transportation is increasing quickly as the world gets smaller [2]. Technology both facilitates and offers answers for this process, functioning as both a catalyst and a supporter of it. Planners and engineers are interested in finding solutions for urban transportation, despite its complexity and difficulties. Public transit, or PT, is one such option that has shown promise in addressing the aforementioned issue. This paper explores the potential of TOD and IPT, as well as its viability in a developing country like India. This novel kind of urban transportation is thoroughly discussed in the paper, along with the transportation needs and potential use and solution for this technology to address them.

Snigdha (✉) · C. Nangia
Amity School of Architecture and Planning, Noida, India
e-mail: snigdhachaudhary2@gmail.com

C. Nangia
e-mail: cdawan@amity.edu

M. Kumar
N.I.T, Patna, India

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Keywords Transit oriented development · Rapid transit · IPT · Sustainable solution · Public transportation · Feeder services · Urban mobility

Introduction: India is rapidly urbanizing, with urban population growth outpacing that of the country's overall population. India is up against the world's fastest growing nations. Urban sprawl issues were brought on by the cities' horizontal growth resulting in urbanization. Trip lengths have risen, private vehicle use has increased, there are pollution issues, and infrastructural needs have expanded as a result. Many cities have improved their public transportation systems to deal with these problems. To make cities liveable, healthy, and sustainable, it is crucial to combine land use and transportation infrastructure effectively [3].

Transitopia of Tomorrow: Transportation options are widely recognized as facilitating access to education, employment, and leisure activities, but they are also the source of many issues that cities face. Identifying the significance of change is needed to prevent the future of transportation from being dystopian. So to understand the need for alternative methods, think about planning for sustainable utopian transport. The mobility of people and goods, the physical aspects that support and inhabit mobility, and the governance framework with respect to formulating and implementing transportation policies and minimizing the negative effects of traffic on the environment to make the city liveable, sustainable, and healthy are the three components of the transportation system that should each be separately "utopianized" in Transitopia.

1 Urban Mobility Index in Transit-Oriented Development Zone

Urbanization is now occurring at the fastest rate ever. Urban agglomerations will be home to more than 5 billion people by 2030. With the urbanization of the world, a new age of prosperity, economic growth, and resource proficiency will start. Mobility is a key factor in urban economic growth [4]. It is true to say that the modern city's rise is based on mobility. Only improvements in mobility have allowed cities to grow from the mediaeval metropolis, where all moves were on foot, to today's enormous agglomerations. However, transportation systems need to change significantly, as cities develop.

When faced with a growing population, can a city that occupies a fixed area reduce congestion? Would it be possible to stop the lengthening of journey times as more people wish to travel? Can a city sustain or even improve its quality of life with or without making large expenditures on its transportation infrastructure? So on.

The demand for transportation in cities must be met through the effective and seamless use of already available transportation infrastructure and urban space in order to minimize bottlenecks by minimizing the frequency and length of vehicular

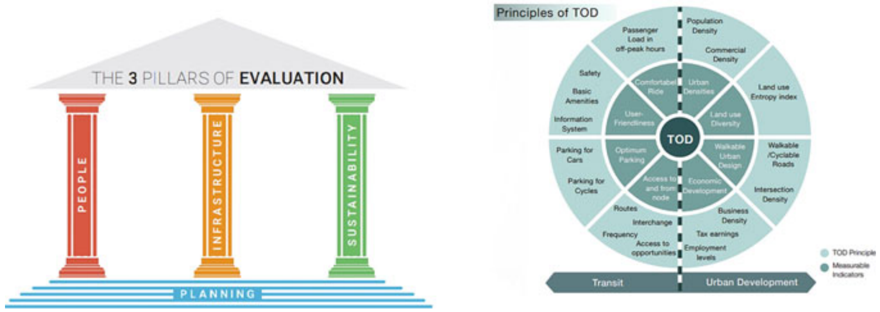


Fig. 1 Principles of TOD and measurable indicators (*Source* http://moud.gov.in/link/urdpfi-guidelines.php)

trips as well as the transit ridership itself. Less noise and air pollution, as well as lower greenhouse gas emissions, are the projected results of these initiatives. In metropolitan regions, there is worry over the growing influence of transportation on the environment, particularly the quality of the air [5]. Consequently, the innovative urban objective is to develop sustainable mobility based on eco-friendly modes of transportation. With a proper modal share of various modes of transportation and by figuring out how to provide transportation services in cities, sustainable mobility should satisfy the transportation demands of all groups.

Assessment of cities' accessibility in three crucial areas: sustainability, infrastructure, and people. These factors are frequently cited in statements of visions, aims, and goals, as well as in mobility planning papers for cities all over the world, which makes them a natural fit for the pillars of the Ease of Moving Index. Utilizing the Three Pillars of Evaluation—People, Infrastructure, and Sustainability—we can assess the general mobility of a city. Among the main dimensions of evaluation, the Accessibility of Moving Index would include details on how easy it is to relocate to a specific city [2]. How should my city develop going forward (Fig. 1)?

2 Pillars of Evaluation

Urbanization is a current and future trend since more than partial of the world's residents now live in cities. This number is projected to increase to 6.5 billion by 2050, or two-thirds of the completely human population. Urbanization offers a variety of opportunities and difficulties that call for planning with the goal of achieving an ideal coexistence and viable growth [6]. Metropolises all over the world have come to the realization that if we are to achieve the global agenda on sustainable development, our approach to planning and managing urban areas must undergo a profound transformation. In actuality, what makes cities distinct from one another are the different urban transportation systems that they have created to negotiate their particular surface topography and urban consequences density, demographic trends, and form.

Urban mobility is defined as the movement of individuals through a Mode between a journey's senders to the receiver. Based on the assumption that people migrate to obtain housing, jobs, and amenities including education, health, recreation, etc., designing for urban mobility is necessary. Additionally, they anticipated that as cities improve and community grows more rich, users will prefer motorized transportation over non-motorized transit since the former is more practical and viewed as being more time-efficient than the latter. These assumptions may not be true, particularly in the current climate where technology has helped to modify perceptions about how people travel and how cities function. Due to the development of e-mobility and mobility as a service, commuters no longer need to move in order to access services. Due to growing public awareness of the negative effects that motorized mobility has on the environment, human health, and other factors, as well as the increasing acceptance of non-motorized transportation (NMT), such as travelling and walking, the trend of the future of mobility, as we currently understand it is changing.

As Shanghai Declaration on Better Cities, Better Life "Cities should respect nature, view the urban ecological environment as a resource, include environmental concerns into urban **planning** and management, and quicken the shift to **sustainable** development. They ought to encourage the development of low-carbon eco-cities and the utilization of renewable energy sources. They should fervently support resource preservation and **infrastructure** that is friendly to the environment [7]. Cities and their **citizens** should work together to develop ecological civilizations and sustainable lifestyles that allow people and the environment to coexist together." The four key principles of urban mobility—planning, infrastructure, and sustainability—are endorsed in this proclamation. We observe significant influences in India, in which the National Urban Transport Policy of India (NUTP), enacted in 2006, is considered as the cornerstone of Indian mobility [3]. According to the National Urban Transport Policy (NUTP) of India, our cities are the most liveable in the world and have the capability to become the "engines of economic growth" that drive India's development in the twenty-first century. Recognizing that people are at the centre of our cities and that all planning is for their benefit. Allowing our cities to grow into an urban shape that is most appropriate for the unique topography of their locations is the best approach to promoting the fundamental, social, and economic activities that take place in cities.

3 Global Trends Challenges and Forecasts

Although the transition to a largely urbanized world situated formally recognized everywhere, it acquired more than ten years to begin developing multinational regulatory frameworks on climate, sustainability, and biodiversity. Local and regional governments have aggressively embraced change alongside national governments, and occasionally even more actively. They are on the front lines of everyday difficulties, including an extensive range of stakeholders from the communities and the commercial region. The most urgent issues affecting communities worldwide are those related to transportation, health, environmental responsive infrastructure, air index, and emissions. Cities now rely on quicker environmental transformation and adaptability as a result. This is taking place in the midst of more extensive industrial developments taking place on a worldwide scale, comprising digitization and expansion of on-demand mobility, which have prospective to greatly aid in the expansion of viable mobility approaches [1]. However, the leap from dispersed experimental tactics to major structural changes still needs to be in the world.

The Commonwealth of Independent States has seen an increase in the trend of car ownership during the last ten years. Nevertheless, because initial reference levels were low, these countries' motorization levels are today noticeably lower than those of industrialized nations; however, the ratio of automobiles per 1,000 people in several of these countries' largest cities is approaching 300–400, and it is expected to continue to climb. The majority of countries had seen increases in both the number of privately owned automobiles and the number of kilometres travelled per person in automotive usage (and the trend continues in many).

Local governments and civil society are pushing in the opposite direction in various parts of Europe because they believe that private car ownership and private car mobility, especially in cars that use fossil fuels, are major obstacles to living sustainably [8]. The recent significant social unrest in France, which was the idea of raising the price on fossil fuels, particularly diesel, in order to finance a more carbon–neutral economy, demonstrates that the equation is not that straightforward. Along with the ideas, steps were to lower the posted speed limits on the nation's roads. Car ownership is not just seen as a lifestyle choice that may be altered to fit current trends in the peri-urban and rural areas surrounding France's major urban centres.

Global trends, whether they are related to electro mobility, shared mobility, or active mobility, are altering mobility patterns throughout the UNECE member nations and having an impact on transportation systems and cars. Industry, society, and urban governance are impacted by this. Urban patterns and mobility difficulties can be rethought in many ways, thanks to the economy's rapidly growing digitization, but doing so will require future cross-sectoral and multi-stakeholder collaboration.

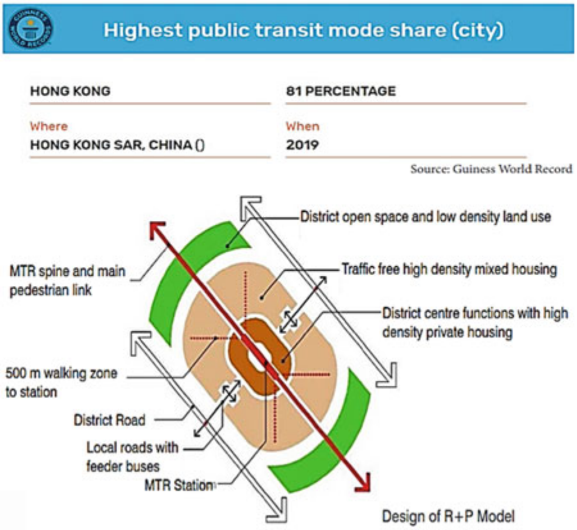
4 Remarkable Success in Transit-Oriented Development

4.1 Case Study—Hong Kong

Geographical constraints have caused Hong Kong to grow into a dense metropolis. The public transportation network has expanded alongside the growth of the city to accommodate citizens. One of the most effective and diverse public rail networks in the entire globe is Hong Kong. The city's vitality depends on its mass transit systems. A rail Transit-Oriented Development (TOD) has the ability to provide a superior alternative to private transportation in metropolitan areas and considerably enhance the quality of life for people by blending residential needs with alluring public transit options. It has been placed as the leading supplier of light rail, tramway, and metro conveyance in Hong Kong [9]. The World Bank (2019) ranked 14 cities with exceptional TOD achievement and chose Hong Kong as one of the top three benchmarking cities in its report, "Benchmarking Transit-Oriented Development."

Source: Forbes

The largest number of individuals who use public transportation is in Hong Kong. Public transportation accounts for 81% of all journeys undertaken in the city, with 12.4 million passengers boarding each day (Fig. 2).



R+P (RAIL + PROPERTY) DEVELOPMENT MODEL

1. Rail-oriented community (Rail + Property as a living style)

2. People-vehicle segregation (A safe and healthy living environment)

3. Station-Property Integration (A compact development with seamless connections)

Fig. 2 Design of R+P Model in TOD Zone and measurable indicators (*Source* http://moud.gov.in/link/urdpfi-guidelines.php)

Fig. 3 Demand estimation and route network design technique (*Source* Author)

5 Ideologies of TOD in Hong Kong

The five "Ds" Approach of TOD applicable in the case of Hong Kong (Fig. 3).

6 Ease of Access and Growth Versus Congestion

> A city living on total automotive dependence becomes dysfunctional, inefficient and inconvenient for life. The goal of the transport system is to move people, not vehicles [10].

Urban transportation experts concur that traditional and developed cities don't elongate at ease to living as an outcome of the unchecked increase in the usage of privately owned cars. Urbanization and population growth increase the need for transportation, population mobility, and concomitant difficulties with access to some metropolitan areas, travel destinations, and transportation services. Large metropolitan road networks get congested because transportation demand exceeds the capacity of the available road infrastructure. Major city administrations have long viewed expanding the capacity of urban highways through their rehabilitation and development as the primary method of reducing traffic congestion [11]. The paradigm of "planning for vehicles in cities" served as the foundation for the respective transport planning theories that were adopted during the century noted for "rapidly growing motorization." The practise has demonstrated that these attempts to address the problems of enhancing accessibility to urban areas and reducing congestion never produced long-term favourable results of the creation of so-called "induced" mobility [12].

The reality of rising car ownership rates that have significantly exceeded the growth of urban road networks, as well as rising pollution and environmental damage brought on by increased road infrastructure, have emphasized the necessity for an innovative paradigm for urban transport development. The idea of "sustainable urban transport" or "sustainable mobility" is sought to retain the population's mobility by moving transportation demand towards safer and more environmentally friendly types of transportation, or "urban mobility planning" [13]. However, despite all the advantages of this strategy, which is adopted in many large cities, it is still a result of the specific transportation needs for which the public transportation system was created. Forecasting metropolises and transportation infrastructure nearby motor vehicle traffic flow remains to have significant negative externalities related to transportation activities in particular, resulting in 1,250,000 deaths annually from traffic accidents and 3,200,000 deaths annually from air pollution. It is obvious that we need to change the current transport paradigm and concentrate efforts on building vivacious, vibrant cities that can accommodate people's daily activities. A rising number of experts are beginning to recognize the significance of this method of urban planning.

7 Comprehensive Mobility Plan (CMP)

Comprehensive Mobility Plan (CMP) is introduced in Indian cities by the Ministry of Urban Development as a toolkit, for Sustainable Urban Transport with the support of Global Environment Facility under the influence of the National Urban Transport Policy [14]. The main objective is to provide desired ease of access and mobility patterns for residents in the urban cluster. It emphasizes the mobility of people to address the issues and problems towards urban transport and encourage good practice around the globe which is essential for cities. The objectives of the tool kit were prepared to enhance the mobility pattern of residents rather than of vehicles, advancement of public transport, NMVs, and pedestrians in the context of Indian cities. The Sustainable Mobility Plan is a method to deal with transportation concerns efficiently [15]. In the existing practices, the governing outlines are formulated on a participatory approach for sustainability and an integrated approach to outline the vision, objectives, and measurable targets to review the costs and benefits of transport. CMP emphasis on four substantial essentials to promote sustainable urban mobility in the cities includes transit system, Land use, NMT, and Public Transport.

8 Lessons Applicable to Indian Cities

The outcome of the study is to provide steadily rising number of city residents with sustainable, rapid, comfortable, inexpensive, and safe access. This is intended to accomplish by

- **Local Area Planning for TODs**: Effective planning for TODs begins at the regional scale followed consistently by the level of station area planning, as evident in the case of Hong Kong.
- **Station Area Planning**: In India, the absence of station area planning and integration of adjoining private developments as part of the overall station design has led to substandard development, which is adjacent to transit. MTR station and its

above-station property development are excellent examples of TOD value capture [16].

- **Strategic Intensification along transit corridors**: High-density, high-rise development concentrated along strategic transit interchange nodes is a stable feature amongst a majority of Hong Kong's transit stations.
- **Design of the Public Spaces alongside Station Development**: Emphasis on, physical integration of R+P project with stations and surrounding buildings, vertical connectivity for pedestrians at above ground levels and vehicular connectivity at ground floor level and underground levels, integrating in-station retail with pedestrian footbridges and corridors; and presence of high-quality public spaces are some of the elements that have contributed in enhancing the overall quality of life and increased property values.

9 Issues and Gap

The types of pollutants produced by cars in cities that are contributing to an increase in air pollution have been the focus of numerous specialists' investigations. In several studies, researchers made an effort to monitor various data, including AQI of various city neighbourhoods, and then compare the primary data acquired with National Ambient Air Quality Standards to identify areas with high pollution levels. In megacities, some academics have tried to explore the connection between traffic congestion and air quality, while others have looked at how traffic congestion affects air pollution, which has had a negative impact on health, and still others have attempted to investigate the relationship between public transportation and its environmental impact. Some scholars have recently discussed vehicle air pollution in terms of CO_2 emissions, while others have attempted to examine the failure of TOD in terms of public transit. A few researchers have attempted to discuss modes of transportation in some studies, with the findings that vehicular congestion is the major cause of air pollution, and that the cause of vehicular congestion is a lack of proper connectivity and a shortage of public transportation within the city [17]. There was no thorough study that could highlight the various effects of traffic congestion in a city or the connection between transit-oriented development and urban mobility. In order to improve public transportation and investigate the effects of traffic congestion in the city, it has been decided to undertake thorough research and propose a recommendation on last-mile connection and TOD strategy [8].

10 Parameters of Evaluation

All around the world, there is a focus on assuring connectivity, ease of access, and sustainability. The Indian Government's Ministry of Urban Development (MoUD) has lately published a study titled Livability Standards in Cities that examines how

Fig. 4 Parameters of evaluation and measurable four key components of urban mobility (*Source* Author)

liveable Indian cities are [10]. The study names transportation and mobility as essential principles of assessment, highlighting mobility's importance in urban development and its commitment to enhancing the standard of living for Indian city dwellers [18]. When previous efforts by different organizations working on urban mobility are analysed, it is evident that mobility planning is prepared with a vision that is in accordance with the overall goals of sustainable development. A prime example of such a multinational endeavour was the Shanghai Declaration [19]. The Shanghai Declaration on Sustainable Communities, Better Standard of Living, which is identified as a major statement leading the world towards liveable cities, was signed by 192 countries in 2010, including India. This proclamation identifies consumer, governance, infrastructure, and sustainability as the four essential elements of urban transit (Fig. 4).

11 Conclusion

The outcome of this study is on how transit systems affect land use, which raises crucial questions about the locations, types, and costs of development projects, as well as accessibility issues and traveller preferences and performance. By focusing on parameters of evaluation, which include principles of TOD variables and measurable indicators of mobility patterns, the study seeks to uncover the traits of urban transportation users, cars, modes, infrastructures, and services [20]. The strategies and recommendations for reducing traffic congestion, last-mile connectivity, and the environmental effects of transportation are required to investigate the effects of these elements on commuters' travel characteristics and mode selection choices. The indices outline critical goals to help each index achieve its objectives, but they are not viewed as least significant as achieving sustainability metrics. Based on the above case studies, the attributes and indicators are categorized to review the quality assessment to identify the intention of people from public transportation to private vehicles. Once the cities are willing to compete with fundamental knowledge of TOD and sustainable practices across and within various sectors of urban development, this index might be more advantageous in assessing efficiency guidelines for reimagining mass transit pertaining to urban mobility as a sustainable solution.

References

1. INAE Forum on Civil Infrastructure (2019) Urban transportation: challenges and way forward, pp 1–133
2. Hermans J (2017) The road to sustainable transportation. EPJ Web Conf 148:1–9. https://doi.org/10.1051/epjconf/201714800006
3. Verma A, Harsha V, Subramanian GH (2021) Evolution of urban transportation policies in India: a review and analysis. Transp Dev. Econ. 7(2):1–15. https://doi.org/10.1007/s40890-021-00136-1
4. (European Environmental Agency) EEA (2020) The first and last mile—the key to sustainable urban transport. Transport and environment report 2019, no. 18
5. S. Nema and P. A. Sharma, "Analysing City Urban Transport System and Impact of TOD Proposal," vol. 8, no. 05, pp. 972–977, 2019.
6. Yogi RJ, Kavina J, Darji PV (2017) Transit-oriented development: lessons from Indian experiences. CUE Work Pap Ser 36(January):299–315
7. FICCI (2020) India roadmap on low carbon and sustainable mobility. Decarbonisation of Indian Transport Sector
8. IIHS (2015) Challenges and recommendations: IIHS RF paper on urban transport, p 42
9. Institute of Urban Transport (2013) Development of toolkit under sustainable urban transport project, no. December, p 168
10. A. Framework, "Ease of living"
11. Chidambara (2019) Walking the first/last mile to/from transit: place making a key determinant. Urban Plan 4(2). Public Space in the New Urban Agenda Research into Implementation, pp 183–195. https://doi.org/10.17645/up.v4i2.2017
12. Al Suwaidi N (2020) Integrating all mobility systems to reduce traffic congestion
13. Jain AD, Singh E, Ashtt R (2020) A systematic literature on application of transit oriented development. Int J Eng Adv Technol 9(3):2542–2552. https://doi.org/10.35940/ijeat.C5415.029320
14. C. Mobility, P. CMP, and T. Government, "No Title"
15. Morring F, Dornheim MA (2004) Last mile. Aviat Week Sp Technol (New York) 161(17):56–57. https://doi.org/10.18060/24844
16. "Transit Oriented Development (TOD)-study for existing metro corridor between Chattarpur and Arjangarh of Delhi metro project of phase II and."
17. Medina-tapia M, Medina-tapia M (2021) PhD thesis, Urban mobility network design: urban mobility network design

18. Ann S, Jiang M, Yamamoto T (2019) Influence area of transit-oriented development for individual Delhi Metro stations considering multimodal accessibility. Sustainability 11(16). https://doi.org/10.3390/su11164295
19. NTOD (2017) National transit oriented development (TOD) policy, pp 1–18
20. Dalla Rosa J (2007) A step towards sustainable transportation behavior: understanding automobile ownership and mode choice through qualitative research. ProQuest Diss. Theses, p 115