Sediment distribution and its impacts on Hirakud Reservoir (India) storage capacity

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Abstract
Construction of dams causes reduced flow velocities, inducing gradual deposition of sediments carried by the inflowing stream, and resulting in sedimentation and ultimately diminishing reservoir storage capacity. This study focuses on sedimentation of Hirakud Reservoir in Odisha, India, using available reservoir capacity and numerical simulation data. Reduced trap efficiency, observed and projected capacity curves, rising reservoir bed level and the capacities of the different storage zones for various projected years are analysed. The area-reduction method indicates the loss in the live, gross and dead storage will be 58%, 63% and 100%, respectively, of their original capacities by 2057, which represents 100 years of impounding of water in the reservoir. If the present sediment inflow rate continues without regular flushing of the deposited sediment, it is predicted the reservoir bed level will rise to the full reservoir level of 192.02 m by the year 2110. Brune's trap efficiency and step method indicate the gross storage zone of Hirakud Reservoir will be completely depleted by the end of 2110, with the trap efficiency reduced to zero. The empirical area-reduction method is found to be more suitable for determining the storage capacities of Hirakud Reservoir in the absence of sedimentation survey data. An attempt was also made to solve the combined hydrodynamic and sediment transport equations numerically to predict morphological changes in Hirakud Reservoir. The finite-element code TELEMAC-2D and finite-volume code for SISYPHE, respectively, were applied to solve the above set of equations in order to predict the bed profiles at different reservoir cross sections for the period of 1958–2008. Analysis of the simulated results demonstrates that, considering the model inputs, the model performs well in simulating the morphology and dynamic characteristics of a reservoir. Projection of the numerical results indicates a complete loss of reservoir operational life due to sedimentation by around 2150.

Key words
morphology, sediment transport, sedimentation, storage capacity, trap efficiency.

INTRODUCTION
Great civilizations have developed along rivers, with some having perished because of changing water availability at these sites. Construction of a dam, thereby creating a reservoir, changes the natural conditions of a stream or river, with the resulting reduced flow velocity enhancing gradual deposition of sediments carried out in the inflowing waters. This increased sedimentation typically results in a reduced reservoir water storage capacity. The heavier particles (gravel; coarse sand) settle first, with finer sediments entering further within a reservoir. With a dam restricting the passage of most particles downstream, sedimentation is increased, hindering reservoir operation and causing such problems as floods due to reduced storage capacity, and abrasions on dam structures, gates, pipes and turbines attributable to the sediment-laden water flow.

HIRAKUD RESERVOIR STUDY SITE AND MODELLING BACKGROUND AND METHODOLOGY
The state of Odisha in India has ample surface and groundwater resources in its river systems, with the Mahanadi river basin (sixth largest river in India), contributing a large share (Panda *et al.* 2013). Hirakud is a major project in India, consisting of a 4.8-km-long masonry dam, 61-m-high spillway and 25.8-km earthen embankments and dykes. It was commissioned in 1957 and has served the aspirations of the people effectively and efficiently over the past 59 years. Figure 1 shows the location of the study area, while Figure 2 highlights the

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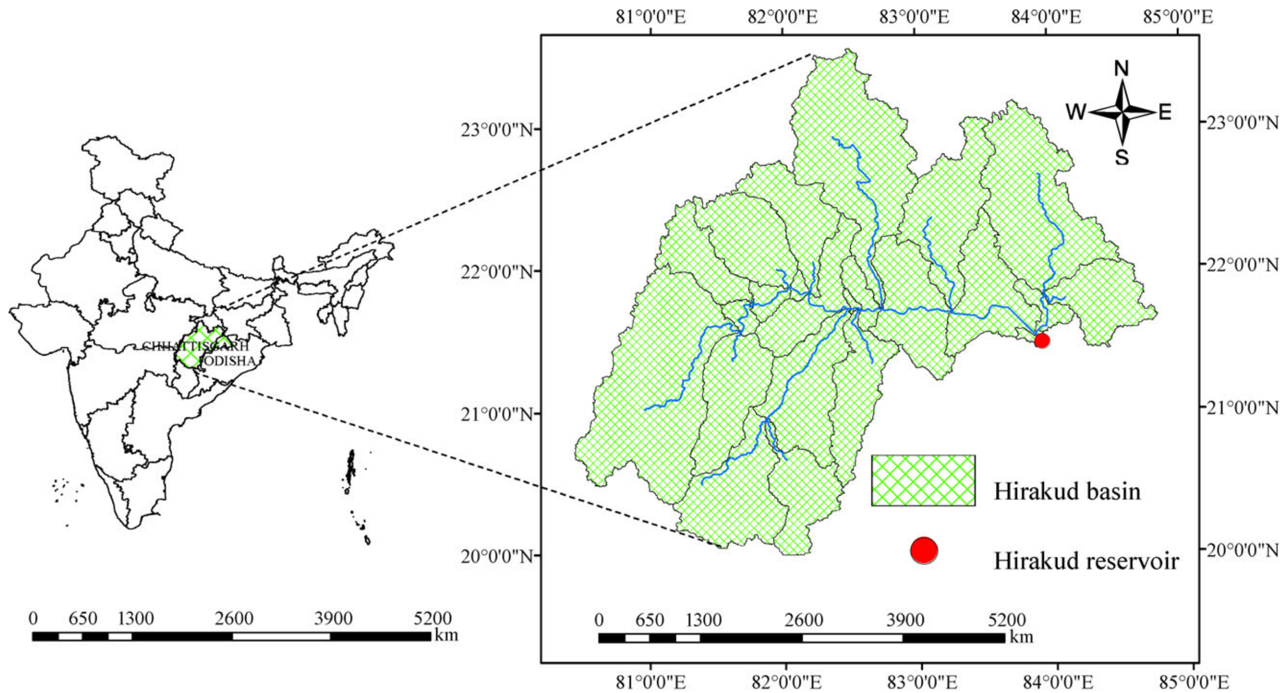

Fig. 1. Location of study area.

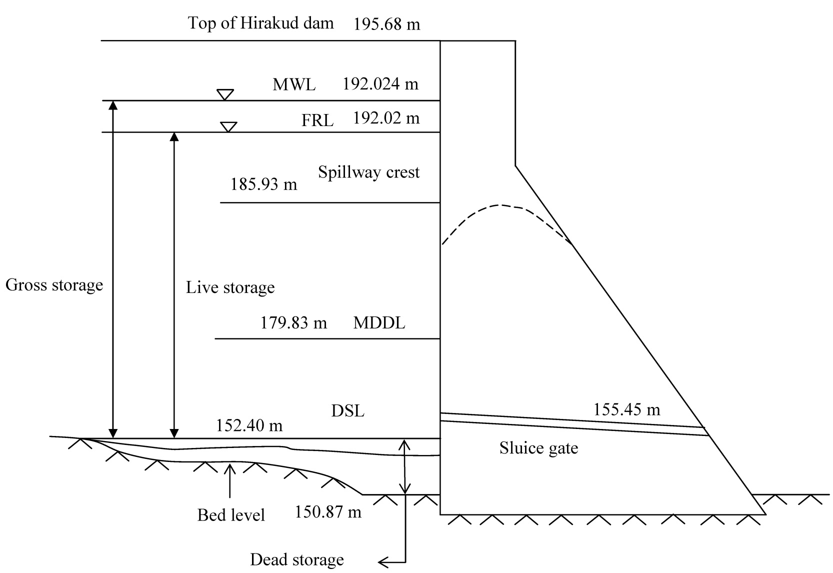

Fig. 2. Schematic of different Hirakud Reservoir storage zones.

different Hirakud Reservoir storage zones. The Mahanadi River catchment area covers about 133 120 km^2 among, with the Hirakud Reservoir catchment covering about 83 400 km^2. The land uses in the catchment area are primarily agricultural land (52.58%), forest land (42.88%), pasture land (0.19%), urban area (0.58%) and waterbody (3.77%). The catchment soils are classified as loamy (55.15%), fine (44.11%) and clayey (0.74%) in character. The main upstream tributaries are Seonath, Jonk, Hasdeo, Mand and Ib. During the monsoon period (June–September), flood control is the main purpose of the dam, with the reservoir being used to meet water demands or irrigation, power generation, industrial needs, municipal water supply and ecological requirements during the postmonsoon period. The reservoir is used to irrigate about 0.152 million ha and to generate about 200 MW of hydropower, as well as facilitating flood mitigation. The salient features of Hirakud Reservoir are summarized in Table 1. The hydro-meteorological data were obtained from gauge–discharge stations maintained

Table 1. Salient features of Hirakud Reservoir

Location	
Latitude	21°29′27.83″N
Longitude	83°55′31.04″E
River	Mahanadi
Purpose	Multipurpose
Year of impoundment	1957
Hydrology	
Catchment area	84 788.94 km^2
Mean annual rainfall	1122.28 mm
Maximum annual rainfall	1928.42 mm
Minimum annual rainfall	691.46 mm
Mean annual run-off	3.313 M-ham
Maximum annual run-off	9.09 M-ham
Minimum annual run-off	1.13 M-ham
Design flood discharge	1500 000 cusec
Reservoir	
Maximum water level (M.W.L.)	R.L. 192.024 m
Full reservoir level (F.R.L.)	R.L. 192.02 m
Minimum drawdown level (M.D.D.L.)	R.L. 179.83 m
Dead storage level (D.S.L.)	R.L. 152.40 m
Bed level	R.L. 150.87 m
Gross storage capacity	8105 mcm
Live storage capacity	5843 mcm
Dead storage capacity	2262 mcm
Water spread area at F.R.L.	743 km^2
Water spread area at D.S.L.	274 km^2
Available drawdown	12.192 m

by the Central Water Commission (CWC), India. This study attempts to determine the operational life of Hirakud Reservoir, based on analysis of observed and forecasted sedimentation data highlighting the trap efficiency, bed level and different storage capacities of the reservoir during various projected years on the basis of empirical and numerical techniques.

Reservoir sedimentation studies

The transported sediments get deposited in the reservoir, reducing its storage capacity. Analysis of sediment distribution in the reservoir storage zones is important for tackling the problems of bed level rise, increased flood levels and sediment entry into the reservoir. Various studies have been carried out on estimating reservoir sedimentation. Jain *et al.* (2002) assessed the sedimentation in Bhakra Reservoir on the Satluj River in India using remotely sensed data (IRS LISS-II) and compared the results with the hydrographic survey. They found the average sedimentation rate for the reservoir was 25.23 Mm^3 over a period of 32 years (1965–1997). Yang (2003) reported a world average annual soil loss of 0.5%–2% of the water storage capacity of the reservoirs. Among the most sedimented reservoirs, the lost storage capacity of Nizam Sagar (India) was about 60.7% over a period of 62 years, whereas the corresponding loss in Maithon was about 55% over 50 years (Rathore *et al.* 2006). Chaudhuri (2006) predicted the operational life of Maithon Reservoir on the Barakar River in India in regard to its sedimentation characteristics. Construction of another reservoir as a siltation trap was proposed to increase the Maithon Reservoir operational life. The Water Resources Department, Government of Odisha (2007), studied various aspects of water usage for Hirakud Reservoir, considering the reservoir sedimentation, concluding that the loss in live storage over the past 50 years was around 20.1%. Using remote sensing techniques, Mukherjee *et al.* (2007) studied sedimentation of Hirakud Reservoir, finding the annual rate of siltation to be around 61.05 mcm, and a capacity loss of 24%, between 1957 and 1989. Sahay (2011) analysed the sediment distribution of Getalsud Reservoir in the Jharkhand State of India, concluding that the reservoir bed level would rise to the full reservoir level by the year 2500. This study indicates the provision made at the planning stage of the reservoir was more than adequate, with the assessed useful life of the reservoir being greater than the design life of 100 years.

The Central Water Commission conducted a reservoir sedimentation study using remote sensing techniques in 1995. The gross and live storage of the reservoir were found to have reduced to 6145 and 4934 mcm, respectively. The average loss of gross, live and dead storages was computed as 0.64%, 0.41% and 1.22% per annum, respectively. Using the inflow and outflow method, Murthy (1968) calculated the silt index of Hirakud Reservoir to be 78 acre-ft 100 m^{-2} year^{-1}. It is essential to conduct periodic sedimentation surveys to obtain data regarding new storage capacity in different zones of the reservoir, as well as to ascertain future water resources management needs. It is also necessary to take preventive measures in the upstream watershed area of the reservoir to reduce sediment inflows, as well as reducing sediment accumulation in the reservoir.

Numerical reservoir sedimentation studies

Empirical formulae based on laboratory data are not always sufficient accurate, therefore being unable to properly obtain practical conditions due to errors in the scale ratio and fluid properties. Furthermore, field data based on empirical formulae suffer from subjective errors. To overcome these deficiencies, computational fluid dynamic tools may be used to predict hydrodynamic and morphodynamic parameters within a reservoir experiencing varying flow conditions.

Morris and Fan (1998) discussed the sedimentation phenomena of reservoirs, concluding numerical modelling can be used to simulate overall reservoir behaviour, including sediment accumulation patterns, evolution of grain-size distribution of the deposits and the material discharged from the dam. The numerical models have several important advantages over physical models in terms of lower cost, ease of re-running to simulate a variety of different conditions, the ability to simulate a wide variety of problems numerically that are unsuitable for physical modelling because of the involved scaling laws, portability and reproducibility. Nevertheless, some attention is needed for the application of numerical techniques to ensure the basic assumptions are not grossly violated by the prototype system, and to be aware of the direction and potential magnitude of errors introduced by assumptions inherent to the computational techniques.

A number of numerical one-dimensional, two-dimensional and three-dimensional (1D, 2D and 3D, respectively) models have been developed over the last two decades, to evaluate morphodynamic changes of river systems. They are based on flow and sediment transport equations. According to Huybrechts *et al.* (2010), the choice of the model dimensions depends on the domain scale. 1D computational models provide information in a section-averaged manner, without providing any information about the flow characteristics in the vertical and transverse directions. The depth-averaged 2D models divide the total computational domain into a network of two-dimensional elements. However, no variation is considered in the vertical direction. Three-dimensional numerical models are based on the assumption of hydrostatic pressure in the vertical direction, providing information for all three flow directions within a reservoir. Dutta (2016) noted that numerical models estimate water routing on the basis of equal surfaces, whereas physical-based models do so on the basis of equal volumes for reservoirs with outlet structures such as weirs and orifices. In comparison with empirical and physical models, numerical models provide good predictions of shapes and magnitudes of the effluent sediment concentration graph.

Rinaldi *et al.* (2008) reported the use of the 3D depth-averaged hydrodynamic computational model, DELFT-3D, including the effects of pore water dynamics (WL | Delft Hydraulics 2006). As a commercial model, however, it is not freely available and may only be useful for simulating single flow events due to the high computational memory requirements typical of a 3D model. Moreover, the above model uses structured rectilinear meshes that limit accurate characterization of irregular channel planform and its temporal adjustments.

SRH-2D, a nonlinear river morphodynamics model that simultaneously solves the flow and sediment transport equations on an unstructured two-dimensional mesh system (Lai 2008), has been successfully employed for simulating river flow and sedimentation. Other computational fluid dynamics models, including MIKE-21 (Waren & Bach 1992), ECOMSED (Blumberg 2002) and ROMS (Warner *et al.* 2008), generally include different flow modules, mostly 2D and 3D for flow and sediment transport simulations. Numerical models such as GSTARS 3.0 (Yang & Simoes 2001), CCHE-2D (Wu 2001) and Wolf-2D (Erpicum 2006) have also been employed for many important studies on river and reservoir flow and sedimentation. Simulating morphological changes in reservoir, however, is a very complex process, involving considerations of erosion, deposition, sediment transport, etc. This reality was discussed by Wu (2008), who stated that, due to improved numerical simulation techniques over last few decades, various numerical hydraulic and sediment transport models are now widely applied as a major research tool by the scientific community to solve hydraulic and morphological problems.

The TELEMAC (Desombre 2013*)* modelling system, another widely used numerical flow simulation model, is combined in this study with SISYPHE (Tassi 2014) to simulate the change in morphodynamic patterns for Hirakud Reservoir. Both software packages are open source products, providing the users the opportunity to adapt and modify the codes to facilitate a better simulation performance. The combination of the two models forms an integrated package for simulating and analysing free-surface flows, sediment transport and morphological processes. The governing equations used to simulate the hydraulic parameters are the continuity equation, along with the momentum equations in the horizontal x and y directions. The sediment transport and bed deformation equations are used to simulate the morphological parameters, also in the horizontal directions.

Although some studies (e.g. Fan 1988) have reported the use of different numerical models may yield different simulated results, this study is probably the first of its kind employing a numerical flow and sediment transport model for a wide reservoir such as Hirakud Reservoir. Furthermore, the simulations have been made on a near-continuous timescale from 1958 to 2008 (barring low-flow periods), which also may be first among different Indian reservoirs.

Methodology for predicting reservoir sedimentation

Area-increment and area-reduction methods are mostly used to analyse distribution of sediment deposition in a reservoir. Cristofano (1953) developed the area-increment method to calculate the reservoir surface area at any depth.

The area-increment method is based on the assumption that the sediment deposition volume per unit height of reservoir is constant. This assumption works well for most reservoirs if the depletion of storage is small, compared to the total capacity.

The distribution of sediment is expressed by the following equation:

$$V_S = A_0(H - h_0) + V_0 \tag{1}$$

where V_S = total sediment volume; A_0 = original reservoir surface area at depth h_0; H = maximum reservoir depth; h_0 = sediment depth at dam wall position (new zero depth of the reservoir); and V_0 = original reservoir capacity at depth h_0. Figure 3 presents the schematic of the area-increment method to determine the sediment distribution in the reservoir.

The Borland and Miller method (Borland & Miller 1958), also known as the area-reduction method, was developed to express the sediment distribution at any level (h_0) above the reservoir bed. The basic equation for this method is expressed as:

$$V_S = \int_0^{h_0} A\mathrm{d}h + \int_{h_0}^{H} Ka_p\mathrm{d}h \tag{2}$$

where A = reservoir surface area at any depth h; dh = incremental depth; and K = constant of proportionality for converting relative areas a_p to actual areas.

The equation of relative area is expressed as:

$$a_p = C'p^m(1-p)^{n'} \tag{3}$$

where relative depth $= \frac{h_0}{H}$; and C', m and n' are coefficients, the values of which depend on the classification of the reservoir, as presented in Table 2.

Table 2. Values of C, m and n for four types of reservoirs (Borland & Miller 1958)

Type	C	m	n
I	3.4170	1.5	0.2
II	2.3240	0.5	0.4
III	15.882	1.1	2.3
IV	4.2324	0.1	2.5

The reservoir classification is based on the value of shape factor M, which is the reciprocal of the slope of a best fit line obtained by plotting reservoir elevation above bed as the ordinate, against reservoir capacity at that elevation as the abscissa, on a log-log graph paper. Table 3 represents the classification of the reservoir, while Figure 4 illustrates the schematic of sediment distribution in the area-reduction method. Following the method of reservoir classification, Hirakud Reservoir falls in category Type II.

Brune (1953) studied the records of reservoir trap efficiency, also analysing the factors affecting the trap efficiency, concluding the capacity–inflow (C/I) ratio exhibits a good correlation with the trap efficiency, compared to the capacity–watershed (C/W) ratio. The C/I ratio increases with increased trap efficiency, due to reduced sediment release from a reservoir. The annual sediment inflow is multiplied with trap efficiency (TE) to calculate the value of the annual sediment volume deposited in the reservoir. Thus, the time required to fill the different reservoir storage zones is obtained after dividing the actual volume of different storage zones by

Table 3. Reservoir classifications (Borland & Miller 1958)

M	Reservoir type	Standard classification
3.5–4.5	Lake	I
2.5–3.5	Floodplain-foothill	II
1.5–2.5	Hill	III
1.0–1.5	Gorge	IV

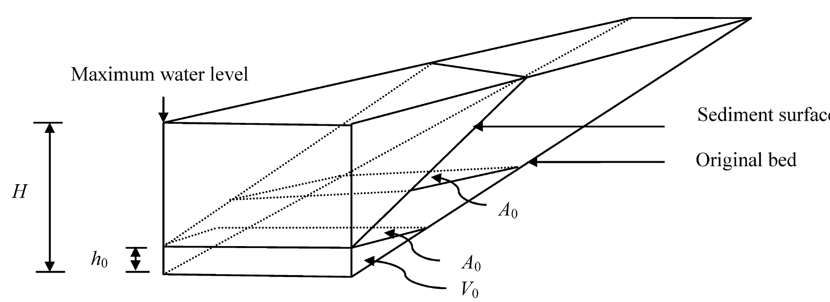

Fig. 3. Schematic of sediment distribution in the area-increment method.

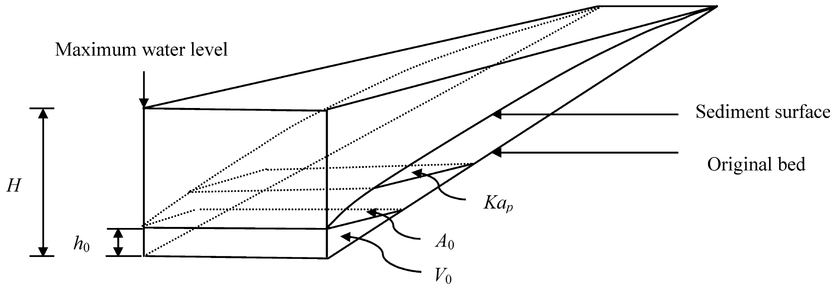

Fig. 4. Schematic of sediment distribution in the area-reduction method.

the annual deposited sediment volume. The trap efficiency of a reservoir reduces gradually during its useful life due to the reduced C/I value resulting from sediment deposition.

The future storage capacity of the reservoir is determined using a step method, which incorporates the physical and hydrological properties of sediment particles.

The future storage capacity of the reservoir is expressed as:

$$C_0 = C_T + \frac{K'A'^{0.88}TE}{2178\overline{\delta_T}}\Delta T \quad (4)$$

where C_0 = storage capacity (acre-ft) of the reservoir at time T_0; C_T = reservoir capacity (acre-ft) at time T; K' = an empirical regional constant (tons year^{-1} mile$^{1.76}$); A' = watershed area (mi^2); TE = trap efficiency of the reservoir (%); T = time period (years) during which reservoir capacity has to be determined; ΔT = time elapsed ($T - T_0$) in years; and $\overline{\delta_T}$ = average density of sediment particles (pounds ft^3). This methodology was used to assess the impacts of sedimentation on the Hirakud Reservoir storage capacity.

Numerical simulation of reservoir sedimentation

The initial and boundary conditions of the numerical models TELEMAC-2D and SISYPHE are described below, followed by analysis of the simulated results, and the conclusions regarding its ability to represent sediment transport rates and bed evolution for Hirakud Reservoir. Figure 5 presents a flow chart describing the connections between the different modules of TELEMAC-2D and SISYPHE.

Initial conditions

It is necessary to specify the initial state of the functional domain, as well as the conditions at its boundaries, in order to solve the governing partial different equations. As an initial condition for simulating the numerical experiment, a constant elevation of water surface of 192 m was selected for the whole domain. Clear water conditions were also initially assumed, for which the sediment concentrations at the initial step and the inlet boundaries were set at zero. The vertical variations of flow and sediment concentration during the entire simulation are considered small compared to that in the horizontal directions.

Boundary conditions

Boundary conditions are applied at each boundary point. The present model has two inlet boundaries, one for the Mahanadi River flowing from west to east and the other for the smaller Ib River flowing from north to south into the reservoir. The time-varying continuous inflow discharge values for the two inlet boundary are applied as a daily time series for the entire duration from 1958 to 2008. The very low-flow periods were omitted, however, because these were assumed to contribute no substantial sediment load into the reservoir. The outlet boundary was defined at the Hirakud Dam spillway, and a constant water surface elevation of 186 m was considered. Time series of daily inflow sediment discharges and corresponding sediment concentrations were also imposed at the inlet boundaries.

Hydrodynamic component

The hydrodynamic model TELEMAC-2D solves the governing equations of 2D flow within an unstructured triangular mesh by the finite-element technique. The following two-dimensional approximate equations, derived from the Navier-Stokes equations by taking the vertical average, are used in the model, as follows:

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \quad (5)$$

$$\frac{\partial(hu)}{\partial t} + \frac{\partial(hu^2)}{\partial x} + \frac{\partial(huv)}{\partial y} = -hg\frac{\partial Z_S}{\partial x} + \frac{\tau_{xx}}{\rho} + F_x \quad (6)$$

$$\frac{\partial(hv)}{\partial t} + \frac{\partial(hv^2)}{\partial y} + \frac{\partial(huv)}{\partial x} = -hg\frac{\partial Z_S}{\partial y} + \frac{\tau_{yy}}{\rho} + F_y \quad (7)$$

where h = depth of water (m); u, v = depth-averaged flow velocity components in x and y directions, respectively

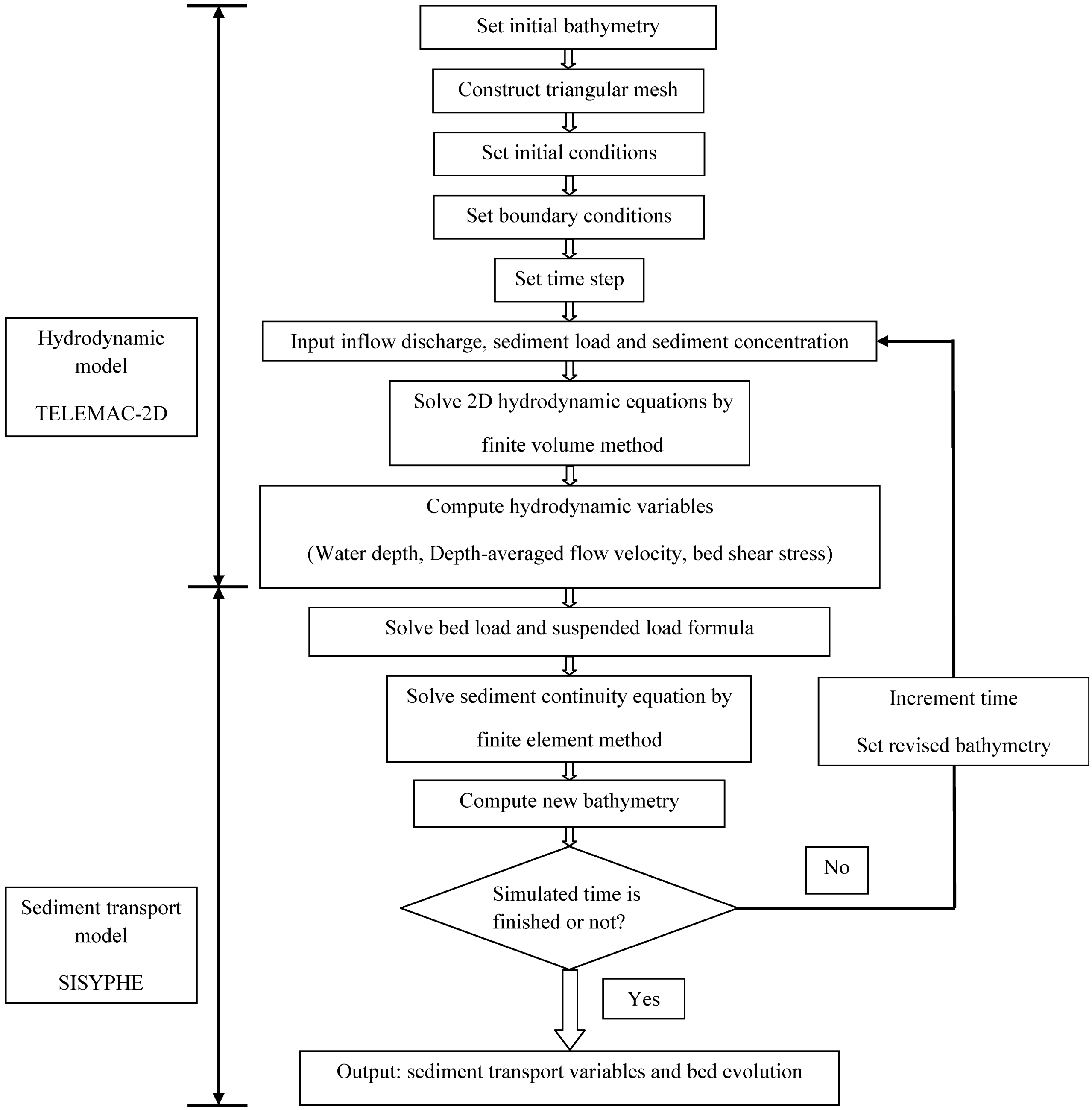

Fig. 5. Flow chart of algorithms for hydrodynamic and morphodynamic computation modules and their linkage.

(ms^{-1}); g = gravitational acceleration (ms^{-2}); Z_S = free-surface elevation (m); t = time (s); x, y = horizontal Cartesian coordinates (m); ρ = density of water ($kg\ m^{-3}$); τ_{xx} and τ_{yy} = depth-averaged turbulent stresses; and F_x and F_y = Coriolis forces.

Sediment transport component

The sediment transport model, SISYPHE, simulates bed morphodynamics by calculating temporal changes in bed elevation Z_b using the following Exner equation, as follows:

$$(1-p')\frac{\partial Z_b}{\partial t}+\frac{\partial(\delta_b c_b)}{\partial t}+\frac{\partial(q_{t,x})}{\partial x}+\frac{\partial(q_{t,y})}{\partial y}+n'_e-n'_d=0 \tag{8}$$

where Z_b = bed elevation; δ_b = bed load layer thickness; p' = bed porosity; c_b = sediment concentration in bed load layer; $q_{t,x}$ = total sediment transport in x-direction; and $q_{t,y}$ = total sediment transport in y-direction.

SISYPHE assumes the Rouse concentration profile, from which the equilibrium depth-averaged concentration is calculated and the near bed, equilibrium concentration is obtained from the Zyserman and Fredsoe equations (Zyserman & Fredsoe 1994).

Mesh generation

TELEMAC-2D requires the discretization of the flow domain into an unstructured triangular mesh. The original predam river-bed elevation data, obtained from the contour map based on the bathymetric survey (Fig. 6), were used for this purpose. The triangular unstructured mesh, representing the entire reservoir extent, which contains 8299 nodes and 15 445 elements (Fig. 7), was constructed with the help of the gridding software Blue-Kenue (2012) applied to the area bounded by the reservoir periphery.

Modelling parameters

The models TELEMAC-2D and SISYPHE employ certain parameters which must be supplied by the user. The velocity diffusivity, which has an impact on both the shape and extent of recirculation, was considered as 10^{-6} m^2s^{-1} for this study. Strickler Law was used as the bottom friction law, influencing the water velocity and the bed shear stress to control the sediment transport rate.

The following percentages of different categories of silt were considered in regard to the sediment gradation: Coarse silt: 100%; Medium silt: 80%; Fine silt: 20% and Bed silt (assumed 10% of total suspended load) 100%.

Information on the sediment characteristics, such as clay (below 0.002 mm), silt (0.002–0.075 mm), fine sand (0.075–0.212 mm) and medium sand (0.212–0.425 mm), was obtained from Reservoir Sedimentation Survey Report (1983).

To predict bed load, the following Van Rijn's formula (Van Rijn 1984) was used as follows:

$$Q_b = 0.053(s-1)^{0.5} g^{0.5} D_{50}^{1.5} D_*^{-0.3} T^{1.5} \quad \text{for } T \le 3 \qquad (9)$$

and

$$Q_b = 0.1(s-1)^{0.5} g^{0.5} D_{50}^{1.5} D_*^{-0.3} T^{1.5} \quad \text{for } T > 3 \qquad (10)$$

where Q_b = bed load transport rate; D_{50} = median sediment diameter; s = relative density; T' = nondimensional excess bed shear stress; and D_* = dimensionless particle size, defined as:

$$D_* = D_{50}\left(\frac{(\rho_S-\rho)g}{\rho v^2}\right) \qquad (11)$$

and

$$T' = \frac{\left((u_*)^2 - (u_{*\mathrm{cr}})^2\right)}{(u_{*\mathrm{cr}})^2} \qquad (12)$$

where ρ_s = density of sediments; v = kinematic viscosity; u_* = bed shear velocity; and $u_{*\mathrm{cr}}$ = critical bed shear velocity.

The computation module of SISYPHE predicts the suspended sediment load by solving an advection–diffusion equation. The simulation comprises the effects of the transverse slope on sediment transport. Thus, the direct effect of gravity on particles on a sloping bed is also considered. The slope effect has also an influence on the

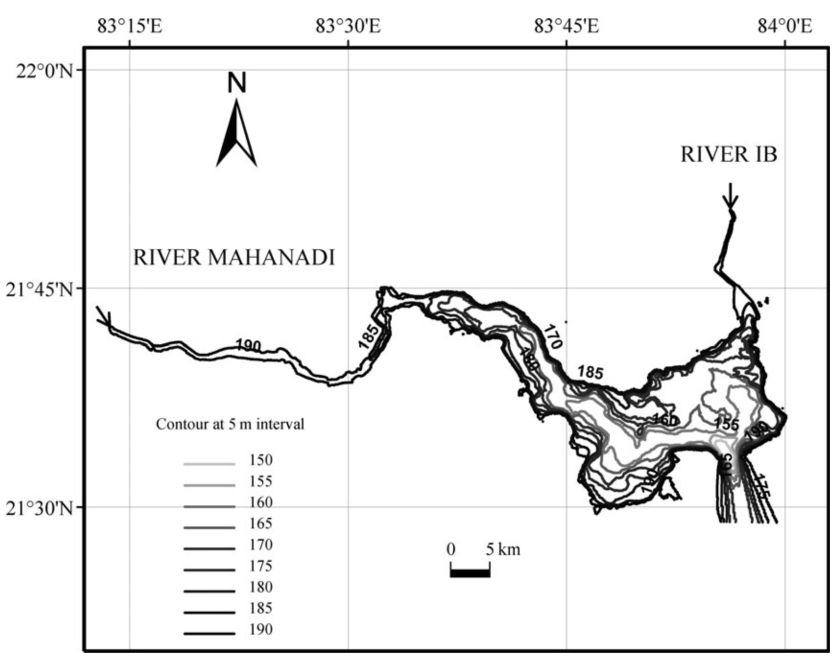

Fig. 6. Contour map of Hirakud Reservoir bed topography.

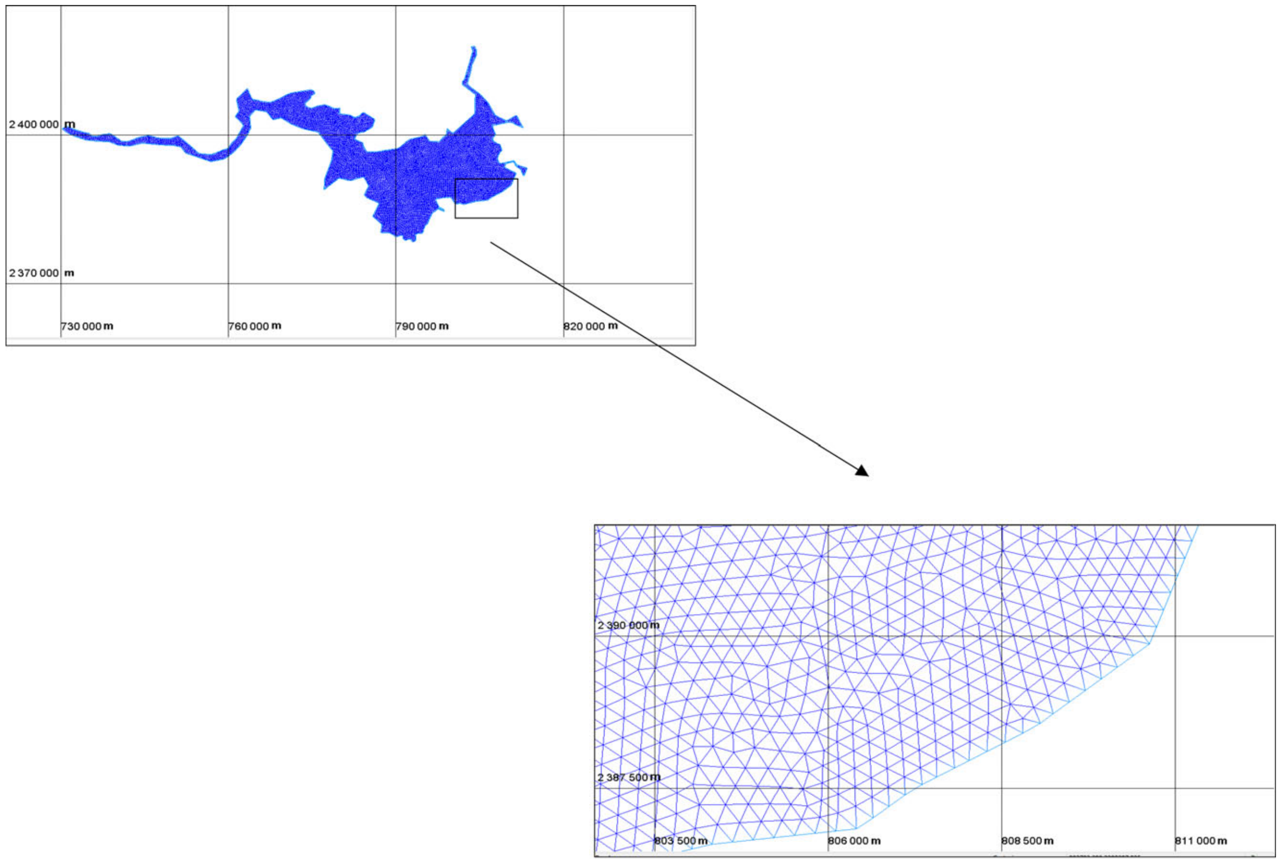

Fig. 7. Computational triangular mesh of reservoir domain.

threshold shear stress. The critical Shield parameter was set to 0.047 for the present simulation.

Time step and simulation time

It is recommended the Courant number should generally not exceed a value of three in adopting a time step. The Courant number is defined as follows:

$$C = \frac{u'\Delta t}{\Delta x} + \frac{v'\Delta t}{\Delta y} \tag{13}$$

where u' and v' are the characteristics of the wave speed; Δt is the time step; and Δx and Δy are the spacing of the grid in x and y directions, respectively, in the numerical model. To satisfy this numerical parameter at all locations within the domain at all points of time in the present simulations, the optimum time step of each iteration was set as t = 60 s.

TELEMAC-2D computes the spatial distribution of hydrodynamic variables (water depth; depth-averaged flow velocity; bed shear stress) at every time step, which can subsequently be used by the model SISYPHE to carry out the sediment transport simulation for that time step. The output of the sediment transport-related variables (bed load rate; suspended load rate; evolution) computed by SISYPHE is communicated back to TELEMAC-2D for updating the reservoir bathymetry. The present simulations were continued for the period from 1958 to 2008 to predict the reservoir's morphological changes. The dry season flow and corresponding sediment load were low, therefore being omitted from the annual computations.

RESULTS AND DISCUSSION

Trap efficiency

Trap efficiency is important for long-term reservoir planning and operation. As estimated with the Brune Method, the Hirakud Reservoir trap efficiency during the period from 1957 to 2110 is plotted in Figure 8, which indicates a trap efficiency of about 92% at the time of initial reservoir impoundment, which decreased rapidly thereafter and becoming 0% at the end of 2110. There is little variation in the trap efficiency during the period from 1957 to 2050 and, after 2050, it will decrease drastically due to the complete filling up of the reservoir dead storage zone. Thus, most of the incoming sediment is trapped in

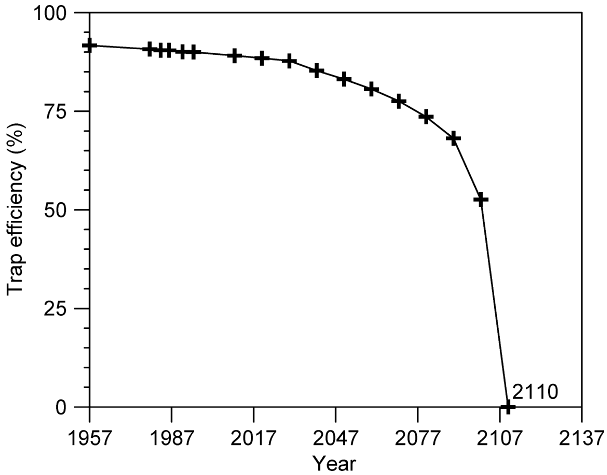

Fig. 8. Hirakud Reservoir trap efficiency.

the reservoir, with little flowing out of the reservoir through its outlets and spillways. In calculating the trap efficiency, it is assumed that 100% of coarse silt, 80% of medium silt and 20% of fine silt would be retained in the reservoir.

Capacity curves

Hirakud Reservoir sedimentation surveys were conducted in three series (1979; 1982, 1986) to determine various sedimentation aspects, such as the sedimentation rate, sediment distribution and loss of storage capacity at different elevations. The capacity of Hirakud Reservoir at different elevations observed by different methods is plotted in Figure 9. The capacity obtained by the remote sensing data for the year 1989 is comparable to sedimentation survey data obtained in 1982 and 1986, illustrating the same capacity curve patterns obtained with different methods. The results of a survey conducted by SPARC (Spatial Planning & Analysis Research Centre Pvt. Ltd.), Bhubaneswar, in 2005 were superimposed in Figure 9, noting the capacity curve coincides with that obtained from the remote sensing data for the year 1989. The objective of their study was to revise the area–capacity curve as part of reassessing the design energy of five Odisha Hydro-Power Corporation (OHPC) hydroelectric power stations. The National Remote Sensing Centre (NRSC), Hyderabad, was later entrusted to continue developing the capacity survey of Hirakud Reservoir for the period between 2005 and 2006, the result being applied to develop the capacity curve at different elevations. The water spread area of Hirakud Reservoir at different operating levels extending between Minimum Drawdown Level (MDDL) and Full Reservoir Level (FRL) was determined from multiple satellite observations, with the corresponding contours to determine the live storage capacity between those observed levels also being determined. Figure 9, however, indicates all the curves exhibit similar patterns and coincide, regardless of the inflow volume into the reservoir or its downstream demands. Subsequently, the sediment is distributed using an area-reduction and area-increment method, with the Hirakud Reservoir elevation–capacity curves for different years being forecasted in Figure 9. These curves help determine positions of the outlets, spillway crests, penstocks and storage zones during the forecasted years, and indicating the forecasted capacity curves at different Hirakud Reservoir water elevations during 2077 and 2110 being parallel to the capacity curves obtained by the capacity survey methods and remote sensing data for the years 1957 to 2007. Thus, the future sediment deposition trends for filling the dead, live and gross storage volume remains the same as for past filling patterns.

Bed level rise

The area-reduction method is the most widely used and accepted method to determine sediment distribution at different reservoir elevations. The sediment distribution

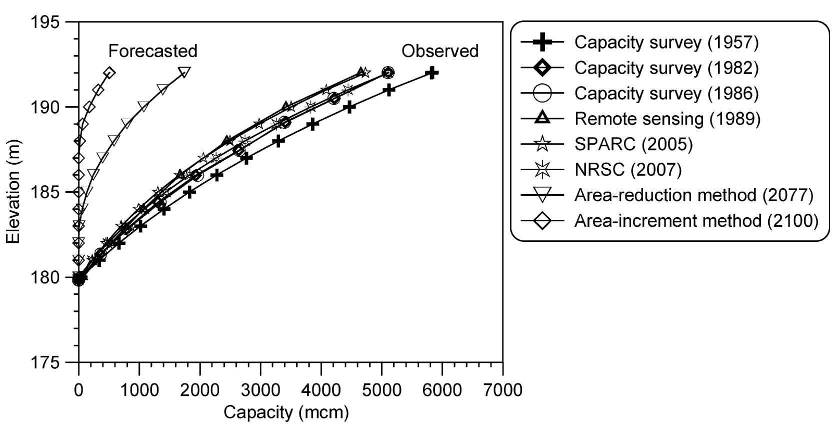

Fig. 9. Hirakud Reservoir elevation–capacity curves.

study was conducted to get an idea about the rise of the Hirakud Reservoir bed level attributable to sediment deposition. Figure 10 illustrates the bed level rise for different projected years obtained from the area-reduction method, indicating it will reach the level of the spillway crest in approximately 2070. The rising bed level reduces the water level, resulting in a decreased hydropower generation. Sediment control measures, such as regular flushing operations through the reservoir under sluices, should be conducted to transport the silts into the downstream channel without its settling at the upstream side of the reservoir. Continued sedimentation without regular flushing operation will lead to a rising reservoir bed level to full reservoir level (192.02 m) by the year 2110.

Declined storage curves

The observed values of dead, live and gross storage of Hirakud Reservoir at different time intervals are plotted in Figure 11, illustrating the declined storage curves.

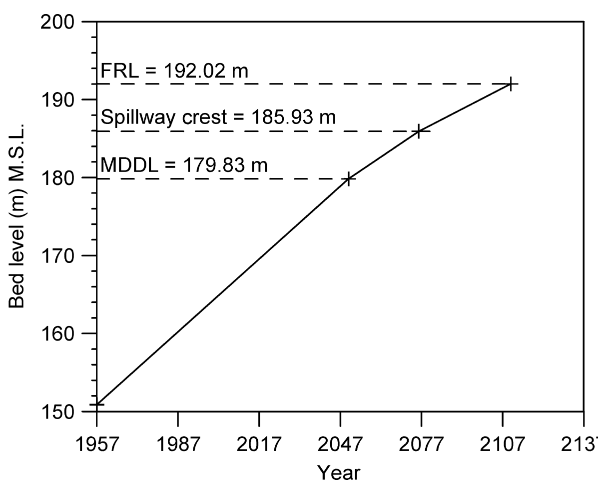

Fig. 10. Rise of reservoir bed level.

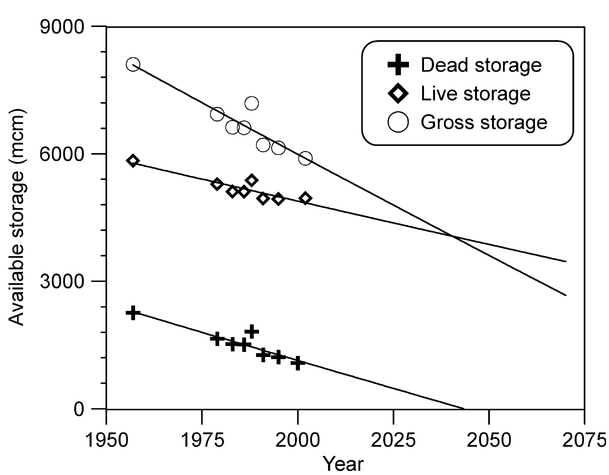

Fig. 11. Declined reservoir storage curves.

Extrapolation of past trends indicates the gross storage decreases rapidly in 2050, due mainly to the complete filling of the reservoir dead storage zone. The under sluices of the Hirakud Reservoir dam, however, periodically flush out the deposited sediment periodically. The regular flushing operation reduces the sedimentation rate, resulting in a prolonged life for the Hirakud Reservoir.

Declined gross storage capacity

Based on the step method and Brune's trap efficiency, Singh and Ali (1989) introduced an algorithm to determine the new reservoir storage capacity attributable to the sedimentation. Figure 12 indicates the gross storage capacity of Hirakud Reservoir will be completely depleted at the end of 2110. The reservoir storage zones progressively fill up with sediments, with the rate of sediment deposition into the reservoir decreasing over time. Thus, the trap efficiency decreases because of the reduced rate of sediment deposition (Chaudhuri 2006; Sahay 2011). Hirakud Reservoir will no longer be in use after 2110 because the storage capacity will be completely depleted because of the deposited sediment, with the trap efficiency reaching almost 0% at the end of this year. The reservoir's sediment deposition rate decreased notably after 1983 because of conservation measures adopted to prevent erosion. According to Kumar (1989), 19%–95% of the Hirakud Reservoir catchment area was treated with conservation steps during 1983, such as bunding, terracing, tree plantation, pasture development and construction of various engineering structures to prevent soil erosion.

Storage loss

The sedimentation distribution in a reservoir provides an indication of the time required to fill up a reservoir's

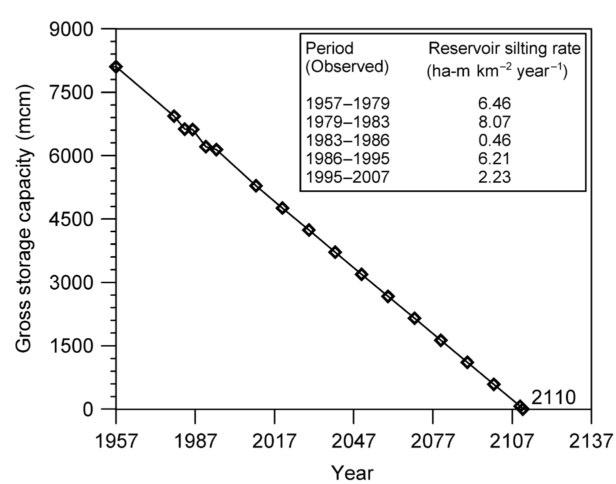

Fig. 12. Declined reservoir gross storage capacity.

storage zone. Figure 13 provides a graph of the percentage of reduced dead, live and gross storage for each year. There is already a 22% reduction in the live storage of Hirakud Reservoir during the first fifty years of its impoundment until 2007. Extrapolation of the same trend line indicates 100% siltation of the live storage by 2110. Hence, Hirakud Reservoir may meet 50% of its water demands until 2040. It has also been observed by the area-reduction method that the dead storage may be diminished by about 100% of its original storage capacity around 2050 because of silt deposition. The gross storage will be fully depleted with silt by the year 2110. The decrease in the live, as well as the gross storage after 2050, is notable, with the dead storage being completely filled with sediments. Thus, flushing the sediments through the sluice gate will not only increase its life, but also reduce flash floods attributable to sediment deposition at the head end of the reservoir. The suspended and bed load enter the backwater region at the head end to form a delta and raise the reservoir bed level, resulting in a reduced channel slope, as well as a reduced reservoir cross section that results in a high flood stage.

Sediment deposition

Figure 14 illustrates sediment deposition variations for the projected years. The Brune method indicates a uniform sediment deposition into Hirakud Reservoir over the years. Due to the variation in the sediment inflow rate into the reservoir, and its trap efficiency, there is a variation in the sediment deposition pattern mainly above the dead storage zone. Within the dead storage zone up to the elevation of 152.40 m, however, there is little variation in sediment distribution. The following relationship was used to predict the sediment deposition into Hirakud Reservoir:

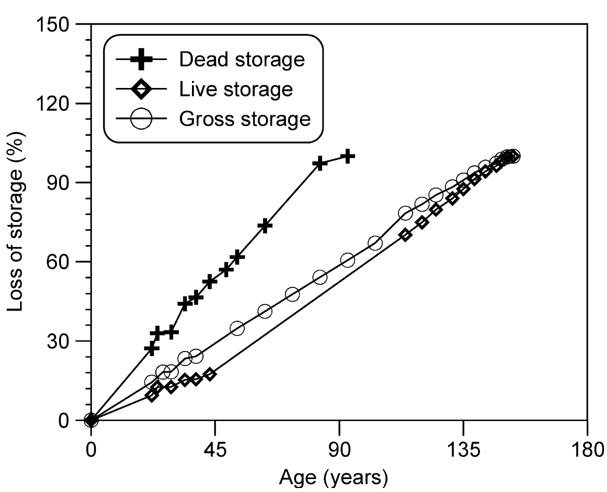

Fig. 13. Loss of reservoir storage study.

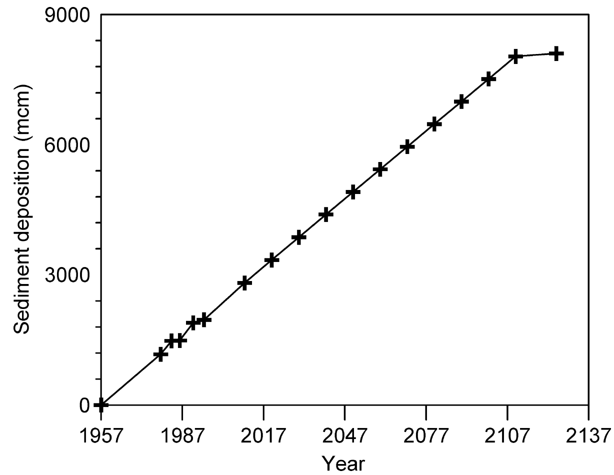

Fig. 14. Projected reservoir sediment deposition.

$$V_S = 45.53 \times x_T + 0.143 \times x_T^2 + 93.28 \qquad (14)$$

where V_S = total sediment volume (mcm) and x_T = reservoir age (years). The coefficient of determination (R^2) is 0.998, indicating a very good correlation between the deposited sediment volume into the reservoir and the reservoir age.

A comparative study is carried out to observe the deviation of the predicted values of different storage capacities for Hirakud Reservoir for 2040, based on sedimentation survey data and the area-reduction method. Table 4 highlights the deviation of predicted values, from which it is evident that the empirical area-reduction method, developed in the United States, gives a satisfactory result for Hirakud Reservoir.

Results obtained by numerical simulation

The previously mentioned numerical simulation models were run to simulate morphological changes in Hirakud Reservoir, considering a shortened discharge hydrograph of each year to about 6 months to represent the high flows during each monsoon season. The flow, as well as the sediment yield, is negligible during the dry season, thereby being omitted from the simulation period.

The most sensitive parameters for the hydrodynamic and sediment transport models are the frictional coefficient and the sediment particle settling velocity, respectively. By varying these sensitive parameters, several simulations were carried out until a good agreement was reached between the observed and simulated values.

To evaluate the performance of the numerical models in terms of the accuracy and consistency in predicting reservoir bed levels, three statistical measures were employed to correlate the results with the observed reservoir sedimentation, as follows:

Table 4. Deviation of forecasted values of storage capacities of Hirakud Reservoir, 2040

Storage capacity	Elevation (m)	Forecasted value based on sedimentation survey data (mcm)	Forecasted value based on area-reduction method (mcm)	Deviation of forecast (%)
Dead	152.40	62.60	60.92	2.683706
Live	192.02	4038.40	3715.15	7.189812
Gross	192.024	4055.60	3764.01	8.004408

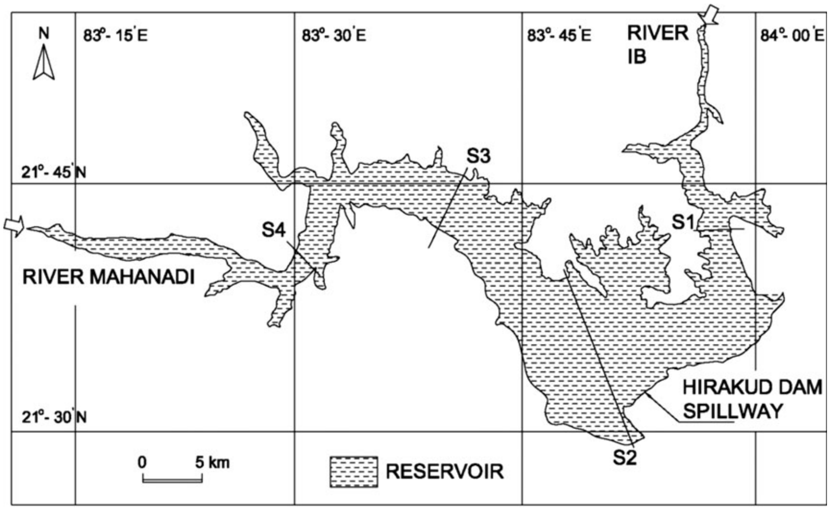

Fig. 15. Positions of four range lines in different Hirakud Reservoir cross sections (S1 = range line no. 37; S2 = range line no. 83; S3 = range line no. 134; S4 = range line no. 160).

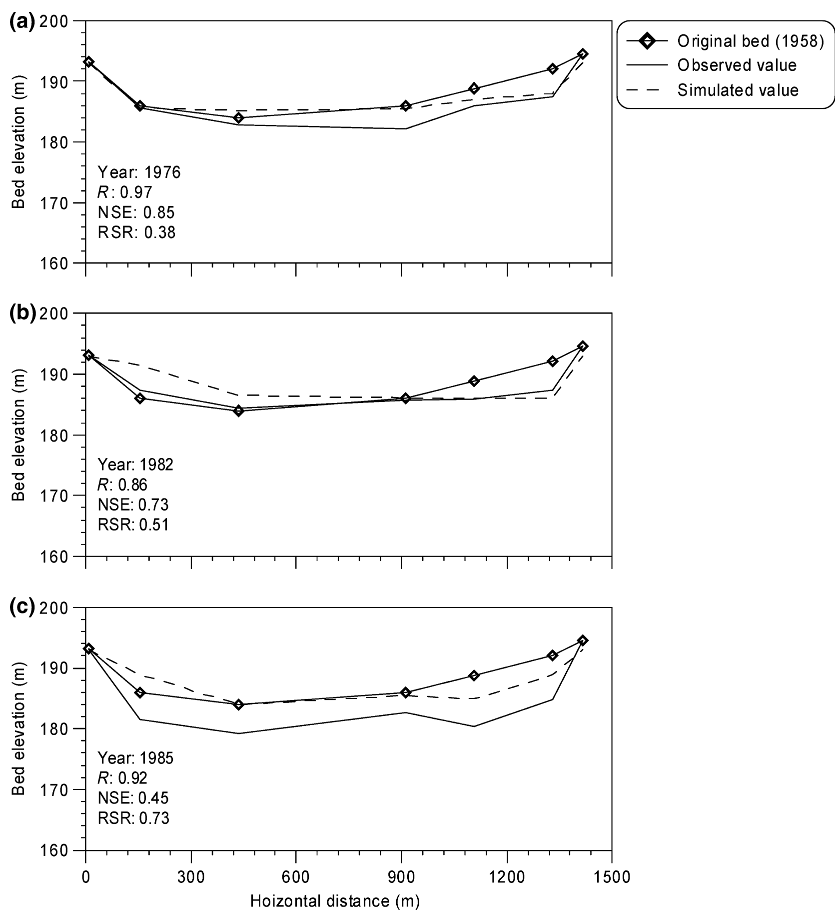

Fig. 16. Bed profile along S1 (range line no. 37) in Hirakud reservoir for a) 1976, b) 1982 and c) 1985 years respectively.

1. Pearson's correlation coefficient (R), which is an index of the degree of relationship between the observed and simulated data, ranging from −1 to +1.

The formula for R is as follows:

$$R = \frac{\sum_{i=1}^{n}(X_i - X_{\text{mean}})(Y_i - Y_{\text{mean}})}{\sqrt{\sum_{i=1}^{n}(x_i - x_{\text{mean}})^2}\sqrt{\sum_{i=1}^{n}(y_i - y_{\text{mean}})^2}} \quad (15)$$

where X_i = i^{th} value of observed data; Y_i = i^{th} value of simulated data; X_{mean} = mean value of observed data; Y_{mean} = mean value of simulated data; and n = total number of observations.

2. Observations standard deviation ratio (RSR), which is the ratio of root mean square error (RMSE) and standard deviation (STDEV) of the observed data, as follows:

$$\text{RSR} = \frac{\text{RMSE}}{\text{STDEV}_{\text{Obs}}} = \frac{\left[\sqrt{\sum_{i=1}^{n}(X_i - Y_i)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(X_i - X_{\text{mean}})^2}\right]} \quad (16)$$

RSR varies from 0 to any positive value. A lower RSR value indicates a better performance of the model simulation.

3. Nash–Sutcliffe Efficiency (NSE), which is a statistical measure to determine the relative magnitude of the residual variance, compared to the measured data variance (Nash & Sutcliffe 1970), as follows:

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(X_i - X_{\text{mean}})^2}\right] \quad (17)$$

NSE ranges from $-\infty$ to 1.

Hydrodynamic surveys for Hirakud Reservoir have been carried out since 1976 with cross sections along 202 range lines with a recording echo sounder mounted on motor launches for sedimentation studies. The recorded data along these cross sections for 1976, 1982 and 1985 were provided by the Department of Water Resources, Government of Odisha, being used to validate the simulated results in the present study.

A comparison of the observed and simulated bed level data was carried out for four range lines (Fig. 15). The results indicated that the numerical simulation models generally performed well in representing the dynamics of the deposited sediment within the study area (Figs. 16–20). Some inconsistency between the observed

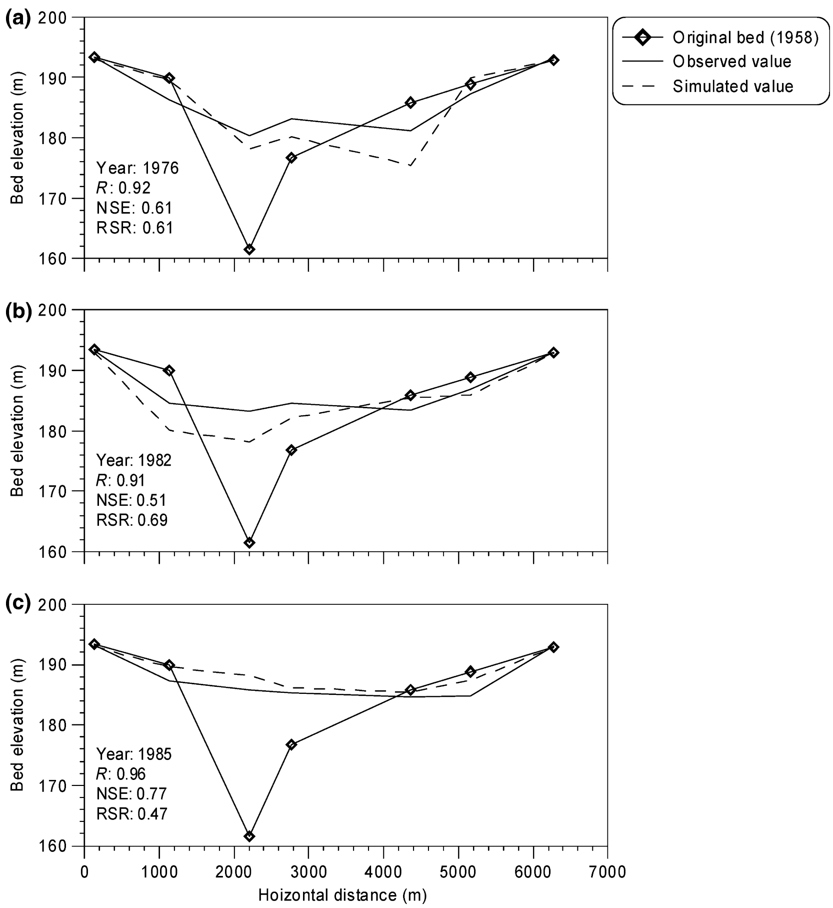

Fig. 17. Bed profile along S2 (range line no. 83) in Hirakud reservoir for a) 1976, b) 1982 and c) 1985 years respectively.

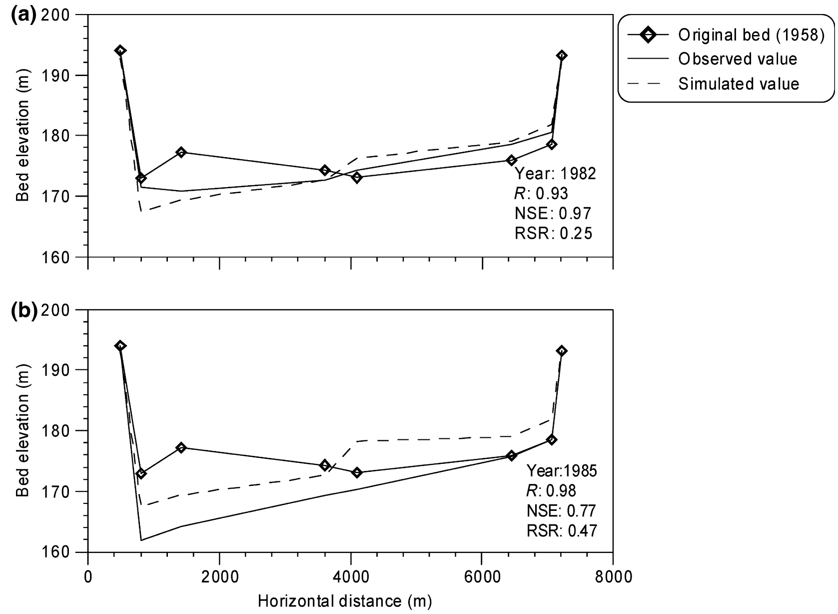

Fig. 18. Bed profile along S3 (range line no. 134) in Hirakud reservoir for a) 1982 and b) 1985 years, respectively.

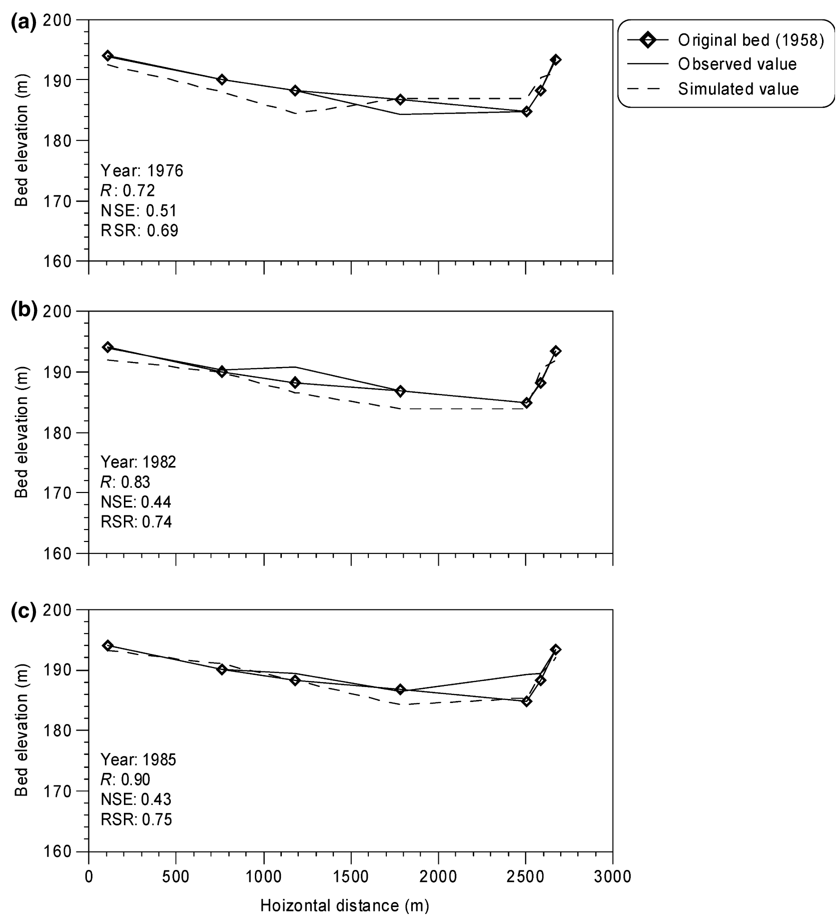

Fig. 19. Bed profile along S4 (range line no. 160) in Hirakud reservoir for a) 1976, b) 1982 and c) 1985 years, respectively.

and simulated data may be observed, however, likely due to inaccuracies in the distribution of sediment deposition in the transverse direction, as well as the complex nature of different deposition patterns in the reservoir.

The simulation model results provide different shapes of delta formation and sediment deposition. Most of the incoming sediments from the two inlets (Mahanadi River; Ib River) are deposited at the

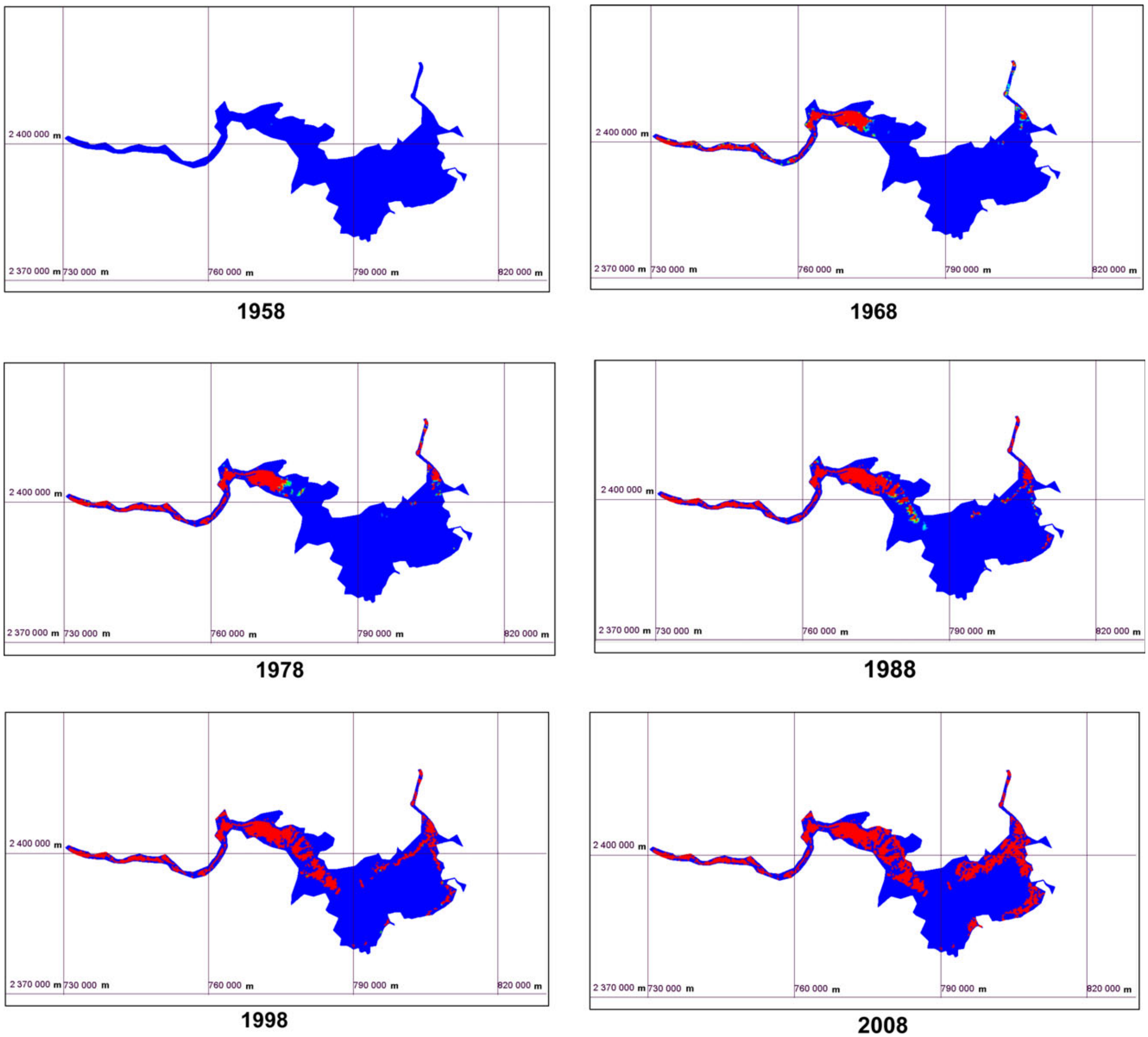

Fig. 20. Changing sediment deposition over study period: Simulation results using TELEMAC-2D and SISYPHE.

beginning of the reservoir because of the sudden widening of the river valley, causing bed level changes and delta formations at those locations (Fig. 20). This is attributable to the sudden change in the hydraulic conditions of the incoming streams from the abrupt change in the geometry of the valley and the resulting reduced sediment transport capacity. Due to variations in the incoming discharge and sediment load, the bed level does not change uniformly, but rather varies alternatively between erosion and deposition according to the water and sediment load fluctuations. This results in different deposition patterns throughout the reservoir. During extreme events (e.g. high floods), the flow velocity increases, causing erosion as well as an increased sediment transport rate along the reservoir in the form of bed load and suspended sediment load. The bed load forms a delta at the reservoir entrance that cannot move downstream because of the larger grain size and reduced water velocity, turbulence and shear stress in the flow occurring within the reservoir. Simulated suspended sediment concentrations greater than the equilibrium concentration imply a tendency for deposition, whereas a smaller concentration results in a tendency to erode the riverbed. The suspended particles remain in suspension when entering the reservoir, however, and move downstream.

Interestingly, the upstream delta in the Mahanadi River forms finger-like shapes instead of spreading laterally, whereas the upstream delta occupies the full valley width from bank to bank in the Ib River. The deposits are mostly massive, being composed of pure sand. The channel flows over the sand deposits, however, without any meandering or bar formation. Thus, no scattered accumulation of appreciable quantity of sediment is observed.

Based on the model simulations, the rate of silting and delta formation for the Mahanadi River is progressively more than that of the Ib River. In case of the Ib River, the maximum sedimentation occurs mostly at a distance of 0.44 L in Hirakud Reservoir between reservoir level (R. L.) 175.26 m and 179.83 m, where L is the total length of the channel along the Ib River from the axis of the Hirakud Reservoir dam. In the case of the Mahanadi River, maximum sedimentation occurs in the reservoir at 0.4 L', where L' is the total length of the channel along the Mahanadi River from the dam axis, just below a reservoir level of 179.83 m. The elevations are the reduced levels above the Mean Sea Level.

Declined storage curves of observed and TELEMAC-SISYPHE

Based on the available data, Figure 21 indicates the trend of reducing gross storage capacity is similar to that of the curve obtained from numerical simulations. Extrapolation of the gross storage diminishing curve, using the observed reservoir survey, indicates the operational life of Hirakud Reservoir will extend until 2110, with the life of the reservoir reduced to zero by 2150 on the basis of extrapolation of the numerical simulation model. The difference between the observed and simulated values may be due to the uncertainty in the observed data and perhaps also to the use of empirical formulae in numerical simulations, which are highly sensitive to the wide range of physical variables.

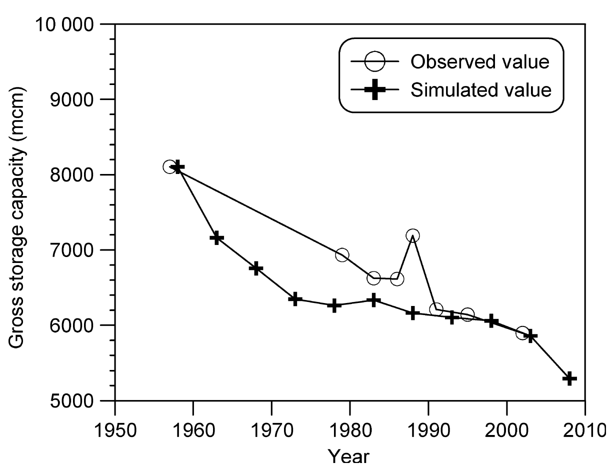

Fig. 21. Comparison of observed and numerically simulated Hirakud Reservoir storage capacity values.

CONCLUSIONS

As it is difficult to avoid sediment deposition in a reservoir, it is necessary to determine the sedimentation distribution pattern, from which necessary preventive measures may be planned. As estimated by the Brune method, there is little variation in Hirakud Reservoir trap efficiency until 2050. It is drastically reduced because of the filling of the dead storage with silt, becoming zero at the end of 2110. There is also little variation of the sediment distribution in the dead storage zone, whereas there is a variation in the sediment deposition pattern in this zone attributable to the variation in the sediment inflow rate into the reservoir and its trap efficiency. All the capacity-elevation curves for Hirakud Reservoir exhibit similar patterns and coincide irrespective of the inflow volume to the reservoir and the downstream water demands. The area-reduction method indicates that the loss in live storage will reach 58% in 2050, after 83 years of impounding of water in the reservoir, whereas the loss in gross and dead storage will be 63% and 100%, respectively. The gross storage zone of Hirakud Reservoir will be completely depleted by 2110, with the reservoir bed level rising to 192.02 m without regular flushing operation for the reservoir. This study indicates the empirical area-reduction method can also be used to determine the storage capacities of Hirakud Reservoir in the absence of sedimentation survey data. Better water management practices, along with sediment management techniques, can also be adopted to reduce the sedimentation rate into Hirakud Reservoir. The results of this study also are helpful in formulating efficient water resource management techniques applicable to the surrounding catchment areas.

The goal of predicting the operation life of Hirakud Reservoir on the basis of numerical simulations was also carried out successfully using TELEMAC-2D, coupled with SISYPHE. However, much more time is needed for their implementation and simulation, as well as higher precision calculations for predicting morphological changes. The limited availability of input data hindered the model simulations to some extent. Nevertheless, both graphical and statistical comparisons for four cross sections along the longitudinal axis of the reservoir indicated an acceptable agreement between the simulated and observed data. The performance of the model varies with different cross sections because of the complex nature of sediment deposition into the reservoir. At the reservoir mouth, the bed load settles down to form a delta because of reduced flow velocities, turbulence and shear stress. The suspended load is carried out by the water along the longitudinal distance, settling near the dam. The numerical simulations predict the end of the operational life of Hirakud Reservoir by 2150. The results of this study will facilitate the ability of researchers to use this numerical model to determine the bottom topography for other reservoirs as well. Further studies on the effects of the interactions between jets for multiple inlets of a reservoir are also needed. This study only considered the quantitative impacts of reservoir siltation on water availability. Thus, further study is needed to predict the life of reservoir on the basis of climatic impacts and consideration of the downstream water demands for which the reservoir was originally designed.

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