Application of GETFLOWS and HEC-RAS in Assessing Sediment Balance Within River Estuary

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Abstract River plays an important role in the human need as it provides water for human usage, irrigation, agriculture and industry as well as a range of other ecosystem services other than intrinsic and biodiversity values. Managing the river can lead to many benefits and convenience. However, due to lack of proper management, rivers can be easily polluted due to human activities. Sediment is one of the components that can damage the ecosystem and diversity of the river especially in local spots which involves soil erosion. Heavy rainstorms can cause an excessive erosion event,

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however, most soil erosion happens gradually over time and is very hard to notice without constant monitoring. Furthermore, the sediment will be mobilized and transported along the river and eventually stored in the bottom of the river, but usually it will deposit near the estuary. A sediment modeling is needed to carter this problem as to predict the behavior of the sediment based on the hydrological components. The comparison between the 1D (HEC-RAS) and 3D (GETFLOWS) will be discussed in this paper to check the suitability and the validity of the model in sediment studies.

Keywords Sediment balance · GETFLOWS · HEC-RAS · Estuary · Sediment transport · Soil erosion · Clean water and sanitation

1 Introduction

The rapid urbanization is one of the factors has an adverse impact on the future land use and soil sustainability. Rapid development occurs when the number of populations increases along with agricultural production, construction as well as other anthropogenic activities [1, 2]. In rivers, erosion takes place as a natural process as the soil erosion typically caused by water which initiates the detachment process of soil particles via raindrops and flowing water and soil particles move downslope [3].

Soil erosion occurs because of the weathering of soil via water, especially when the soil is exposed in rainstorms events for a long time which will then carry sediment along the river [4]. Flooding will result from the transportation of the sediment from the surrounding activities along the river will be deposited at the bottom of the river where the depth of the river will be affected. Practically, forests result in less soil erosion than agricultural land use, whereas agricultural plantation area tends to hasten erosion, which worsens river water quality due to the high transportation of suspended sediment loads [5].

The GETFLOWS simulation model allows to analyze and estimate the river's current condition in three-dimensional (3D) models. River simulation in 3D models required input details of meteorological records, land cover, geology, and soil characteristic from secondary data collection [6]. The outcome of the simulation can predict and estimate the water cycle (surface water, groundwater and seawater) for the future by comparing the field monitoring data based on concentration of the suspended sediment, river erosion and deposition and also water flow rates.

The widely used software application to simulate sediment transportation is HEC-RAS. The computation of this software utilizes one dimensional (hydraulic property, cross section averaged from RAS's hydraulic engines to analyze sediment transport rates and revolution of channel geometry based on sediment continuity calculations) [7, 8]. This enables the calculation for river aggregation or erosion, temporal entrainment, transport and deposition of sediment and alteration of the cross sections.

2 Source, Transport and Storage of Sediment

Sediments originates from anthropogenic activities and natural processes. These two factors that are human conditioning or nature can contribute to soil erosion. Centuries ago, soil erosion triggered by the improper land use practices has been regarded as a global threat to soil sustainability and food security [38, 39] and major environmental and agricultural sector [40]. Ouillon [41] discussed the sediment mobility process includes the process of erosion and the role of water to transport the sediment. Unconsolidated sediments are transported by erosion match the energetic forces that able to drive the sediment downstream of the river. Physical weathering and chemical weathering induce the degradation of rocks and soil, after which particles are eroded, removed and carried into the waterbody. Rainfall and surface runoff act as the driving force behind soil erosion. Meanwhile, the bottom shear and turbulence level acting as the primary transport agent for all collected material.

The deposition of sediment into a waterway can significantly degrade the water quality and aquatic habitat. Accumulation of sediments in a waterway has high level of suspended solid concentration and less light penetration. Elevated water temperature causing the dissolved oxygen levels to drop [9].

2.1 Estuarine Sediment

Terrestrial matter is transported to the sea by the estuarine confluence between the two water bodies that are the freshwater and seawater. The coastal region has been severely affected by the surrounding's rapid economic development. The problems that arise at the coastal area due to the significant anthropogenic inputs (industrialization and urbanization activities, and ecological issues) transported by estuaries. Consequently, a few researchers agreed that the ecosystem at the estuary can be count as one of the most exploited and universally endangering environment systems [10–13].

The geology and morphology of the estuaries depend on the landscape setting. The primary origin is the crucial component to the classification of the estuary itself because it varies substantially [14, 15]. Townend et al. [15] asserts that the origin is influenced by the antecedent landform such as surface deformation of the hard geology, marine derived embayment and fluvial/glacial river valleys. Accordingly, there were evidence confirmed by researchers, namely Townend et al. [15], Dalrymple [16] and Rees et al. [17] that the marine transgression of estuaries produced from marine and fluvial sediment is transported toward river valley under the effect of sea-level rise.

The floodplain is formed alongside the estuarine based on the volumetric difference between freshwater and seawater. The formation of the estuaries natural landscape setting is depicted in Fig. 1. The alluvial estuaries in river valleys respond to marine tide as to maintain its position in the tidal frame where the estuary moves

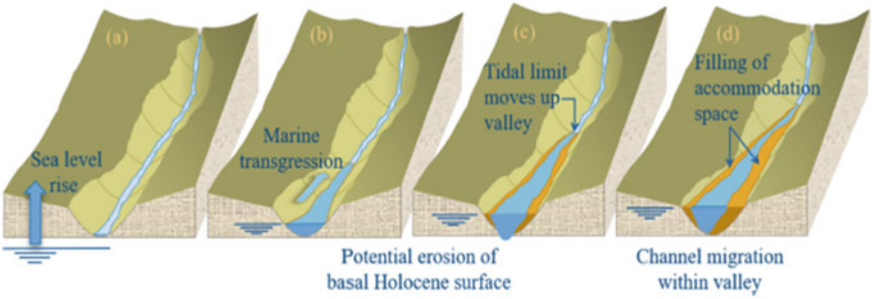


Fig. 1 Progression of river valley due to effect of sea level rise (*Source* [15])

landwards indicating the implication of marine transgression. The kinematic movement along the estuary morphology can potentially cause erosion. It enables the relative significance of the space open to sediment deposition from river and marine. The system is more susceptible to changes in sediment supply or the rate of sea-level rise when the size of the floodplain is smaller because the transgression distance is reduced. The changes in the estuary form with the greater landward movement will manipulate the sediment demand. Conversely, more space is available when the floodplain is separated from the estuary. Therefore, restoration of the estuarine landscape will rely on the availability of sediment and the rate of sea-level rise.

2.2 *Sediment Balance*

In river system, the concept of sediment balance in rivers describes the equilibrium between the amount of sediment supplied to a water channel and capacity of the flow to transport that sediment. Long-term sediment supply to rivers, sediment transport via rivers and sediment storage in watersheds collectively known as the sediment regime, generally achieve a state of dynamic equilibrium resulting in distinct channel morphologies [18, 19]. Wohl et al. [20] mentioned that the natural sediment regime is hardly observable, given the degree of human alteration to land cover (inputs) and instream modification (storage and movement). As a result, researchers differentiate between natural and balanced sediment regimes, where balanced sediment regime happens when the water flow have enough energy to carry sediment is proportional to availability of sediment over a specified period and the river shape is stable in equilibrium. He further stated that when the whole river system such as water and sediment is altered where the ecosystem and biota are attuned.

2.3 *Equation Involved in Sediment Balance*

2.3.1 Fringe's Equation

A study made by Frings et al. [21], an analysis to quantify the downstream fluxes of different sediment particles size through the Rhine River for the period 1990–2010 and identifying sediment source in the upstream and sediment deposition within the channel. As illustrated in Fig. 2 shows the sediment balance components for both sediment input, output and storage. The sediment inputs consist of sediments carried from the upstream area, sediments carried from the tributaries, riverbank erosion, artificial sediments fed into the river channel. While the sediment outputs and storages occur when the sediments are exit from the targeted channel, riverbed sediments removed by river mining, sediments in the floodplains and/or groin fields, riverbed material abrasion. The parameters used in this study are sediment transport analysis, bed-level analysis, sediment budget analysis and grain size analysis.

Frings mentioned that sediment budget is the balance of whole sediment process ($I - O = \Delta S$) between the mass of sediment entering the targeted river (I), the mass of sediment exiting the targeted area (O) and the differences in sediment mass stored inside the targeted river area (ΔS) as shown in Eq. (1). However, a mathematical sediment transport model is required to analyze the stored sediment in the channel where which benefits from a precise spatial distribution and more reliable prediction [22]. The sediment balance equations are extracted as shown below (tonnes/area):

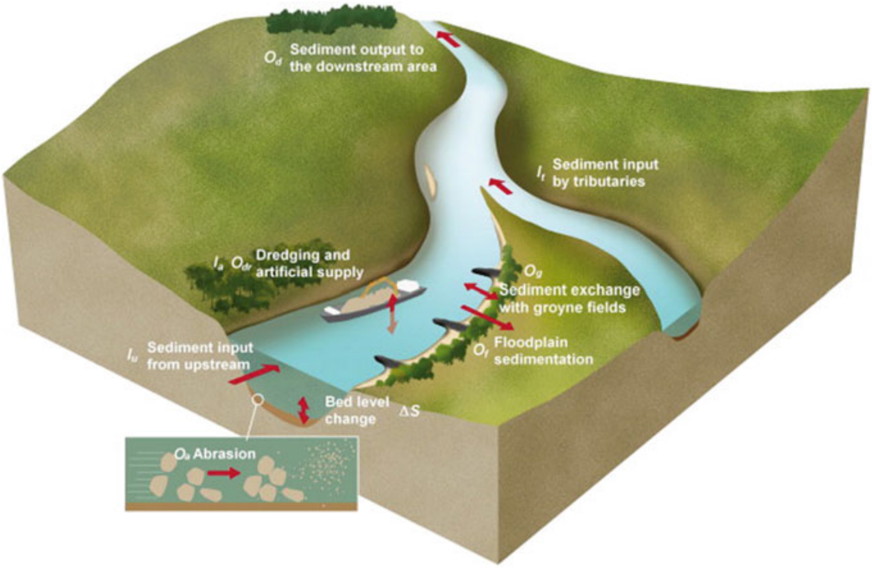


Fig. 2 Scheme of sediment balance components (*Source* [21])

$$
\begin{aligned}
&I_{\text{tributary}} + I_{\text{Upstream}} + I_{\text{sediment feeding}} + I_{\text{bank erosion}} - O_{\text{dredging}} \\
&- O_{\text{downstream}} - O_{\text{abrasion}} - O_{\text{floodplains/groynefields}} = \Delta S
\end{aligned}
\tag{1}
$$

where

ΔS—change in the storage of sediments.

(a) Sediment Input (I)

I_{Upstream}—sediments carried from upper part of the river.

$I_{\text{tributary}}$—sediments carried from the river tributaries.

$I_{\text{bank erosion}}$—sediments generated from bank erosion.

$I_{\text{sediment feeding}}$—sediments artificially dump into the river.

(b) Sediment Output (O)

$O_{\text{downstream}}$—sediment mobilized to the end of the river.

$O_{\text{floodplains/groinfields}}$—sediments retained in the floodplains and/or groin fields.

O_{abrasion}—river-bed material abrasion.

Finally, the changes in the net morphological sediment stored in the study area (ΔS) are shown in Eq. (2):

$$
\Delta S = ((\Delta z - \Delta zt)/\Delta t)) \cdot W \cdot L \cdot \Delta \mathrm{P}s(1 - p) \tag{2}
$$

where

ΔS—net changes in sediment.

$\Delta z - \Delta zt$—river-bed change in time interval Δt.

W—river width.

L—river segment's length.

$\mathrm{P}s$—specific weight of sediments.

p—porosity of the bed material.

The results demonstrate that the suspended solid, which included clay and silt as characteristics and was also known as a wash load, was transported more frequently than the bed load. According to Fig. 3, the transported sand dominated over gravel in the sense of morphologically sediment cycle. While the mobility of coarse gravel (including cobbles) remained small toward downstream and once more the fine gravel is increasing.

Fring et al. [21] provide further evidence that according to budget analysis of sand and gravel being supplied to the targeted river segment is limited. There were 3 major sediment source which occurs in the study area that are 1/3 total of sediment flux originated from the upstream, 1/3 was supplied by the bed degradation and 1/3

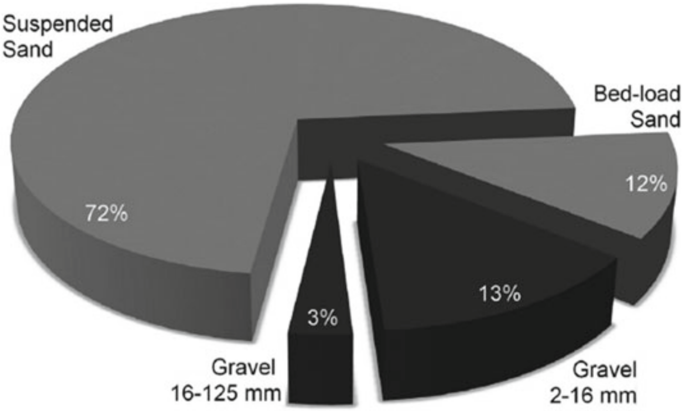


Fig. 3 Composition of the sediment load at the study area

was added artificially by humans to stabilize the bed as demonstrated in Fig. 4. The transition zone between gravel and sand, mining-induced subsidence and places with tertiary sand close to the bed surface is where bed degradation is the most severe. The study confirms that the erosion occurs on the riverbed will generate high sand and fine gravel loads. While the bed slope and flow velocities decrease in further downstream, the coarse gravel and cobble loads will decrease due to a reduced sediment mobility. Just a little amount of sediment was lost to abrasion can be found throughout the study.

3 GETFLOWS

The General-purpose Terrestrial Fluid Flow simulator or GETFLOW is a simulation code for numerical modeling of multiple flow analyzes code to minimize the discrepancy between numerical simulation and observation. The surface flow data is in two dimension, while the subsurface data is in three dimension. A study by Hazart et al. [23] stated that the GETFLOWS are used to compute the water balance component that will be used to train the surrogate model to obtain the global water balance indicator. This is also to estimate the movement of water flow in surface and subsurface sections of a basin watershed which requires a thorough analysis of precipitation patterns, land use, soil properties, and hydrological modeling. This modeling ensures the data to be obtained and estimation of water balance without having additional steps to execute an expensive hydrological model. It is also said suitable to be the new support-decision strategy for regional watershed stakeholders lacking numerical modeling knowledge [24]. In other instances, the GETFLOWS are used to simulate the hydromechanical behavior during gas migration and consider the mechanical stability of engineered barrier system [42].

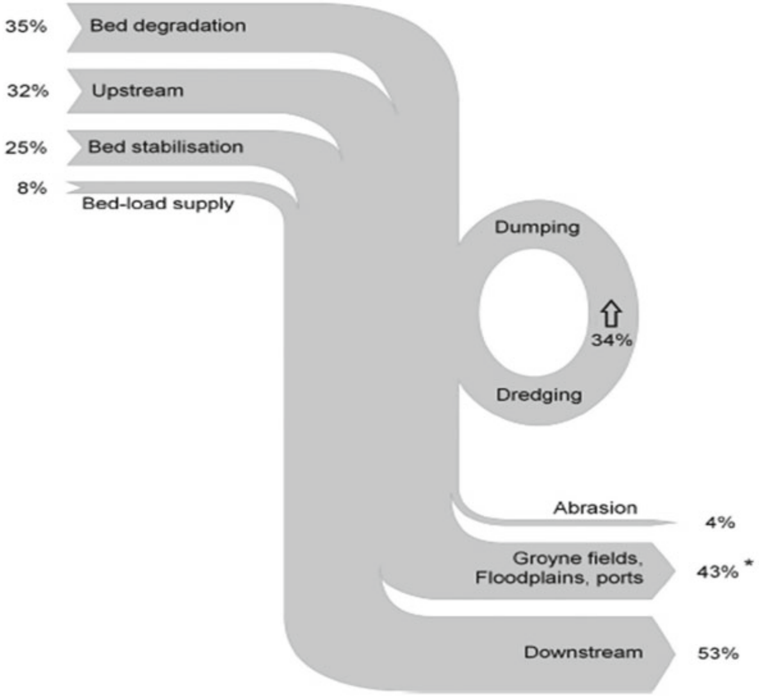


Fig. 4 Sediment budget (*Source* [21])

3.1 Application of GETFLOWS in Environmental Monitoring (Sediments)

According to study by Mori et al. [25], a fully integrated watershed modeling simulator was developed to simulate the mobility of radionuclides. The GETFLOWS also be utilized in the study of the radiocesium (^{137}Cs) fate and transport process from Fukushima Dai-ichi earthquake and the subsequent tsunami to reproduce the redistribution of ^{137}Cs in an actual watershed. The study objectives were achieved through few key assumptions in the modeling. The initial assumption by using the diffusive wave approximation of the shallow water equations is that surface water dynamics, including that of rivers, streams, and hillslopes, will be addressed. Second, a two-phase isothermal compressible air or water flow model of the fluid system is used. Third, the concentration level of radionuclide and suspended sediment does not impact fluid properties such as compressibility, viscosity and fluid density.

Fourth, the appearance of suspended sediment can only be seen on the surface water, while colloid transport in groundwater is ignored. Fifth, the surface soil composed of different particles grain sizes and can easily be detached by the water flow. Sixth, the fate and transport of radionuclides is influenced by suspended sediment, surface and subsurface water. All the assumptions above are used to understand the conceptual model of the watershed system. Data needed in mathematical part of the governing equations are the fluid flow, radionuclide transport-coupled processes and sediment. Fluid flow is represented by coupled surface and subsurface fluid flows. From the generalized Darcy Law, the continuity and the shallow water equations for surface flow serve as the governing equation. The model can generate an accurate estimation of the water saturation, air pressure and temperature for the entire watershed in both surface and subsurface. The required major parameters to conduct the modeling of the radionuclide transport model are listed in Table 1.

The phases in modeling surface/subsurface water flows, sediment and radionuclide transport coupled are summarized into a flowchart (Fig. 5).

Figure 6 shows the schematic diagram of fallout radionuclide redistribution in the watershed system, where the radionuclides deposited on the land surface can be transported by sediment, surface water flow and subsurface water flow in the watershed system. Aqueous phase and solid phase are the two primary transport media for radionuclides. Both in surface and subsurface water flow, the radionuclide redistribution is entirely interconnected with each other [25]. Whereas contaminated sediment particles contained radionuclides element can be mobilized in surface water flows, but groundwater was assumed otherwise. Both surface water and groundwater become the media to transport radionuclide species into surface water bodies.

Another work by Mori et al. [25] simulated the fate and mobility of nitrogen coupled with biogeochemical kinetics reaction. In this study, the kinetic reaction between several chemical elements (i.e., ammonium nitrogen, nitrate nitrogen, etc.) and microbial activities was taken into account. The exchange of polluted water in surface and subsurface can be calculated though the interaction on land surface, where nitrogen loads from point and nonpoint source can be identified.

To grasp better understanding in the conceptual model, this study considers the generalized fluid flow as a compressible, isothermal. (multiphase and multicomponent fluid approach.) They considered the diverse distribution of meteorological conditions, hydrologic processes, land use/land cover (LULC), topography, soil surface and water. Surface water (streams, hill slope and reservoir flows) is portrayed as a depth-averaged, diffusive was approximation including. The concentration of nitrogen levels was mostly regulated by continuous groundwater discharge for a long period where it can be predicted through the discharge of nitrogen from subsurface water to the rivers and the lake water [25]. It further stated that the coding determines water flows, surface water flows, subsurface air and sediment transport by soil erosion, suspension within surface water flows and re-deposition. Cesium-137 transport was estimated in both forms; particulate and dissolved [25, 27].

According to Kitamura et al. [6], a study was made by using GETFLOWS to simulate the sediment migration within five basins focusing around Fukushima Daichi Nuclear Power Plant (FDNPP). The model is used to design and develop as to treat soil erosion from rain splash erosion and hydraulic erosion/deposition. In order to achieve that, the model used to simulate surface and subsurface flows in a fully coupled way. As stated by Sakuma et al. [28], the code is applied for sediment transport, where it simulates raindrop-induced soil detachment, including the impacts of interception by forest canopies, and direct erosion by surface water flows. The model

Table 1 List of major parameters required for the radionuclide transport assessment

Categories	Required specification	Unit	Notation	References
1. Meteorology	Rate of precipitation	(mm/d)	H	[6, 25, 26]
	Air temperature	(C)	T_a	[25, 26]
	Wind velocity	(m/s)	U	[26]
	Daytime length	(s)	H	[25, 26]
	Solar radiation	W/m^2	S_a	[26]
	Saturation vapor pressure	(Pa)	E	[25]
2. Land surface processes	Elevation	(m)	Ξ	[6, 25, 26]
	Manning's roughness parameter	(m − 1/3 s)	n	[6, 25, 26]
	Canopy cover density	(–)	Cc	[6, 25]
	Albedo	(–)	A	[26]
	Bulk transfer coefficient	(–)	C_H	[26]
	Vegetation cover density	(–)	C_L	[6]
	Canopy height	(m)	PH	[6, 25]
3. Subsurface fluid flow	Intrinsic permeability	(m/s)	K	[6, 25, 26]
	Effective porosity	(–)	ϕ	[25, 26]
	Void ration	(–)	e	[6]
	Relative permeability	(–)	kr	[25, 26]
	Capillary pressure	(Pa)	P_c	[25, 26]
4. Sediment transport	Particle density	(kg/m^3)	Pss	[6, 25]
	Grain size composition	(–)	H	[6, 25]
	Soil detachability index	(g/j)	ke	[6, 25]
	Sediment settling velocity	(m/s)	V_{ss}	[6]
	Cohesive strength	(Pa)	J	[25]
	Transport capacity derived from experiment		c, n	[6]
	Bed material cohesiveness (dimensionless)	(–)	β	[6]
5. Radionuclide transport	Decay constant	(1/s)	λ	[25, 26]
	Soil/rock density	(kg/m^3)	Ps	[25, 26]
	Molecular diffusion coefficient	(m^2/s)	Dcw	[25, 26]
	Distribution coefficient	(L/kg)	Kd	[25]
	Tortuosity factor	(–)	t	[25, 26]
	Dispersion length	(m)	aL, aT	[25, 26]
	Decay constant	l/s	λ	[26]
	Heat capacity	J/kg/K	cr	[26]
6. Heat transport	Thermal conductivity	W/m/K	κ	[26]

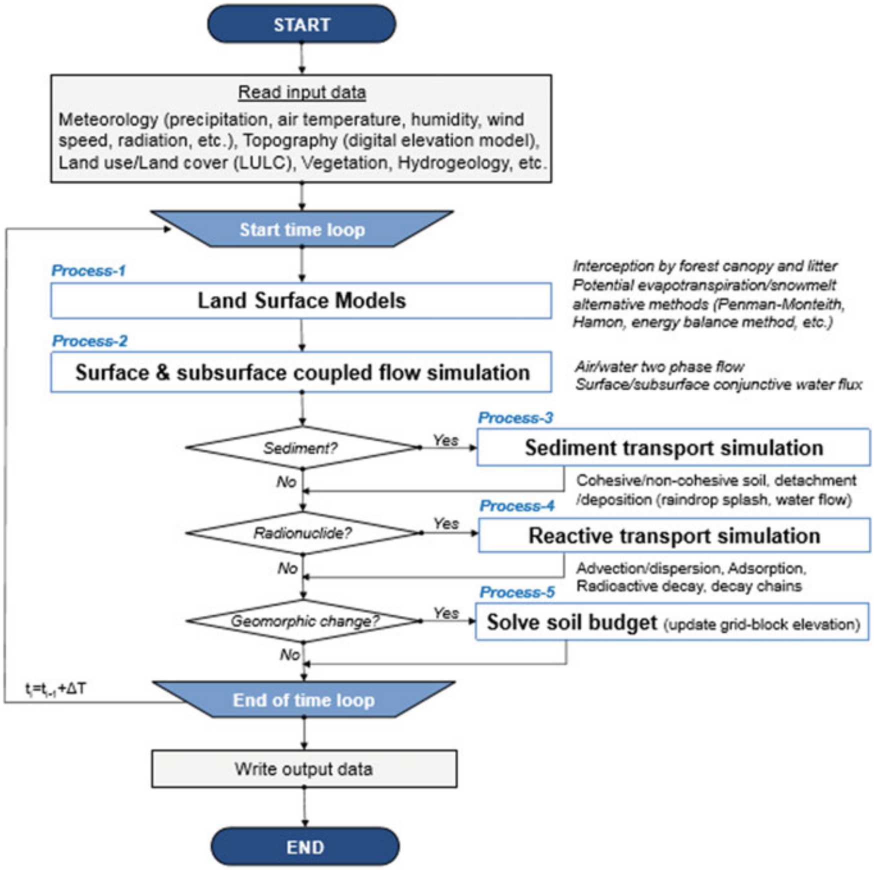


Fig. 5 Coupled simulations flowchart of surface and subsurface water flows, sediment and radionuclide transport (*Source* [25])

input parameters relating to rain splash erosion, such as land use, canopy height and coverage and vegetation type. In this case, to study the radiocesium transport and discharge between basins near the FDNPP following heavy rainfall events.

Sakuma et al. [27] conducted a study to assess the amount of ^{137}Cs redistribution that occurred in the Oginosawa River catchment over a certain period. The goal of study was to grasp the knowledge regarding the difference on the relative contributions between adjacent land to channels and forested areas far from channels to ^{137}Cs input to the watercourses, respectively. This study also emphasized the need to recognize the effect of decontamination work on soil erosion and movability of sediment rates within the catchment area.

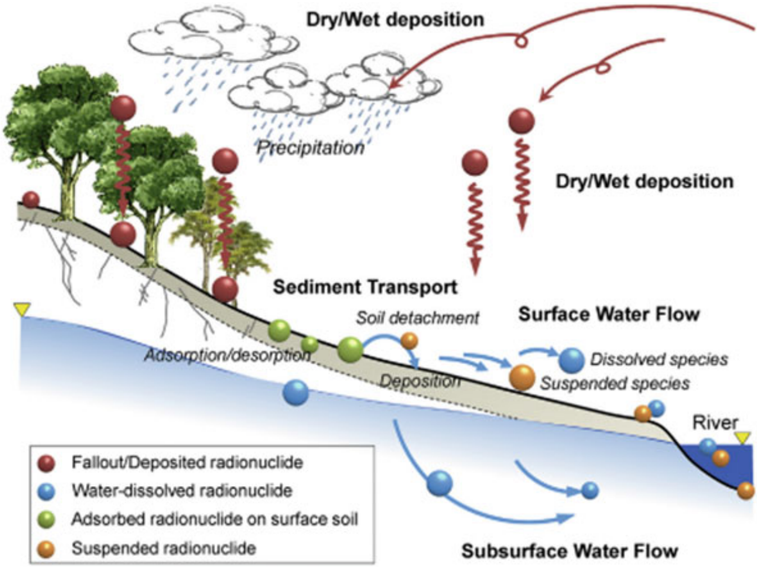


Fig. 6 Schematic illustration of fallout radionuclide redistribution [25]

3.2 *Benefits and Drawbacks of GETFLOWS Application*

Table 2 gives the benefits and the drawbacks of GETFLOWS modeling application in monitoring as well as other applications.

Table 2 Strength and weakness of GETFLOWS simulator [23, 24, 25, 27]

Advantages	Limitation
• No need extra steps to execute a costly hydrological model in water balance estimation • Can construct the conjunctive water flow through watershed components such as rivers, hillslopes and unsaturated and saturated aquifers without requiring any assumption • The simulation automatically covers the whole river basin in terms of surface water flows, therefore there will be no problems with disconnection and reconnection of river segment • The code can be transferred globally to the numerous different aquifer systems near convergent margins	• Inaccuracy—the variability of data caused by the heterogeneity of raindrop size, soil moisture, land cover density and other factors • The need of field monitoring in some cases—the complexity of modeling sediment and pollutant discharge from paddy fields and land adjacent

4 HEC-RAS

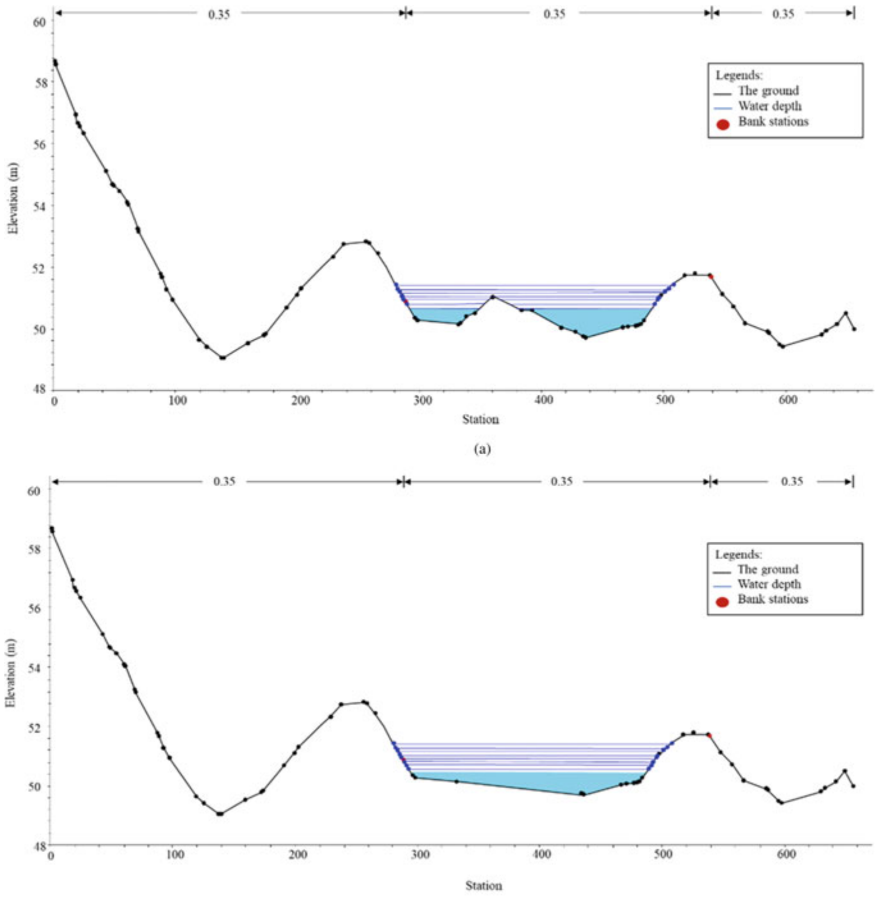
Hydrologic Engineering Center's-River Analysis System (HEC-RAS) is a modeling application that simulate the water flow through rivers and other channels. It was developed by the US Department of Defense, Army Corps of Engineers in order to manage the rivers [43]. This software includes four types of one-dimensional hydraulic components for steady flow, unsteady flow simulation, movable boundary sediment transport analysis and water quality analysis, all of which use a common representation of geometric data and hydraulic computation [29, 30, 44]. HEC-RAS is also an effective tool to simulate the runoff relying on the channel morphology [31]. That said, the HEC-RAS 1D model is often applied to analyze sediment transport. HEC-RAS' version 4.0 was the first to incorporate calculations for 1D sediment transport [7]. The sediment transport model from HEC-RAS requires hydraulic variables (velocity, flow depth and shear stress) and sediment properties to evaluate the transport capacity for cohesive and non-cohesive soils. The user can compute transport potential. (temporal entrainment, deposition and alteration of the cross sections to reflect aggregation or erosion via the HEC-RAS software.)

4.1 Application of HEC-RAS in Sediment Modeling

HEC-RAS was applied by Joshi et al. [8] to develop a sediment transport model analysis in the river channel. The first data used in this study is geometric data that was generated from a digital elevation model with a resolution of 10 m by 10 m using ArcGIS and the HEC-GeoRAS extension This model has to be calibrated and validated to guarantee measurement accuracy and that it fulfill the specified functional goal. Making use of different sediment transport functions and Manning's roughness coefficient, calibration and validation were completed. By assuming the sediment transport equation from the main hydraulic variables, the sediment transport rate can be determined in sediment studies. The predicted and measured sediment transport rates usually differ from each other. According to this study, Meyer-Peter and Mullet (MPM) had the best fit to the field data in contrast to the other six (6) equations. The sediment transport analysis indicated variations in riverbed pattern as well as the areas of river that are vulnerable to erosion or deposition. Consequently, by combining the model, output and local knowledge may assist to mitigate the problem drove by sediment. It shows that most sediments accumulate in the upper stream of the river. Yet, downstream area displays different outcomes. Additionally, the pattern sediment distribution is also not uniform. In short, having more cross section area, bed load and gradation of sediment load data can help to develop a more reliable model for predicting the future sediment behavior.

Research by Foti et al. [32], this study to determine the impact of river removal by analyzing the entire basin to determine the implications of sediment balance. Additionally, it is possible for this model to locate the feasible area and also estimate the potential evolution of river morphology caused by withdrawals. The process of sediment withdrawals will be removed far from the riverbank to avoid affecting them and without eroding the riverbed. Sediment removal will extract from the riverbed that has equal to or higher than that of conjoining lands to minimize the flooding risk (Fig. 7). A total of 1 m in height and 100 m in width removal of accumulated sediments at the middle part of the targeted river section.

In order to carry out the research successfully, there are three (3) main phases involved throughout the process. The early phase involved the development using GIS software to perimeter and morphometrically characterize the river basin and its hydraulically and sedimentological homogeneous sub-basins. Utilizing the HEC-HMS software, the next phase was created to assess the hydrological balance of the basin and its sub-basins. In the final phase, by combining two software of HEC-RAS



(b)

Fig. 7 **a** Before sediment withdrawal, **b** after sediment withdrawal

Table 3 Advantages and disadvantages of HEC-RAS modeling [8, 33–35]

Advantages	Disadvantages
• 1D models can still be used to lengthy river reached because of their straightforward computation and calibration • Need smaller in amount of hydrologic data for calibration and validation • Fast computation	• Capable of developing 1D modeling in sediment studies • Does not consider salinity or how organics can influence fine sediment

software and SIAM model to discover the regions that were experiencing erosion, deposition and equilibrium.

4.2 Benefits and Drawbacks of HEC-RAS Application

Table 3 gives the benefits and the drawbacks of HEC-RAS modeling application in monitoring as well as other applications.

5 Conclusion

This research review's purposes are to help the reader to grasp the concept of sediment transport in the river system by understanding the process of the sediment starting from the source, transportation until the deposition of the sediment and also to determine the benefits of using HEC-RAS and GETFLOWS. This is significant because rivers have different types of situations and management according to the current event that can affect the river system in the specific time interval. There has been much research and discussion conducted on the behavior and the mobility of the sediment. Most of the research found was on the composition of the sediment and sediment load. Apart from that, this review showed that the benefit of using GETFLOW, it can develop a 3D modeling and it can illustrate the whole hydrological cycle based on the sediment mobility. As for the HEC-RAS, it has been widely used by many researchers in this field to identify the mobility of the sediment and it is in 1D modeling and easy to use. More research and testing are required to gain a better prediction in identifying the behavior of the sediment by using sediment modeling.

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