Chapter 23
Attaining Optimal Sustainability for Urban Wastewater Management Using Open Source Tools Like QGIS, EPANET and WATERNETGEN

Devang Shah and Dilip Shete

Abstract Nearly 3 in 10 people worldwide lack access to safe, readily available water at home, and 5.5 in 10, lack safely managed sanitation. WHO stated that the total economic return on sanitation spending is US $5.5 for every one dollar invested. Still, M.D.G. for sanitation was missed by 700 million people globally. The primary reason behind this problem is the lack of an integrated approach. In most developing countries, due to a lack of infrastructure, wastewater is not properly disposed of. The status of the water supply system is also pathetic. After a detailed study, it was found that treated wastewater usage in the residential, industrial and agricultural sectors with proper pricing is the best alternative to mitigate water stress, ensure sustainability and generate revenue. The methodology to design and implement water reuse project with economic feasibility is presented with a case study in the present article.

Keywords Water reuse · IRR · EPANET · WATERNETGEN · QGIS · Economic feasibility

23.1 Introduction

The challenge of water availability does not sensitize a layman regarding critical conditions prevailing as urban people generally enjoy sufficient water supply for daily consumption in class I and class II cities in India. In contrast, the situation is quite challenging in many underdeveloped and developing parts of India, facing moderate-to-severe water stress.

Keeping apart the Indian context, one-third of the total population lives in areas under water stress worldwide. Total water on earth is constant for millions of years

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P. Kumar et al. (eds.), *Water Resources Management and Sustainability*,
Advances in Geographical and Environmental Sciences,
https://doi.org/10.1007/978-981-16-6573-8_23

as the same water is changing form continuously and being used and reused millions of times as a part of the hydrologic cycle. While minor population growth has been observed for quite a long, the world's population had grown exponentially and increased more than seven-fold in the last three centuries. The last 90 years contributed to three-fold growth (Daigger 2007). The increase in industrial and agricultural needs has created water stress in most regions of the world. Water reuse is being adopted as sustainable practice in developed and highly water-scarce areas for the last four decades at a municipal scale (Leverenz et al. 2011).

In India, at least the water supply sector shows a bit satisfactory performance as 94% of the population has access to drinking water in class I and class II cities. But in the sanitation sector, the capacity exists to treat only up to 40% of sewage generated in class I and class II cities, causing 60% of generated sewage to be disposed of in an unsafe manner in natural water bodies (Central Public Health and Environmental Engineering Organization 2005). Further, using this untreated or partially treated wastewater in agriculture is prevalent in India, causing severe health hazards and soil characteristics deterioration (Mekala et al. 2008).

Further considering the nutrient value of treated wastewater, a study for coastal towns and cities has shown that wastewater valued at Rs. 1091.20 million are released into the coastal waters of India (Central Pollution Control Board 2009). Thus, if unplanned and unofficial reuse of wastewater can be converted to planned and official reuse, it can open the new horizon to utilize the wastewater's nutrient value and sell water to industries. The revenue generated this way can be utilized to construct much-needed infrastructure in the sanitation sector.

With this in view, data collection and study have been conducted to understand water reuse feasibility and optimize urban wastewater management with a case study of the Vadodara Urban Development Authority Area (VUDA) in the Gujarat state of India.

23.1.1 Why Water Reuse?

Human beings' excreta and faecal discharges are nothing but food for microorganisms, which converts them into the best source of nutrients. In ancient times due to less population density, these were discharged safely to nature to return the nutrients in natural cycles. As observed from the excavations at Harappa and Mohenjo-daro, the Sindhu–valley civilization had, more than 5000 years ago, baths in many of the houses with ceramic pipes for water supply and brick conduits under the centre of the streets for drainage (Rouse and Ince 1957).

The best way adopted for disposal of drainage water in that time perhaps consisted of disposal to river or sea. As ample water was available for dilution, these discharges perhaps had served as the minimum organic load required to sustain the natural self-assimilative cycle of rivers keeping the food chain intact and fruitful. Unluckily, due to the exponential growth of population, this organic waste quantity has increased to such an extent that inland water bodies can no longer sustain this load. That is why treatment for the removal of this organic matter is given in wastewater treatment plants. The only grievance is; we are putting a lot of energy input to remove the nutrient value of this wastewater instead of directly returning it to the natural cycle for beneficial use. Here is where an engineer's intervention is required to redefine the treatment criteria and find a safe way of handling wastewater. Treated wastewater utilization in beneficial uses such as irrigation, peri-urban irrigation, watering of lawns, gardens, golf courses, green belts, etc. The nutrient value of wastewater can be adequately addressed, and load on treatment facilities can be reduced. If proper treatment technology is existing safeguarding this type of reuse patterns, the nutrient value of wastewater can be tapped. Wastewater treated as per existing treatment technologies should be sold to industries. Industries have significant ecological footprints, and they have the revenue to bear the treatment cost. Selling wastewater to industries will reduce the load on freshwater resources and generate much-required funds for developing sanitation facilities in India and all developing countries.

23.1.2 State of the Art

Sustainable Development: The spike in population growth and high standards of living for significant portions of the human population have increased resource demands beyond the ecosystem's capacity. This brings in the concept of sustainable development as a significant factor based on evaluating enhanced water supply and wastewater management approaches.

The U.N. Report on "our common future" known as the Brundtland Report, defined sustainable development as "paths of progress that meet the needs and aspirations of the present generation without compromising future generations' ability to meet their needs" (Brundtland 1987). Many definitions of sustainable development exist, but a useful one is a balance between economic, environmental and social considerations in selecting and implementing an approach to any issue—the so-called triple bottom line (Daigger 2007).

The water available on earth today is no different in quantity from what was available thousands of years ago. The world's water resources will never change, but the human population and its demands are overgrowing. Meeting these demands will require wise investment in how we use and reuse our water (UN Water Statistics 2010). Aspiring to install a concept of sustainable development has now become broadly accepted (Wallbaum et al. 2011). A systematic research review of global urbanization research from 1991 to 2009 revealed increasing interest in urbanization studies' ecological and environmental issues (Wang et al. 2011).

Water Stress: There is a constant rise in recognition for water-related problems as one of the most severe and immediate environmental concerns. Water use has been increased three-fold globally since 1950, and one-sixth population of the world does not have regular access to safe drinking water. In the absence of access to a safe water supply and sanitation, the health of 1.2 billion people gets affected annually. The latest Global Environment Outlook of the United Nations Environmental Programme (UNEP) reports that about a third of the world's populations live under moderate-to-high water stress. In such countries, water consumption is more than 10% of renewable freshwater resources.

Urban water demand has been increasing steadily due to population growth, urbanization, industrial development and peri-urban agriculture. Population growth in urban areas is a significant concern for developing countries. Population growth is expected in developing countries, as the developed region's population is projected to decrease by 6% over the next 50 years. Many parts of the world face changes in climatic conditions, such as rainfall patterns, flood cycles, and droughts, which affect the water cycle.

So there is an acute need to augment the present water supply with alternative sources. Several approaches, modern and traditional, exist all over the world for efficiency improvements and augmentation. From numerous options available, wastewater reuse has become increasingly important in water management for both environmental and economic reasons.

Wastewater reuse has an ancient history of applications, primarily in agriculture, and other areas of applications, like industrial, household, and urban, are becoming more and more adopted. Among them, wastewater reuse for agriculture still represents the most significant reuse volume and is expected to increase further in developing countries. With the growing increase in applications, there exists concurrent recognition that water resource management and scheduled water cycle maintenance need up-to-date knowledge regarding basic practices, benefits and potential risks, capacity building of practitioners and planners, and appropriate policy frameworks to protect humans and the environment.

In developed countries, wastewater collection and treatment have been common practice, and wastewater reuse is practiced with proper sanitation, public health and environmental protection. The scenario is quite different in many developing countries due to the lack of appropriate infrastructure and strict wastewater treatment standards for its reuse. Unofficial wastewater reuse for irrigation is quite common in many places, causing a substantial threat for the farmers and consumers of those agricultural products due to the poor quality of wastewater. The World Health Organization (WHO) has published and updating the guidelines for wastewater reuse in agriculture. The efforts are also being made to find out easy and economical ways to localize treatment and reuse wastewater at the source.

Global Scenario: Environmental budgeting for requirements shows that the abstraction of water for domestic, food and industrial uses already has a huge footprint on ecosystems in several parts of the world, even though not considered "water scarce." Water will be a major constraint for agricultural development in coming decades and particularly Asia and Africa will require major institutional adjustments (Rijsberman 2006).

Currently, less than 0.5 billion people live in countries with water stress. Still, by 2050, this is expected to increase to about 4 billion, with over 2 billion in water scarcity areas (worst-case) estimates are 7 billion living in areas of water stress and

5 billion in areas of water scarcity (Daigger 2007). The world's urban population will increase from 3.5 to 4.9 billion in 2020, and maximum growth will take place in developing countries (United Nations Human Settlements Programme (UN-Habitat) 2011). So, the reuse of treated wastewater can act as a solution, an imitation of the hydrologic cycle's natural process and help in saving freshwater resources. As depicted from several pioneering studies worldwide, technological confidence has been gained for the safe reuse of reclaimed water at a municipal scale for beneficial purposes. Initially, emphasis was mainly on reuse for agricultural and non-potable reuses; the current trends prove that direct potable reuse is possible for applications that are closer to the point of generation.

There is a large gap between consumption and extraction of water, which establishes that water reuse and recycling can solve the water scarcity problem globally.

There are several well-known examples of indirect potable reuse worldwide, including facilities in Orange County, California, the NEWater facility in Singapore and Windhoek, Namibia (Miller 2006). Starting from the U.S., the practice of recycling/reuse of wastewater is a large and growing industry. Recycled water use on a volume basis is growing at an estimated 15% per year in the U.S. (Schmidt et al. 1975), systematic guidelines at the federal level (U.S. E.P.A. 2004) and state level are well developed, and a lot of research and implementation is going on towards sustainable water use (Burian et al. 2000; Draper et al. 2003; Rozos et al. 2010; Nicklow et al. 2010; May et al. 2008; Liner and DeMonsabert 2011; Mays and Schwartz 1983; Law 1996). Increasing interest in the reuse of effluent from sewage treatment plants in Australia has been observed in recent years and established to solve water shortage by various studies (Anderson 1996; Hurlimann and McKay 2007; Hurlimann 2009; Hamilton et al. 2005; Mekala et al. 2008). Development and validation of design principles for water reuse were rigorously conducted under AQUAREC Project, and remarkable progress has been achieved in E.U. countries (Joksimovic et al. 2006, 2008; Bixio et al. 2008; Hernandez et al. 2006; Urkiaga et al. 2008; Hochstrat et al. 2008; Tsagarakis 2005; Tziakis et al. 2009; Tsagarakis et al. 2004; Iglesias et al. 2010). Mediterranean region had also practiced water reuse and rapid developments regarding criteria and guidelines (Seguí et al. 2009; Hernández-Sancho et al. 2010; Shelef and Azov 1996; Marecos do Monte et al. 1996; Bahri and Brissaud 1996, 2004; Brissaud 2008; Pedrero et al. 2010). Taiwan (You et al. 1999) and Japan (Maeda et al. 1996) also started water reuse, and it has been recognized as an integral part of the water management scheme in China (Yi et al. 2011; Chu et al. 2004; Peng et al. 1995; Yang and Abbaspour 2007; He et al. 2007) and countries like Thailand (Sa-nguanduan and Nititvattananon 2011; Sujaritpong and Nitivattananon 2009).

Wastewater Reuse Perspective in India: Though proportion of population using an improved drinking water source in urban area is 96%, the challenges of availability as well as quality in the distribution of drinking water still persist across various areas in the country, and the proportion of population using an improved sanitation facilities is only 54% (Ministry of Environment and Forests 2011). Some major challenges cited in 11th five-year plan are regaining agricultural dynamism, providing essential basic services to the poor, protecting the environment and bridging the divide between rich and poor (Planning Commission 2006). Improved sanitation and wastewater management are central to poverty reduction and improved human health (Corcoran et al. 2010). Though the significance of wastewater reuse and recycling is accepted (Central Pollution Control Board 2009; Ministry of Water Resources Govt. of India 2012), the full potential is not utilized. To summarize, one can say that there is lack of funds to establish basic infrastructure for sanitation; which leads to pollution and informal reuse of untreated or partially treated wastewater. On other side, there is growing demand of water for domestic as well as industrial use. Projected percentage increase in industrial water use over level of year 2000 would be 61.06 if India continues to follow the path of development followed by developed countries (Jia et al. 2006). So, instead of using precious freshwater resources for industrial uses, wherever possible, marginal quality-treated wastewater should be reused, which can reduce freshwater demand, availing more water for domestic use. By proper establishment of facilities with reliability of supply, revenue generation can be achieved from industries against supplied reclaimed wastewater. Further considering nutrient value of treated wastewater, study for coastal towns and cities has showed that wastewater worth Rs. 1091.20 million are discharged into the coastal water (Central Pollution Control Board 2009). Thus, it is ironic to notice that at one end one is spending handsome amounts on fertilizers for better production and on the other hand nutrient-rich wastewater is wasted. Thus proper wastewater management implied under correct policy framework can generate revenues which can be used to build much-needed infrastructure for sanitation and to augment water supply facilities; by providing nutrient-rich wastewater for peri-urban agriculture and horticulture and cooling or process water for industries.

Public Health Concerns: In India, where wastewater is mainly used in agriculture, a policy framework covering the issues associated with it is lacking. The new WHO guidelines for wastewater irrigation recognize infrastructure problem in developing countries and emphasize the potential of post or non-treatment options (World Health Organization 2006). There is no standard or guideline available except CPHEEO and CPCB standards in India regarding quality of treated wastewater to be used for irrigation. These standards do not address the coliform count criteria which is most crucial for prevention of health risk to consumer or farmers. A guideline balancing between utilization of maximum nutrient value of wastewater without compromising with the health of farm workers or consumers (Haruvy 1997) should be prepared at the priority basis. This guideline should be prepared after exhaustive research and sharing outcomes of long-term research carried out in developing countries regarding critical issues like fate of volatile organic compounds, pharmaceuticals, endocrine disruptors and antibiotics etc. in wastewater reuse (Snyder and Benotti 2010; Le-Minh et al. 2010; Rodriguez et al. 2012). In addition, a number of social concerns like impaired quality of life, loss of property value, food safety, health and welfare and sustainability of land use, groundwater contamination also should be considered for formation of guidelines. Controlling potential health risks will allow urban water managers to build on the benefits from the already existing (but largely informal) wastewater reuse, those being the contribution to food security and reduction of fresh water demands (Rooijen et al. 2009). Research can be conducted to find out best suitable crops in Indian context keeping in view minimum risk to consumer health.

Attainment of Economic Viability: Strictly speaking in Indian context, though greater emphasis must be placed on environmental considerations, public acceptance and public policy issues rather than mere cost-effectiveness as a measure of the feasibility of a water reuse project, attaining economic viability is essential for implementation. To attain this, exhaustive research should be carried out to find out cost-effective technology solutions like improved UASB technology with simple and better operational control, use of dead ponds in town or city may as maturation pond or polishing pond for treated wastewater before reuse (Mahapatra et al. 2011) or sewage reuse after treatment in oxidation pond and duckweed pond (Ghangrekar et al. 2007) or reuse of greywater in decentralized system (Godfrey et al. 2009). The analysis tools and models developed after long-term research all over world to strike the balance between environmental and economic criteria should be used to do cost–benefit analysis (Hamilton et al. 2005; Mekala et al. 2008; Joksimovic et al. 2006, 2008; Bixio et al. 2008; Hochstrat et al. 2008; Lim et al. 2008).

Wise and immediate investment in wastewater management will generate multiple future benefit (Corcoran et al. 2010). Regarding the funds availability, the scenario is gloomy. In India, water is a highly subsidized commodity leading to market inefficiencies and hence inefficient use of the already scarce resource. A majority of urban centres (79%) show revenue deficit on water management account, that is, the revenue receipts are not sufficient to meet the revenue expenditure on the service (Central Public Health and Environmental Engineering Organization 2005). This would demand the establishment of water prices that reflect the full cost recovery principle on the one hand, and the monetarization of the environmental and social benefits of water reuse, on the other. Recycled water valuation is considered as corollary for implementation of reuse. As the present tariff for industrial users is higher and as they have ability to pay higher charges, maximum water reuse with proper price allocation should be targeted for this demand. Just to cite some examples—Chennai Metropolitan Water Supply and Sewerage Board sells 65 M.L.D. of treated wastewater to various industries at 10.75 Rs./K.L. and this demand is going to be doubled in next five years (Ravikumar 2009), Surat, Bhavnagar, Rajkot, Ahmedabad and several other cities have initiated the water reuse. The Government of Gujarat (2018) has published official guidelines for achieving targets for recycling of treated sewage (Government of Gujarat 2018). This shows the light at the end of tunnel in form of acceptance of the theory that water is an economic good and prices can be used to promote equity, efficiency and sustainability (Rogers et al. 2002). Studies have shown willingness to pay by even low-income households for improved water supply and sanitation services (Davis et al. 2008).

Reduction in Cost of Reclaimed Water Distribution Network: Water reclamation and reuse is not a cheap option as the infrastructural requirements are usually high, in particular because of the need to construct and/or retrofit the distribution system (Joksimovic et al. 2006). In order to reduce the cost of reuse option, optimization of wastewater distribution networks should be considered. Remarkable achievements are obtained in form of various analysis techniques and optimization models for water distribution networks (Simpson and Elhay 2011; Cheng et al. 2011; Kang and Lansey 2011a; Agrawal et al. 2007). Where treated wastewater is to be used for domestic non-potable consumption, provision of dual-purpose water distribution network is required. Studies conducted in this regard to validate and optimize the network (Kadu et al. 2008; Kang and Lansey 2011b; Tudor and Lavric 2011). One of the important limitation pointed out by Bhave and Pandolkar (2004) was risk of exposure to possible severe health hazard due to use of marginal quality water in dual-purpose network by poor, illiterate people and children for drinking purpose. Giving due regard to this and not considering dual-purpose supply system for domestic use in India, still requirement for distribution system is there for supplying treated wastewater to industries and irrigation fields and as distribution system is to cost up to 70%, it should be optimized. If different approach is used for this compared to optimization of water distribution networks with congested and looped layout, generally better and quick results may be achieved. This can be identified as research gap in this area as optimization of reclaimed water network for supplying reclaimed water to potential users is not yet been carried out in India. By applying known techniques to this kind of specific problem, a new technique or modification of existing one could be found out to attain optimal results.

Policy Framework: Review of National water policy gives a pleasing experience as most of the relevant, renowned and successful practices and criteria regarding water resource management are getting reflected, namely consideration of increasing participation of all stakeholders, proper maintenance of existing infrastructure, proper identification of economic value of water and setting price to recover the full cost, good governance, integrated water management, evolving an agricultural system which economizes on water use, generation of database and information management system based on modern techniques available and much more, but it surely lacks the directive for generation of framework guideline for water reuse and secondly the approach for setting up pricing of water seems to be indecisive and soft, also it doesn't reflect the strategy to safeguard poor people lifeline water needs. As India's economy has grown, so too has the spending power of its citizens. Real average household income in India has roughly doubled over the past two decades. With a booming economy and increasing disposal income, there is an urgent need to introduce a new cost head in the urban water bills and introduce the "polluter pays" principal for urban water consumers. The new cost head will contribute to sewage treatment before it enters to inland water bodies and pollutes them and increases chance of availing benefits of wastewater reuse also. Geographically targeted system would result in significant improvements in performance, for example, lifeline rates could be set at lower levels in slum areas while increasing prices for non-poor users (McKenzie and Ray 2009). Thus bringing pricing reform is the need of the hour and without prior pricing reform private sector engagement will be difficult. Private sector engagement is a welcome step towards full privatization of water management under build-own-operate-transfer (BOOT) contracts reducing economic burden on government. Australia has already implied privatization in water and wastewater sector since 1980, which has improved its economic performance in terms of productivity and returns to the shareholder, however, consumers have not substantially benefited from this process in terms of lower prices (Abbott et al. 2011). So, the "Service Provider" role of the government has to be gradually shifted to that of a regulator of services and facilitator for strengthening the institutions responsible for planning, implementation and management of water resources. The water-related services should be transferred to community and/or private sector with appropriate "Public Private Partnership" model.

To be effective and to be implemented, a requisite shift to sustainability requires active community engagement processes, political will and a commitment to political and administrative accountability, and measurement (Ling et al. 2009). Some of the examples of this political will are raising of finance for water and sewerage expansions through municipal bonds in 1998 by Ahmedabad Municipal Corporation (A.M.C.) (becoming the first Indian municipality to use this mode of raising capital, though it is not common in South Asia) (McKenzie and Ray 2009), formation of Gujarat Green Revolution Company and encouraging use of drip irrigation and appointing an international consultant for deciding pricing of water across the state for various purposes by Gujarat Government (2005). As in most democracies, any major reform needs to survive (indeed, be part of) the political process, while even small changes in prices require public approval, it is very much required to highlight the benefits and improved performances achieved by government and win the public opinion.

The management of water has become a complex policy issue bringing into its fold state, market and civil society. Attempts of commercialization of water are evident and there appears to be some justification in the criticism. The study started as an attempt to understand the politics of inter-relation between state and market in India for provisioning for water to the people. It shows that water is fast becoming a tradable commodity the consequences of which is seen and felt (Samanta 2009). The detailed description of the state of the art and methodologies used in this article is available with full details in Shah and Shete (2019).

23.2 Objective and Goal of the Work

Goal: To attain sustainable water reuse management by full-cost recovery, economic efficiency and economic optimization considering an idea of "negative pricing."

Objective: To achieve optimal sustainability for urban wastewater management for Vadodara Urban Development Authority Area.

Criteria for evaluating this objective are:

Economic returns and profitability
Reliability of water supply.

Specific (Measurable) Indicators:

Amount of water being reused
Cost of distribution network
Selling price of reclaimed water
Internal Rate of Return.

23.3 Methodology

23.3.1 Study Area

The area around Vadodara city under jurisdiction of Vadodara Urban Development Authority is considered in the present study (Fig. 23.1).

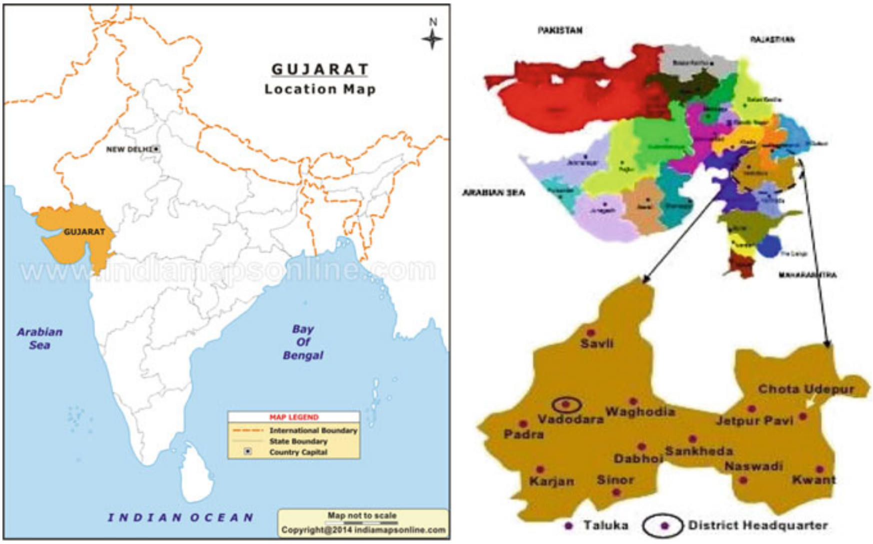

Fig. 23.1 Study area

23.3.2 Data Collection

From the VMSS, data were collected for location, input and output parameters for different sewage treatment plants, cost of treatment, present and future demands, population forecasting, etc. Population was projected using various established and latest techniques, and population to be served in VUDA area was considered as 13 lakhs as obtained by auto regression method.

23.3.3 Specific (Measurable) Indicator

(a) Amount of water being reused

Mainly two type of uses were identified

Agricultural reuse
Industrial and residential reuse.

The criteria for water reuse as given in various standards were studied and considered. The amount of water being reused depends upon demands for industrial and residential reuse and irrigational reuse. These demands had been worked out as explained on page 11 and amount of water being reused was determined.

(b) Cost of distribution network

The major part of the cost of the distribution network depends on diameter of the pipe. Diameter depends on loss of head due to friction. Loss of head due to friction depends on friction factor.

(c) Selling price of reclaimed water

Assuming the profit over the cost of distribution of treated water should be 15%, selling price of reclaimed water was determined.

(d) Internal Rate of Return

IRR is the interest rate at which the net present value of all the cash flows both positive and negative over the period from a project equals to zero.

Based on cost analysis Internal Rate of Return was calculated.

To achieve the goal as stated earlier reclaimed water distribution network model was formulated using QGIS and EPANET.

The proposed land use map for Vadodara is obtained and superimposed on Google Earth view of VUDA area.

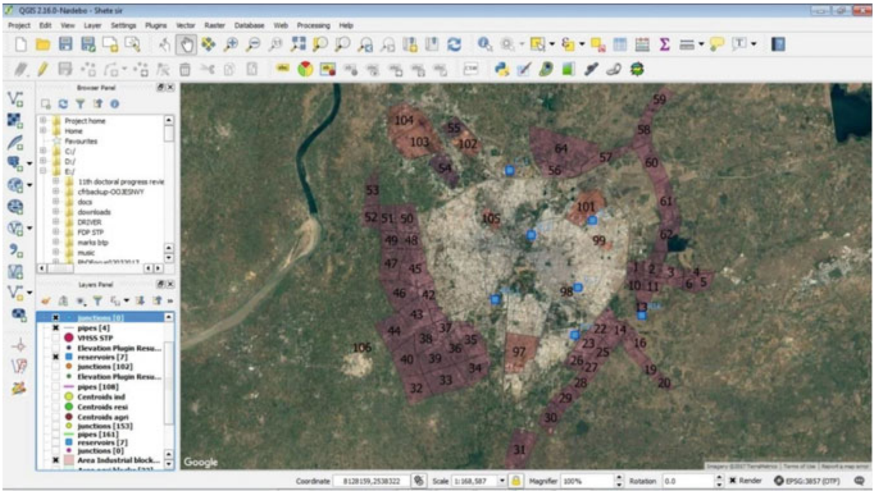

Fig. 23.2 The industrial and residential areas marked in light magenta and light burgundy colour, respectively, surrounding Vadodara city as per proposed land use map 2031 for VUDA area

23.3.4 Identification of Residential, Industrial and Agricultural Areas

The proposed land use map obtained from Vadodara Urban Development Authority (VUDA) was superimposed on Google earth exactly by adjusting scale and matching landmark points. After superimposing proposed land use map various areas had been identified for industrial, residential and agricultural use as per land use zones shown in the VUDA map for developing outskirt areas of Vadodara City. These areas were then marked with different layers in Quantum G.I.S. (QGIS) software as shown in Fig. 23.2.

The areas were divided into small compartments so as to create one node for laying out of proposed reclaimed water pipelines. The network of proposed reclaimed water pipeline was prepared in QGIS using GHydraulics plug-in as shown in Fig. 23.3.

The locations of sewage treatment plants, agricultural zones, industrial and residential zones were identified and the reclaimed water distribution networks from various sewage treatment plants to these areas were prepared.

With seven sources available, question of what should be the optimal proportion of reclaimed water distribution from various sources to different destination arose.

To solve this problem (Vogel Approximation Method) as a special case of linear programming with optimality checks was utilized.

Before doing distribution by V.A.M., primary distribution by visual observation based on vicinity was carried out and network was prepared.

From QGIS, details of area for industrial and residential and agricultural zones were obtained, and centroid of each area was taken to allocate node of pipe network.

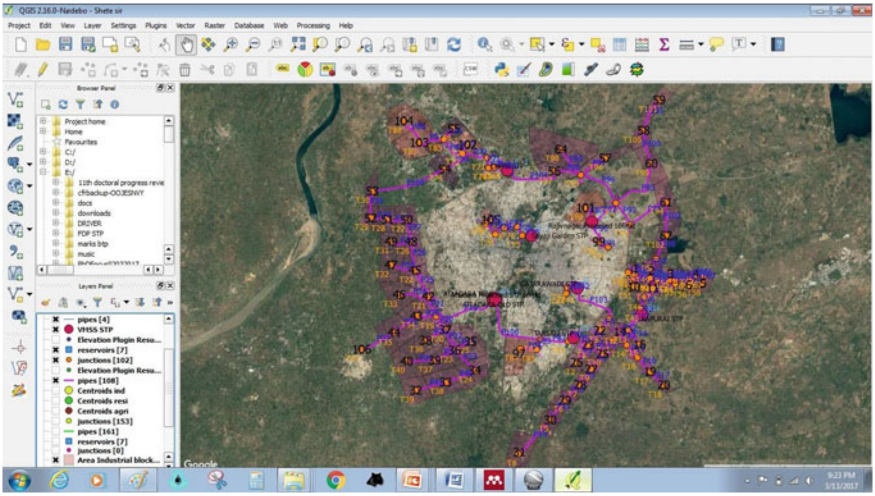

Fig. 23.3 The industrial and residential areas and proposed reclaimed water distribution network from various sewage treatment plants in VUDA area

Elevation of all nodes and lengths of all pipes were obtained from QGIS for networks. Using GHydraulics plug-in input file in the .inp format was prepared from QGIS and imported in EPANET for further analysis.

Considering per capita supply of reclaimed water to be 100 l/day, the demand for each residential zone was found out. For determination of industrial demand, case study of Makarpura GIDC was taken. From VCCI, directory listing of industries in Makarpura GIDC was obtained. For each type of industries, demand was identified and ultimate demand for conglomeration was worked out. Agricultural demand was worked out considering banana crop and drip irrigation system.

After importing .inp file from QGIS, GHydraulics plug-in the .net file was prepared to be run in WaternetGen (an EPANET extension for sizing pipes using simulated annealing algorithm of optimization). First of all separate networks for each treatment plant were considered and design of optimum size of pipes was carried out. Then considering spatial distribution of industrial and residential zones, the integrated model was prepared. The cost of networks was worked out considering material cost, cost for excavation, cost of lowering, laying and joining, refilling the trenches, accessories, etc. complete using GWSSB schedule of rates. As there were several destinations and demand locations with demand and supply constraints, the distribution of treated wastewater from different sewage treatment plant formed an excellent transportation problem.

V.A.M. is considered to be the best method for solution of transportation problem which is a special case for linear programming. To form transportation problem, transportation tableau was required to be prepared and for that from each individual source cost/unit of transportation to each destination was required to be found out.

In order to do this first networks with individual sources were prepared and then optimized. After designing each of these networks cost of transportation from source to each destination for all sources to all destinations was required to be found out.

For this purpose, Elevated Service Reservoirs were required to be designed.

Using mass curve method E.S.R.s were designed and costs of pump and E.S.R. were found out. For calculating the cost of piping from each source to each destination, the links involved in each route were calculated and accordingly piping cost was arrived for each route.

Similarly, pumping cost was calculated for each route considering head loss in each pipe and elevation difference between concerned nodes. Calculation of O, M and R Cost was carried out using Maximum Accelerated Cost Recovery System method for depreciation.

As this was annual cost, the capital cost was also required to be brought in annual format, so total capital cost of sewage treatment plants, tertiary treatment plant, pipe, E.S.R. and pump was multiplied with capital recovery factor using interest rate at 7% and then O, M and R cost and annual capital cost were added. Knowing total supply from each source, the final demand for each node, and transportation cost for each node, the transportation model was prepared.

Finally, AMPL solver (Taha 2011) was selected for the task of solving the tableau by V.A.M. method and optimal allocation was achieved.

Using this final allocation network was prepared and the cost of all components was determined.

23.4 Results and Discussion

Real opportunity cost of providing the reclaimed water was calculated.

Following five scenarios were considered:

Scenario 1: Considering all costs

Scenario 2: Considering only Elevated Service Reservoir, Pump and Piping cost

Scenario 3: Considering only O, M and R Cost

Scenario 4: Considering selling prices as per Sardar Sarovar Narmada Nigam Limited

Scenario 5: Considering saved fresh water cost as per selling prices.

The optimal cost of transportation of reclaimed water from each source to different demand nodes using AMPL solver was determined. There was slight difference in cost calculations in scenarios 1 and 5. In scenario 1, selling price of saved water for irrigation purpose was considered as charged by Sardar Sarovar Narmada Nigam Limited, whereas in scenario 5 selling price of saved water was based on the cost of treated water plus 15% profit for irrigation purpose.

Tableaus for all scenarios were prepared. AMPL solver (Taha 2011) was used to solve the tableau by V.A.M. method and optimal allocation of reclaimed water from each source to different destinations and the optimal costs of transportation of

Table 23.1 **c** Cast distribution for industrial and residential purposes and **d** cast distribution for irrigation purpose

(c)	
Total ESR cost	309,600,000
Total piping cost	871,876,597
Total pump cost	6,370,000
Capital cost of piping, ESR and pump	**1,187,846,597**
(d)	
Total ESR cost	407,720,000
Total piping cost	1,015,388,449
Total pump cost	10,015,543
Capital cost of piping, ESR and pump	**1,433,123,992**

Bold values show the summative or decisive values for different important parameters

reclaimed water from various sources to all destinations for various options were determined.

After selecting all the plants connected network as optimal solution, based on V.A.M. output from AMPL software, the reclaimed water distribution network was prepared.

For this final optimal network, all the costs like pipe network cost, pumping Cost, E.S.R. and pump Cost, O, M and R cost etc. were calculated that is shown in Table 23.1c, d.

For calculation of Internal Rate of Return total capital costs were calculated as follows:

(a) Capital cost treatment plants for primary and secondary treatment—Rs. **4,294,049,105**
(b) Capital cost treatment plants for tertiary treatment—Rs. **457,846,259**

Total Capital Cost 7,372,865,953

(a + b + c + d) Say 7.37 × 10^9.

Selling price for industrial and residential reuse for scenario 1 was calculated as Table 23.2.

This selling price is similar to selling price of Sardar Sarovar Narmada Nigam Limited selling price of Rs. 40.17 Rs./KL in 2020.

Similarly, the selling price for irrigation purpose reuse was also determined and it came to be Rs. 9/K.L.

Internal rate of return was calculated using selling price of reclaimed water and all the costs to treat the urban wastewater for each of the five scenarios to ascertain the economic sustainability of the project (Table 23.3).

The optimal solution for scenario 1, Table 23.4 was subjected to sensitivity analysis by increasing and decreasing demand by 5, 10 and 15%, and % variations in AMPL optimal output were found out.

Table 23.2 Details of selling price for industrial and residential reuse for scenario 1

Total demand in MLD	177.946
The annual cost of the treatment plant, including O and M	Rs. 278,161,627
The annual cost of additional treatment	Rs. 457,846,259
Cost of additional treatment O and M	Rs. 1,335,605,508
Annual cost of E.S.R., pump and piping	Rs. 95,724,285
Total O, M and R cost for piping, E.S.R. and pump	Rs. 66,945,285
Total pumping cost	Rs. 25,729,757
TOTAL COST	Rs. **2,260,012,721**
i.e. COST/MLD	Rs. **12,700,554**
i.e. COST/Kilo Liter	Rs. 34.80
Adding 15% profit	5.22
Selling price/K.L	Rs. **40.02**
Say	**Rs./KL 40.00**

Bold values show the summative or decisive values for different important parameters

As % variation in AMPL optimal output varied from −0.02 to 1.23%, it was considered as negligible for practical considerations. Therefore, internal rate of return was not calculated for increase and decrease in demand by 5, 10 and 15%.

The next alternative for sensitivity analysis is variation in selling price. Considering increase and decrease in selling price by 5, 10 and 15%, internal rate of return was calculated for all the five scenarios, whereas 3 scenarios shown in Fig. 23.4.

Internal rate of return was also calculated considering negative pricing. At present, there are five existing S.T.P.s and one proposed S.T.P. at Rajivnagar. Looking to the future need of VUDA area, it is assumed that a new additional S.T.P. at Chhani is required. Table 23.5 represents IRR with and without negative pricing consideration for with and without 35 M.L.D. Chhani new plant.

IRR with and without considering Chhani new plant for different scenarios were calculated. Scenario 5 is the best choice under given conditions which is normally prevalent everywhere.

Achievements with respect to objectives

Specific (measurable) Indicator

(a) Amount of water being reused

For irrigation, gardening and tree plantation purposes = 248.584 MLD.

Total water to be reused = 426.530 MLD.

(b) Cost of combined distribution network

Industrial and residential purposes = Rs. 871,876,597.

(New Chhani plant was not considered for industrial and residential purposes network because all the reclaimed water from Chhani new plant was given for irrigation purpose.)

Table 23.3 IRR for scenario 1 considering all costs

Sr. No.	Particulars	0th year	1st year	2nd year	3rd year	…	28th year	29th year	30th year
1	**CAPITAL COST, Rs.**	7.37×10^9				**…**			
1.1	**LOAN RECEIVED FROM BANK, Rs.**	6.06×10^9				**…**			
2	**FIXED COST**					**…**			
2.1	Rate of depreciation for first half year as per MACRS, %			3.75	7.219	**…**	0	0	0
2.2	Rate of depreciation for second half year as per MACRS, %		3.75	7.219	6.677	**…**	0	0	0
2.3	Depreciation for 1st half year, Rs.		0	1.38×10^8	2.66×10^8	**…**	0	0	0
2.4	Depreciation for 2nd half year, Rs.		1.38×10^8	2.66×10^8	2.46×10^8	**…**	0	0	0
2.5	Total depreciation, Rs.		1.38×10^8	4.04×10^8	5.12×10^8	**…**	0	0	0
2.6	Cumulative depreciation, Rs.		1.38×10^8	5.43×10^8	1.05×10^9	**…**	7.37×10^9	7.37×10^9	7.37×10^9
2.7	Amount of repayment of loan, Rs.		4.46×10^8	4.46×10^8	4.46×10^8	**…**	4.46×10^8	4.46×10^8	4.46×10^8
2.8	Interest obtainable in 1st half year, Rs.		0	2.76×10^6	1.10×10^7	**…**	1.54×10^8	1.54×10^8	1.54×10^8
2.9	Interest obtainable in 2nd half year, Rs.		0	5.58×10^6	1.66×10^7	**…**	1.57×10^8	1.57×10^8	1.57×10^8
2.10	Total interest to be received on depreciation money, Rs.		0	8.35×10^6	2.76×10^7	**…**	3.10×10^8	3.10×10^8	3.10×10^8

(continued)

Table 23.3 (continued)

Sr. No.	Particulars	0th year	1st year	2nd year	3rd year	…	28th year	29th year	30th year
2.11	Interest lost on 25% capital cost as seed money, Rs.		7.37×10^7	7.37×10^7	7.37×10^7	**…**	7.37×10^7	7.37×10^7	7.37×10^7
3	Insurance, Rs.		5.53×10^7	5.53×10^7	5.53×10^7	**…**	5.53×10^7	5.53×10^7	5.53×10^7
4	Cost of O and M for primary and secondary plant, Rs.		1.73×10^8	1.73×10^8	1.73×10^8	**…**	1.73×10^8	1.73×10^8	1.73×10^8
5	Cost of O and M for tertiary plant, Rs.		1.34×10^9	1.34×10^9	1.34×10^9	**…**	1.34×10^9	1.34×10^9	1.34×10^9
6	Maintenance and repairs of E.S.R., pump and piping, Rs.		1.54×10^8	1.54×10^8	1.54×10^8	**…**	1.54×10^8	1.54×10^8	1.54×10^8
7	Pumping cost, Rs.		6.10×10^7	6.10×10^7	6.10×10^7	**…**	6.10×10^7	6.10×10^7	6.10×10^7
8	Operator's salary, Rs.		1.44×10^6	1.44×10^6	1.44×10^6	**…**	1.44×10^6	1.44×10^6	1.44×10^6
9	Other charges, Rs.		3.69×10^7	3.69×10^7	3.69×10^7	**…**	3.69×10^7	3.69×10^7	3.69×10^7
10	CASH OUTFLOW, Rs.		2.34×10^9	2.34×10^9	2.34×10^9	**…**	2.34×10^9	2.34×10^9	2.34×10^9
11	**NET CASH OUTFLOW, Rs.**		$\mathbf{2.34 \times 10^9}$	$\mathbf{2.33 \times 10^9}$	$\mathbf{2.31 \times 10^9}$	**…**	$\mathbf{2.03 \times 10^9}$	$\mathbf{2.03 \times 10^9}$	$\mathbf{2.03 \times 10^9}$
12	**INCOME**					**…**			
12.1	Selling price of treated water for industrial and residential purpose Rs./KL		40.00	40.00	40.00	**…**	40.00	40.00	40.00
12.2	Total treated water to be sold for industrial and residential purpose, K.L		6.50×10^7	6.50×10^7	6.50×10^7	**…**	6.50×10^7	6.50×10^7	6.50×10^7

(continued)

Table 23.3 (continued)

Sr. No.	Particulars	0th year	1st year	2nd year	3rd year	…	28th year	29th year	30th year
12.3	Income from selling treated water for industrial and residential purpose, Rs.		2.60×10^9	2.60×10^9	2.60×10^9	**…**	2.60×10^9	2.60×10^9	2.60×10^9
12.4	Total saved fresh water income as per SSNNL rates for industrial and residential purpose, Rs.		2.60×10^9	1.69×10^9	1.69×10^9	**…**	1.69×10^9	1.69×10^9	1.69×10^9
12.5	Selling price of treated water for irrigation purpose, Rs./KL		9	9	9	**…**	9	9	9
12.6	Total treated water to be sold for irrigation purpose, K.L		8.15×10^7	8.15×10^7	8.15×10^7	**…**	8.15×10^7	8.15×10^7	8.15×10^7
12.7	Income from selling water for irrigation purpose, Rs.		7.34×10^8	7.34×10^8	7.34×10^8	**…**	7.34×10^8	7.34×10^8	7.34×10^8
12.8	Total saved fresh water income as per SSNNL rate for irrigation purpose		4.32×10^7	4.32×10^7	4.32×10^7	**…**	4.32×10^7	4.32×10^7	4.32×10^7
13	**CASH INFLOW**		5.06×10^9	5.06×10^9	5.06×10^9	**…**	5.06×10^9	5.06×10^9	5.06×10^9
14	**NET CASH FLOW, Rs.**	$\mathbf{-1.34 \times 10^{10}}$	2.73×10^9	2.73×10^9	2.75×10^9	**…**	3.04×10^9	3.04×10^9	3.04×10^9
15	**INTERNAL RATE OF RETURN**		***27.47%***			**…**			
			1ST YEAR	**2ND YEAR**	**3RD YEAR**	**…**	**28th YEAR**	**29th YEAR**	**30th YEAR**

Bold values show the summative or decisive values for different important parameters

Table 23.4 Sensitivity analysis of optimal solution for different scenarios

Description	Internal rate of return						
	Original selling price (%)	% Increase and decrease in selling price					
		5%	10%	15%	−5%	−10%	−15%
Scenario 1	27.47	29.99	31.97	32.92	25.56	22.99	22.03
Scenario 2	NA						
Scenario 3	17.76	19.20	21.19	23.22	16.31	14.29	12.18
Scenario 4	22.37	NA					
Scenario 5	32.88	36.04	37.95	38.91	30.97	27.82	26.86

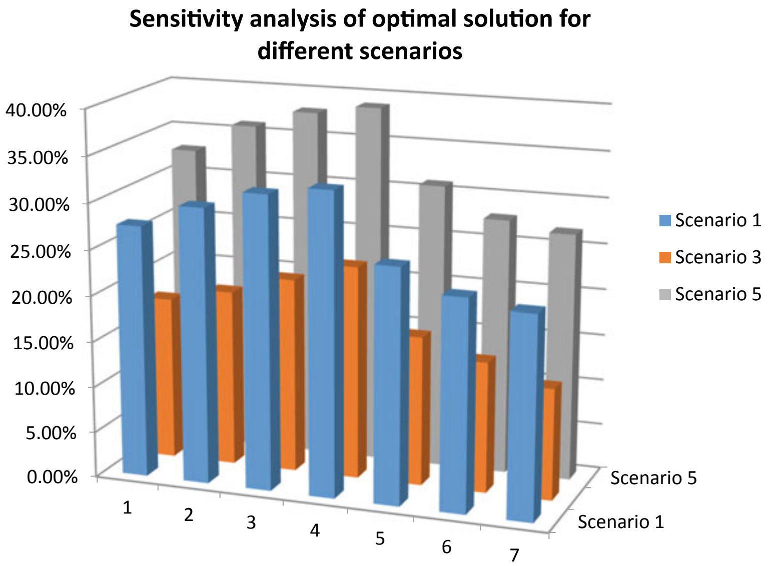

Fig. 23.4 Sensitivity analysis of optimal solution for different scenarios

Table 23.5 IRR with and without considering Chhani new plant for different scenarios and considering negative pricing

Description	Considering 35 M.L.D. Chhani new plant		Without considering 35 M.L.D. Chhani new plant	
	Original (%)	With negative pricing (%)	Original (%)	With negative pricing (%)
Scenario 1	26.33	20.10	27.47	21.01
Scenario 2	NA		NA	
Scenario 3	16.52	12.77	17.76	13.83
Scenario 4	20.91	16.78	22.37	18.03
Scenario 5	32.35	26.13	32.88	26.42

Table 23.6 Internal rate of return with and without negative pricing consideration for with and without 35 M.L.D. Chhani new plant

Description	Considering 35 M.L.D. Chhani new plant		Without considering 35 M.L.D. Chhani new plant	
	Original (%)	With negative pricing (%)	Original (%)	With negative pricing (%)
Scenario 1	26.33	20.10	27.47	21.01
Scenario 2	NA		NA	
Scenario 3	16.52	12.77	17.76	13.83
Scenario 4	20.91	16.78	22.37	18.03
Scenario 5	32.35	26.13	32.88	26.42

Irrigation purposes:

Without New Chhani STP = Rs. 1,015,388,448.

With New Chhani STP = Rs. 1,062,799,022.

(c) Selling price of reclaimed water

Industrial and residential purposes = Rs. 40/K.L.

Irrigation purpose:

Without New Chhani S.T.P. = Rs. 9/K.L.

With New Chhani STP = Rs. 10/KL.

(d) Internal Rate of Return, Table 23.6 with Chhani New Plant.

Criteria

(a) Economic returns and profitability

IRR for scenario 1 considering option with and without Chhani new S.T.P. plant were 26.33% and 27.47%, respectively.

IRR for scenario 5 considering option with and without Chhani new S.T.P. plant were 32.35% and 32.88%, respectively.

As the IRR is above 11% (criteria of Asian Development Bank), the distribution of reclaimed water is economically sustainable.

(b) Reliability of water supply

As the IRR is above 11% (criteria of Asian Development Bank), the distribution of reclaimed water is sustainable. Therefore, the prospect of sustainability will make the reclaimed water distribution reliable.

As all plants are connected in selected option, during failure of any plant, water can be diverted from other plant and thus reliability of supply can be achieved.

The most important point to be noted is the cost of reclaimed water will become Rs. 29/KL in 2020 if yearly increase of 10% in anticipated till 2050. The present rate of Sardar Sarovar Narmada Nigam for non-agricultural usage is Rs. 26/KL in 2020.

That means the cost of reclaimed water is almost equal to fresh water. Further the IRR obtained is 34% which is very high and practically 12% is sufficient to make the project economically attractive. Considering 12% IRR, the cost of reclaimed water will be Rs. 7/K.L. and water for irrigation can be made available at Rs. 1/K.L. Considering 10% increase annually, it will further reduce to Rs. 3/K.L. for industrial purpose and Rs. 0.5/K.L. for irrigational purpose.

If the cost of saved fresh water by using reclaimed water is not considered than also the cost of reclaimed water for industries is coming to be Rs. 21/K.L. for industrial purpose and Rs. 2/K.L. for irrigational purposes.

Thus, it is clearly established that water reuse from sewage treatment plants for industrial, residential and irrigational purpose is not only beneficial for environmental purpose but also economically attractive and can cater as source of revenue promoting infrastructure growth by P.P.P. model.

23.5 Conclusion

As Specific (measurable) Indicators fulfil the criteria, the objective can be achieved. Thus, it can be stated that reuse of reclaimed water to VUDA area is sustainable. After calculating IRR, sensitivity analysis was carried out by increasing and decreasing the selling price by 5, 10 and 15% for scenario 1 and scenario 5. In all cases, IRR remained well above 11%. So, even if there is decrease of 15% in selling price the reuse option is profitable. The sensitivity analysis reveals that scenario 2, 3 and 4 are not profitable. Scenario 5 is the most profitable option therefore selling price of reclaimed water for industrial and residential purposes should be Rs. 40/K.L. and for irrigation purpose Rs. 10/K.L. Considering 12% IRR, the cost of reclaimed water will be Rs. 7/K.L. and water for irrigation can be made available at Rs. 1/K.L. Considering a 10% increase annually, it will further reduce to Rs. 3/K.L. for industrial purpose and Rs. 0.5/K.L. for irrigational purposes. The successful and reliable designing of reclaimed water can be carried out using QGIS, EPANET and such open-source software with minimum time and site work. From these conclusions, it is no longer appropriate to consider treated municipal wastewater as a "waste" that requires "disposal," but rather, it should be used as a resource that can be put to beneficial use.

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