*Sediment Problems and Sediment Management in Asian River Basins*
(Proceedings of the Workshop held at Hyderabad, India, September 2009). IAHS Publ. 349, 2011.

# Sediment problems and sediment management in the Indian Sub-Himalayan region

**UMESH C. KOTHYARI**
*Dept. of Civil Engineering, Indian Institute of Technology, Roorkee-247667, India*
umeshfce@iitr.ernet.in

**Abstract** Alluvial rivers as well as gravel- and boulder-bed rivers in the Indian Sub-Himalayan region pose many problems for the inhabitants of the region. Landslides and floods triggered by heavy rainfall result in colossal damage to life and property. The design, construction and maintenance of dams, reservoirs, bridges and other infrastructure pose important challenges due to the complex role played by the sediment transported by the rivers of the region. This contribution reviews the current status of sediment management in the region by means of illustrative examples and sample data.

**Key words** sediment; sediment problems; sediment management; Indian sub-Himalayan region

## INTRODUCTION

The middle and lower mountains of the Himalayas represent the most densely populated mountain areas in the world, and the population of the region is still increasing. This has resulted in large-scale depletion of resources and degradation of the hillslopes. In these areas, water availability is already a limiting factor for domestic supply and agricultural production, particularly during the summer months. The fertile topsoil on the hillslopes is readily lost due to surface and gully erosion, and the agricultural land has frequently expanded to areas with a marginal soil cover. The livelihood of people in most of the sub-Himalayan region is mainly based on subsistence farming. However, the vast tracts of land here have been irreversibly converted into infertile areas, due to continued soil erosion.

Soil eroded from upland areas of the catchment is deposited downstream in the rivers, causing aggradation. Deforestation in headwater areas is frequently identified as the prime cause of the frequent flooding and sedimentation in the lowlands of the Gangetic plains. This deposition results in an increase in the extent of the river flood plains, blocking of bridges and culverts, and loss of reservoir storage.

Soil erosion, sediment transport and sediment deposition also cause major problems for the numerous hydropower projects which are found in the Indian sub–Himalayan region. Turbine blades can be rapidly abraded and other structures, including dams, are frequently damaged by sediment abrasion. Furthermore, reservoir storage can be greatly reduced by reservoir sedimentation. As in most environments, much of the sediment load is transported during the onset of flood flows. Detailed information regarding flood hydrographs and the timing of sediment fluxes relative to the hydrograph, as well as estimates of the amount of sediment that is likely to be deposited in reservoirs, are important requirements to support effective sediment management in hydro-power projects. The major problems related to sediment occurring in the Indian sub-Himalayas and their associated management issues are discussed below.

## SEDIMENT PROBLEMS

### Soil erosion and landslides

Most parts of the Indian sub-Himalayas, particularly the Shiwaliks, which represent the foothills of the Himalayas in the northern and eastern provinces of India, are comprised of sandstones, grits and conglomerates, representing former fluvial deposits, mantled by deep soils. Erosion has occurred widely across this region due to intensive deforestation, large-scale road construction, mining and cultivation on steep slopes. An area of approximately 30000 km$^2$ has been severely eroded in the northeastern Himalayas, due to shifting cultivation (Narayana & Ram Babu, 1983). Landslides are the other primary cause of soil erosion and related problems in the Himalayas. In India, landslides mainly occur along the Shiwaliks in the Himalayas. The landslide prone areas also coincide with the locations with high magnitude earthquakes, geological faults and rainfall events characterized by both high intensity and long duration. Landslides also cause various other problems, such as the damming of rivers. The breaching of such barriers and the associated release of the impounded water can have disastrous effects downstream. High intensity cloud burst events also occur frequently in the sub-Himalayan region, where again they trigger landslides. There have been many recent examples of disasters due to cloud burst triggered landslides in this region.

## Reservoir sedimentation

Rivers are an important source of water for drinking and for irrigation, hydropower generation and navigation. Reservoirs are built to store water and thus increase the amount of water available for use. Hydropower development, in particular, generally involves the construction of reservoirs.

The useful life span of a reservoir is determined by the rate of sedimentation in the reservoir. As sediment accumulates in the reservoir behind a dam, the storage capacity of the reservoir gradually reduces and the efficiency of the reservoir decreases. Given the scarcity of good dam sites and the growing resistance to construction of new dams, to avoid overexploitation of rivers and associated environmental degradation, the problem of reservoir sedimentation has attracted increasing interest worldwide, particularly in India. The ultimate objective is to extend the useful life of existing reservoirs by as much as possible and to plan and design new reservoirs to have as long a life as possible.

## The status of reservoir sedimentation in India

There are currently about 40 000 large reservoirs worldwide, used for water supply, power generation, flood control, etc. Between 0.5 and 1 percent of the total storage volume of these existing reservoirs is lost annually, as a result of sedimentation and 300–400 new dams need to be constructed annually just to maintain the current total storage (White, 2001). The increasing population and per capita consumption mean that the demand for water storage in reservoirs is expanding, despite the increasing use of alternative sources of water and the more efficient use of water. Morris (2005) estimates that by the mid-21st century, over 30% of the world’s reservoir capacity will have been lost to sedimentation.

Reservoir surveys undertaken in India have shown that the observed sedimentation rates are frequently much higher than those assumed at the project design stage (Table 1). The useful live storage capacity of many reservoirs in India has been appreciably reduced by siltation, as shown in Table 2.

**Table 1** Comparison of observed and design sedimentation for several reservoirs in India (based on Singh *et al*., 1990).

| Name of river | Name of reservoir | Year of impounding | Year of observation | Sedimentation yield rates ($m^3$ $km^{-2}$ $year^{-1}$) | |
|---|---|---|---|---|---|
| | | | | Design | Observed |
| Beas | Beas | 1974 | 1981 | 429 | 2359 |
| Chambal | Chambal | 1960 | 1976 | 361 | 529 |
| Barakar | Maithon | 1956 | 1979 | 162 | 1215 |
| Damodar | Panchet | 1956 | 1974 | 247 | 992 |
| Manjira | Nizamsagar | 1931 | 1973 | 29 | 634 |
| Tungabhadra | Tungabhadra | 1953 | 1972 | 429 | 611 |
| Ramganga | Ramganga | 1974 | 1974 | 479 | 1730 |

**Table 2** Loss of storage due to sedimentation for selected reservoirs in India (based Singh *et al.*, 1990).

| River | Reservoir | Year of impounding | Year of survey | Loss of storage (%) | |
|---|---|---|---|---|---|
| | | | | Dead storage | Live storage |
| Sultej | Bhakra | 1959 | 1978 | 17.82 | 3.69 |
| Damodar | Panchet | 1956 | 1966 | 27.00 | 13.00 |
| Barakar | Maithon | 1956 | 1979 | 32.00 | 14.00 |
| Manjira | Nizamsagar | 1931 | 1967 | 97.11 | 44.87 |
| Tungabhadra | Tungabhadra | 1953 | 1978 | 100.00 | 10.35 |

Prior to 1971, about 126 dams with a height of 30 m or more were constructed for irrigation, hydropower generation, flood control, etc. Many of these reservoirs now contain significant accumulations of sediment eroded from their catchments. Analysis of the available sedimentation data (Murthy, 1977; Shangle, 1991) indicate that the sedimentation rates in these reservoirs are highly variable. In some reservoirs, such as the $2.4 \times 10^3$ $Mm^3$ Ramganga reservoir, the data indicated a very small rate of sedimentation, while the $3.1 \times 10^3$ $Mm^3$ Srirama Sagar reservoir was found to have lost 25% of its capacity during the first 14 years after impoundment. Based on a screening analysis of the available data, Morris (1995) concluded that only a few reservoirs in India had lost as much as 50% of their capacity by 1995. However, by 2020 it is expected that 27 of the 116 reservoirs would have lost half their original storage capacity and by the year 2500, only about 20% of India's existing reservoirs would not have lost 50% of their original capacity.

## Shifting of river courses

Floods are a common occurrence in Himalayan rivers. Every year floods affect many thousands of people in the Himalayan region. Every year the high magnitude monsoon floods in Himalayan rivers cause huge losses in terms of both damage and disruption to economic activities, businesses, infrastructure, services and public health, basically due to shifting of the courses of the alluvial rivers in this region. Long-term data on natural disasters suggest that floods are by far the most common cause of such natural disasters in this region. Floods accounted for over 55% of people affected by natural disasters. The devastation caused by shifting river courses in the sub-Himalayan region and the resulting inundation of adjacent areas is well illustrated by the example of the Kosi disaster, which occurred in August 2008.

The River Kosi is well known for frequently changing its course, causing floods and hence damage. The river brings an enormous amount of very fine sediment from the Himalayas and deposits this sediment in the plain areas as it descends from the mountains, which extend from Nepal Shiwaliks to the Tibet Himalayas. The Kosi River has shifted eastwards over a distance of 112 km in a period of about 225 years (Fig. 1).

Marginal embankments were constructed along considerable stretches of both banks of the river during the 1960s in an attempt to curb the shifting of the channel. However, the river has frequently attacked this embankment. The Kosi flood that occurred on 18 August, 2008, due to the breach of its eastern embankment, had a devastating impact. The disaster occurred near the village of Kushaha in the Sunsari district, Nepal. The flood entered the settlement damaging national highways, power transmission lines, communication cables, schools, health posts, village roads and private and public houses. Figures 2 and 3 depict the scenes of the damage caused by the flood.

Extensive rescue, relocation and repair work were carried out by the administration, security forces and non-governmental organizations (NGOs) to deal with the damage, and the displaced people were eventually able to return to their homes and farms. The disaster incurred colossal costs, inconvenience and enormous loss of human and animal lives, as well as destruction of property. There are several other examples of such devastation caused in India by the shifting of the courses of alluvial rivers, particularly on the Indo-Gangetic plain.

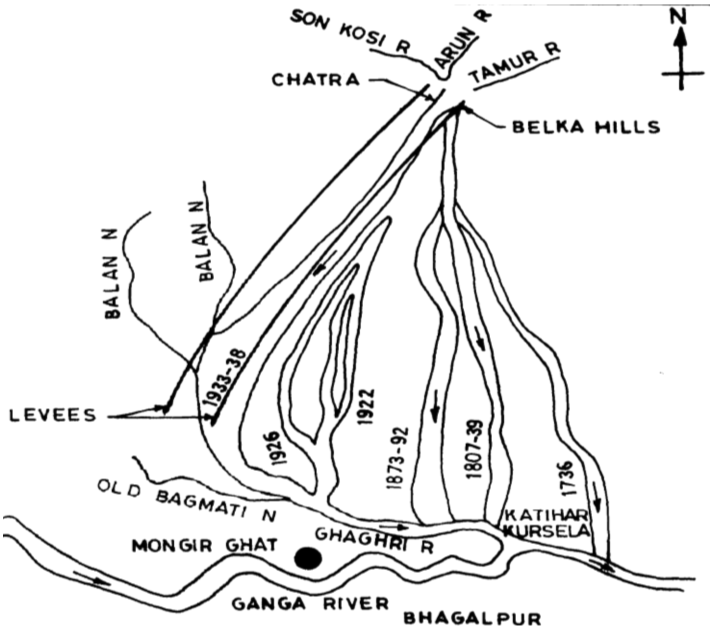

**Fig. 1** The shifting courses of River Kosi (based on Garde *et al*., 1990).

**Fig. 2** Inundation caused by the Kosi flood on 3 September 2008.

## SEDIMENT MANAGEMENT

The rivers originating from the Himalayas pose several challenging problems related to managing their sediment loads. On account of the complex role played by the sediment load it is difficult to provide suitable designs for reservoirs constructed for water storage and hydropower generation. Similarly the design, construction and operation of canals taking water from rivers and reservoirs is also challenging. Construction of a dam or a weir and withdrawal of water from the river invariably disturbs the equilibrium of the river, leading to aggradation and degradation in different reaches of the river. In the case of alluvial rivers, the design of reservoirs and canals requires a

**Fig. 3** Damage caused by the Kosi flood in Birpur, Bihar (India).

clear understanding of the influence of sediment transport and the sediment load must be incorporated as a key parameter in the design. Estimation of soil erosion rates and sediment yields for Himalayan catchments is therefore an important area of investigation by both researchers and practitioners.

## Modelling of soil erosion and sediment yield

At present some information is available about the rates of soil erosion and sediment yield from catchments in India, including those in the sub-Himalayan region (Walling, 1994; Kothyari *et al*. 2002). For project planning purposes, meaningful estimates of sediment yield can be made with available techniques by using data on hydrometeorology and catchment characteristics. Remote sensing (RS) and geographical information system technique (GIS) are being increasingly utilized to provide spatially distributed hydrological data and model output. For soil conservation planning, however, it is necessary to estimate the variation of soil erosion and sediment yield with time during storm events or for a series of storm events. Some of the recent advances made in this area are discussed below.

Work on the mathematical prediction of soil erosion due to water and the sediment yield of catchments was initiated about 5–6 decades ago. The development of prediction equations for soil erosion began with analyses such as those undertaken by Ellison (1944, 1947). Ellison (1947) presented an analysis of soil erosion sub-processes that formed the basis for more recent soil erosion modelling efforts. Later Meyer & Wischmeier (1969) presented mathematical formulations for detachment and transport by rainfall and runoff matching the way these processes were hypothesized by Ellison (1947). Kothyari (2008) has reviewed the current status of mathematical modelling of soil erosion and sediment yield.

The key components of soil erosion can be identified as: (i) sheet erosion, (ii) rill erosion, (iii) inter-rill erosion, (iv) gully erosion, and (v) channel scour and deposition. When a model is constructed using mass conservation and flow equations for water and sediment, it is called a physically-based or process-based erosion and sediment transport model. When developing such models the ground surface is generally separated into areas affected by inter-rill and rill erosion. Auxiliary equations based on experimental investigations are used to describe the processes of sediment detachment from rill and inter-rill areas. Transport of eroded sediment to downstream areas is governed by relationships involving sediment transport capacity. The transport process linked to the component processes of soil erosion is discussed below.

**The transport of eroded soil** When the soil or sediment particles are detached from the ground surface, they become part of the flow and can be transported downslope or downstream over distances varying from a few millimetres to many kilometres. This distance is dependent upon the sediment transport capacity of the flow. In many soil erosion studies the transport rate is expressed in terms of a sediment delivery ratio, which represents the fraction of the total mass of eroded soil that reaches the catchment outlet. In most physically-based models, however, the transport process and resulting particle sorting effect in rill and inter-rill areas and in the channel has been considered by the inter-rill detachment relationships. Foster & Meyer (1975) indicated that inter-rill transport capacity is greatly enhanced by raindrop impact. Meyer & Wischmeier (1969) proposed a relationship for sediment transport capacity, based on the discharge rate and land slope. Other relationships which have been utilized for computing transport through inter-rill areas are the Duboys equation (Young & Mutchler, 1969; Foster & Huggins, 1977); the Meyer-Peter and Muller equation (Lee *et al*., 1997); the Yalin equation (Foster & Meyer, 1972); and the Bagnold equation (Yang, 1972). No single sediment transport equation is recognised to be superior to others, because all these equations require calibration to represent sediment transport by overland flow within the inter-rill areas (Garde & Ranga Raju, 2006). In many of the present-day mathematical models, the component processes of rill, inter-rill and gully erosion, etc. are simulated by subdividing the catchment into sub-areas of relatively homogeneous hydrological characteristics. These models are termed as distributed models. The structure of distributed models and the type of results obtained are described below.

**Results from distributed mathematical models of soil erosion and sediment yield** Physically-based distributed mathematical models (Ivanov *et al*. 2004; Jain *et al*., 2005) of soil erosion and sediment yield produce results that are spatially distributed. Such models first involve catchment discretization (Fig. 4) and the model results are obtained for each of the discretized elements (Fig. 5). The results produced by distributed models help in identification of the areas within a catchment that are vulnerable to soil erosion and which would need priority for implementation of treatment and conservation measures. Details of practices used for conservation of soil are presented subsequently in this report.

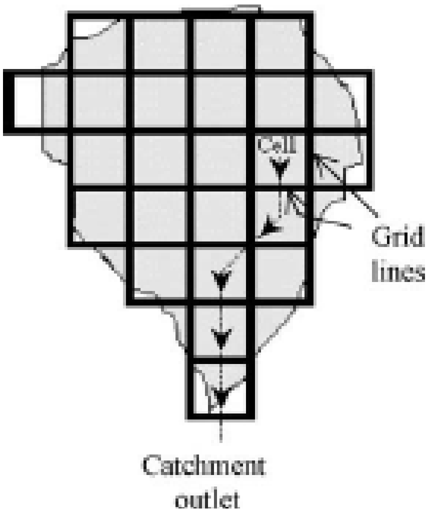

**Fig. 4** Cell based discretization of a catchment (based on Jain *et al*., 2005).

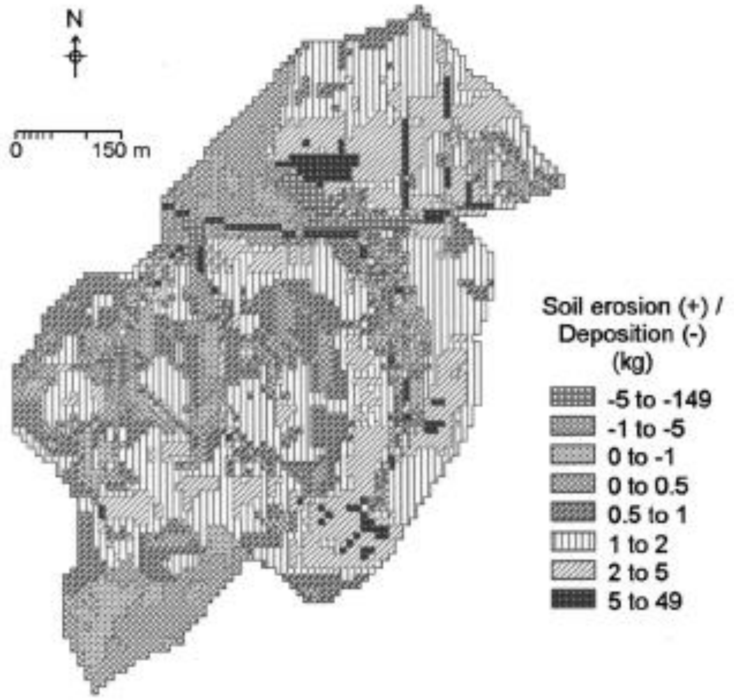

**Fig. 5** The spatial distribution of soil erosion/deposition in the Catsop catchment during the storm event of 26 June 1987 (based on Jain *et al*., 2005).

In spite of the fact that these models are rational and are based on the physics of the processes involved, they are not often used to compute the sediment load from large catchments due to a number of difficulties. Such models are, however, extremely useful in providing guidelines for targeting catchment area treatment to reduce sediment yield.

**Prioritization of areas for application of soil conservation measures** The results of process-based mathematical models are useful for prioritizing specific parts of a catchment for application of soil conservation measures. The implementation of measures for soil conservation requires huge investment. The cost of implementation of conservation measures increases greatly as the area of the catchment required to be treated increases. Prioritization of areas within the catchment for treatment thus becomes an important issue. Distributed mathematical modelling of soil erosion and sediment yield helps in selecting the areas to be treated for soil conservation as a priority. Further details on distributed modelling of soil erosion were provided above. Figure 6 shows the results from a distributed model which depicts the zones within the catchment identified through mathematical modelling to be vulnerable to soil erosion and which may need priority treatment.

### Measures for reduction of reservoir sedimentation

The rate of sedimentation in reservoirs in India is mainly controlled by adopting measures which follow one or more of the following principles:

- Control of sediment inflow to the reservoir
- Control of sediment deposition in the reservoir
- Removal of sediment deposits from the reservoir

Measures for controlling reservoir sedimentation that are commonly applied in India include:

- Management and treatment of the river/reservoir catchment or watershed
- Measures to permit sediment-laden inflows to by-pass the reservoir
- Flushing/sluicing of the reservoirs and venting density currents
- Dredging and excavation

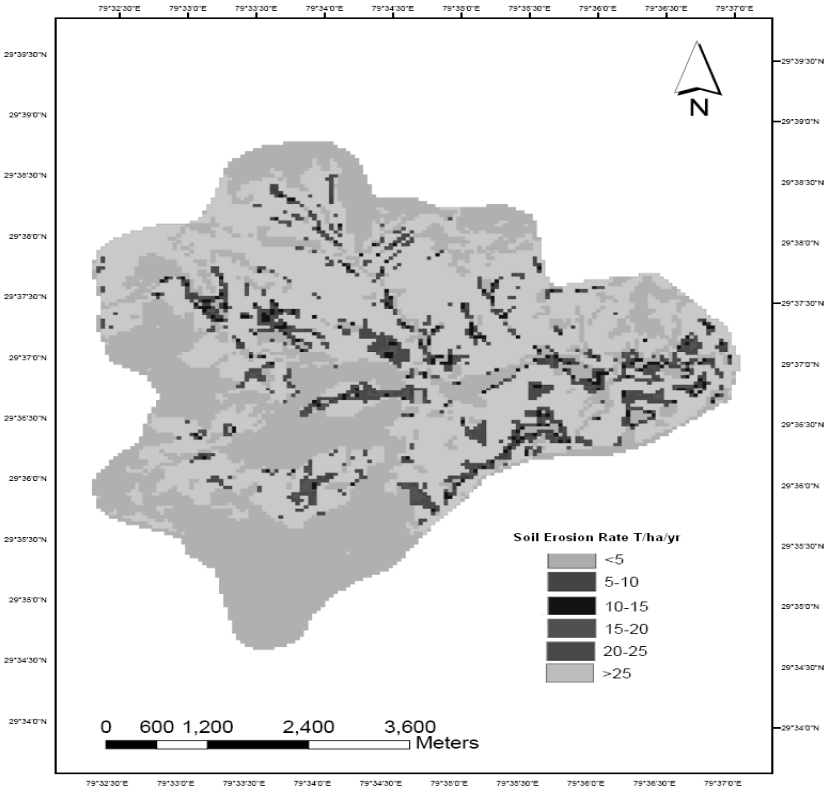

**Fig. 6** A map of the Khulgad catchment, Uttarakhand, India showing areas vulnerable to soil erosion (based on Ramsankaran *et al*., 2009).

All the above sediment management and control measures are applied to both storage reservoirs as well as to run-of-the river projects. More details concerning these measures can be found in Ranga Raju *et al*. (2010).

## Sediment extraction from canals

Canals built for irrigation and hydropower generation often get clogged due to deposition of sediment. It is generally believed that sediment coarser than 0.20 mm in size is harmful for turbine blades and will thus have to be eliminated from hydropower channels and inlets. Also, if the incoming sediment load is in excess of the carrying capacity of the irrigation canal, the excess load will have to be removed. Such extraction devices are located a short distance downstream of the head regulator of the canal and upstream of the canal reach in which the sediment load is to be reduced to a desired value. Considering the general situation in which there is a significant fraction of sediment in suspension that needs to be extracted, settling basins and vortex chamber extractors represent feasible methods of sediment extraction which are commonly used in India. The methods used for the design of such structures in India are briefly discussed below.

**Settling basins** Settling basins operate on the principle of forcing sediment to deposit through a significant reduction in velocity. The reduction in velocity is achieved by an increase in width and an increase in depth (see Fig. 7). The notation used in Fig. 7 is self explanatory.

Settling basins may involve continual flushing – in which case the incoming discharge has to exceed the design discharge by the discharge used for flushing – for removal of deposited sediment, or may rely on intermittent mechanical or manual removal of deposited sediment. Since the early work of Dobbins (1944), several empirical and semi-empirical relationships for determining the efficiency of sediment removal from settling basins have been developed. These include the work of Sumer (1977), Schrimpf (1991) and Atkinson (1992).

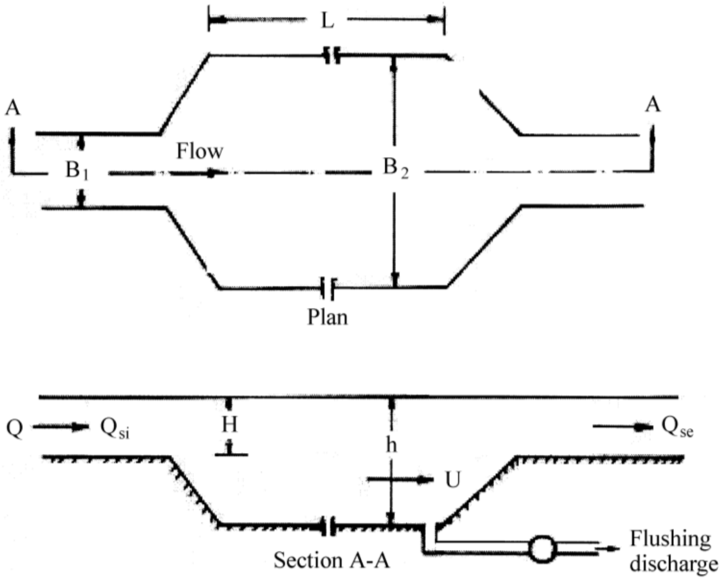

**Fig. 7** Definition sketch of a settling basin.

Dongre (2002) performed laboratory experiments on the efficiency of settling basins and also checked the accuracy of the available relationships for determining efficiency. Finding that none of the available relationships performed satisfactorily over a wide range of variables, he derived the following empirical relationship for predicting efficiency, based on analysis of all the available data:

$$\eta = 102.5\left(1-\exp\left(-0.3\frac{A_b}{A_a}\right)\right)\left(1-\exp\left(-0.1\frac{L}{h}\right)\right)\left(1-\exp\left(-0.42\frac{\omega}{u_*}\right)\right) \quad (1)$$

Equation (1) is applicable for settling basins without flushing. Here $\eta$ is the efficiency of the basins expressed as a percentage, $A_b$ is the cross sectional area of the settling basin, $A_a$ is the cross-sectional area of the approach channel and $u_*$ is the shear velocity in the settling basin. It is observed that equation (1) is able to estimate $\eta$ values with a maximum error of about ±25%.

The effect of continual flushing on the efficiency of the basin was taken into account by Ranga Raju *et al*. (1999), who proposed the relationship:

$$\frac{\eta_f}{\eta} = 1 - 0.12Q_f^{-0.105}\left(\frac{\omega}{u_*}\right)^{0.312} \quad (2)$$

Here $\eta_f$ is the efficiency in the presence of flushing, $\eta$ is the efficiency in the absence of flushing, and $Q_f$ is the flushing discharge expressed as a percentage of the discharge entering the basin. Most of the hydropower stations in the Himalayan region in India are provided with settling basins for extracting the excess sediment. In most cases these have worked satisfactorily.

**Vortex chamber type extractors** This type of extractor makes use of vortex flow in a chamber for sediment removal. A high velocity flow is introduced tangentially into a cylindrical chamber having an orifice at the centre of its base, which removes the highly concentrated sediment. This, along with tangential entry of flow causes combined (Rankine type) vortex conditions with a free vortex forming near the orifice and forced vortex conditions forming in the outer region towards the periphery. Vortex flows cause a sediment concentration gradient across the vortex and a diffusive flux proportional, but opposite to, the centrifugal flux (Julien, 1986). The secondary flow resulting from this phenomenon causes the fluid layers near the chamber floor to move towards the outlet orifice at the centre. The sediment particles present in the flow move along a helicoidal path towards the orifice, thereby experiencing a long settling length compared to the chamber dimensions. The sediment reaching the centre can be flushed out through the orifice into an outlet channel or pipe (see Athar *et al*., 2002).

Vortex chamber sediment extractors have been used in many projects in the Himalayan region in India. These installations are more useful in smaller projects and in situations where site conditions make the construction of larger facilities, like settling basins, difficult.

## SUMMARY

It is imperative that the problems resulting from the heavy sediment loads carried by rivers in the Sub-Himalayan region of India should be managed optimally. Reservoirs and other infrastructure facilities in this region need to be planned, designed and operated such that their sustainable use is ensured, particularly from the point of view of sedimentation. An overview of recent advances in the technology developed for solving problems due to high amounts of sediment in Indian rivers has been presented in this article.

## REFERENCES

Atkinson, E. (1992) The design of sluiced settling basins – a numerical approach. Rep OD124, Overseas Development Unit, HR Wallingford, UK.

Athar, M., Kothyari, U. C. & Garde, R. J. (2002) Sediment removal efficiency of vortex chamber type sediment extractor. *J. Hydraul. Engng, ASCE* **128**, 1051–1059.

Dongre, N. B. (2002) Settling basin design. M. Tech Thesis, Dept. of Civil Engineering, Indian Institute of Technology, Roorkee, India.

Dobbins, W. E. (1944) Effect of turbulence on sedimentation. *Trans ASCE* **109**, 629–653.

Ellison, W. D. (1944) Studies of raindrop erosion. *Agric. Engng* **25**, 131–136.

Ellison, W. D. (1947) Soil erosion studies. *Agric. Engng* **28**, 145–146.

Foster, G. R. & Meyer, L. D. (1975) Mathematical simulation of upland erosion by fundamental erosion mechanism. In: *Present and Prospective Technology for Predicting Sediment Yield and Sources*, US Department of Agriculture ARS-S-40, 190–207.

Foster, G. R. & Huggins, L. F. (1977) Deposition of sediment by overland flow on concave slopes. In: *Soil Erosion Prediction and Control.* Soil Conservation Society of America, Ankeny, Iowa, 21, 167–182.

Garde, R. J., Ranga Raju, K. G., Pande, P. K., Asawa, G. L. Kothyari, U. C. & Srivastava, R. (1990) Mathematical modeling of the morphological changes in the river Kosi. Dept. of Civil, Engineering, Univ. of Roorkee, India.

Garde, R. J. & Ranga Raju, K. G. (2006) *Mechanics of Sediment Transport and Alluvial River Problems*, third edition. New Age International Publisher, New Delhi, India.

Inanov, V. Y. Vivoni, E. R., Bras, R. L. & Entekhabi, D. (2004) Catchment hydrologic response with a fully distributed triangulated irregular network model. *Water Resour. Res.***40**, W11102.

Jain, M. K., Kothyari, U. C. & Ranga Raju, K. G. (2005) GIS based distributed model for soil erosion and rate of sediment outflow from catchments. *J. Hydraul. Engng, ASCE* **131**, 755–769.

Julien, P. Y. (1986) Concentration of very fine silts in steady vortex. *J. Hydraul. Res. IAHR* **24,** 255–264.

Kothyari, U. C. (2008) Soil erosion and sediment yield modelling. *J. Hydraul. Engng, ISH* **14,** 84–103.

Kothyari, U. C., Jain, M. K. & Ranga Raju, K. G. (2002) Estimation of temporal variation of soil erosion and sediment yield using GIS. *Hydrol. Sci. J.* **47**(5), 693–706.

Lee, H. Y., Hsieh, H. M., Yang, J. C. & Yang, C. T. (1997) Quasi-two dimensional simulation of scour and deposition in alluvial channel. *J. Hydraul. Engng, ASCE* **123**(7), 600–609.

Meyer, L. D. & Wischmeier, W. H. (1969) Mathematical simulation of the process of soil erosion by water. *Trans. ASAE* **12**(6), 754–758.

Morris, G. L. (1995) Reservoir sedimentation and sustainable development in India. In: *Proc. 6th Int. Symp. On River Sedimentation* (New Delhi), 57–61.

Morris, G. L. (2005) Reservoirs and sedimentation issues: Worldwide and India. In: *INDIA HYDRO 2005* (Feb. New Delhi), 10–21.

Murthy, B. N. (1977a) Sedimentation studies in reservoirs. *CBIP. Tech. Rep.* 20, Vol. I.

Murthy, B. N. (1977 b). Life of reservoirs. *CBIP Tech. Rep.* 19.

Narayana, D. & Ram Babu (1983) Estimation of soil erosion from India. *J. Irrig. Drain. Div. ASCE* **109**(4), 419–434.

Ramsankaran, R., Kothyari, U. C., Rawat, J. S. & Rawat, G. (2009) Simulation of surface runoff and sediment yield using water erosion prediction project (WEPP) model: a study on Kaneli watershed in the Himalayan region. *Hydrol. Sci. J.* **54**(3), 513–525.

Ranga Raju, K. G., Kothyari, U. C., Srivastav, S. & Saxena, M. (1999) Sediment removal efficiency of settling basins. *J. Irrig. Drain. Div. ASCE* **125**(5), 308–314.

Ranga Raju, K.G., Kothyari, U. C. & Mittal, M. K. (2010) Status report on reservoir sedimentation. Indian National Committee on Hydrology (INCOH), Roorkee, India.

Schrimpf, W. (1991) Discussion of design of settling basins. *J. Hydraul. Res.* **29**(1), 136–142.

Shangle, A. K. (1991) Hydrographic survey of Indian reservoirs. In: *Reservoir Sedimentation* (workshop material), sponsored by IRTCES China and UNESCO, N. Delhi.

Singh, G., Ram Babu, Narain, P., Bhusan, L. S. & Abrol, I. P. (1990) Soil erosion rates of India. In: *Proc. Int. Symp. on Water Erosion, Sedimentation and Resource Conservation* (Dehradun), 32–38.

Sumer, M. S. (1977) Settlement of solid particles in open channel flow. *J. Hydraul. Div. ASCE* **103**(11), 1323–1337.

Walling, D. E. (1994) Erosion and sediment in a changing environment. In: *Proc. of the Int. Symp., East–West, North–South Encounter on the State-of-the art in River Engineering Methods and Design Philosophies, St. Petersburg, Russia.* (UNESCO, Paris, France).

White, W. R. (2001) Flushing of sediments from reservoirs. *Thematic Review IV, 5: Operation Monitoring and Decommissioning of Dams, S. Africa*, 12 pp.

Yang, C. T. (1972) Unit stream power and sediment transport. *J. Hydraul. Div. ASCE* **98**(10), 1805–1825.

Young, R. A. & Mutchler, C. K. (1969) Effect of slope on erosion and runoff. *Trans. ASAE* **12**, 231–233.