CONCEPTUALIZATION OF HYDRAULIC AND SEDIMENTARY PROCESSES IN DOWNSTREAM REACHES DURING FLUSHING OF RESERVOIRS

S. ANDERS BRANDT

Senior lecturer, Division of Geomatics, Department of Technology and Built Environment,
and Gävle GIS Institute, University of Gävle, SE-801 76 Gävle, Sweden
(Tel: +46-26-648500, Fax +46-26-648828, e-mail: sab@hig.se)

Abstract

The main focus of this paper is to describe the active hydraulic and sedimentary processes in downstream river reaches during flushing of sediments from reservoirs. During flushing extreme amounts of sediment may be released. Therefore, these processes are different than those downstream from dams and reservoirs not subjected to flushing. Hence, also the effects differ, which knowledge of may be of value for biologists, etc. During flushing of a reservoir a wave will be released to the downstream reaches. This wave can be divided into one water part and one sediment part. Initially they are in phase with each other, but with increased distance downstream from the dam, the transported sediment lags behind the water due to different traveling velocities. The paper treats when and where sedimentation occurs, and how this is related to the different traveling velocities of water and sediment. Also included are discussions on how the downstream effects during flushing differ from non-flushing effects, how visualization of effects can enhance both the analysis and communication with planners, politicians, etc., as well as discussions on how the studies of these effects can benefit from improved field-work methods.

Keywords: Downstream effects; Flushing; Desiltation; Reservoirs; Dams; Rivers; Sediment erosion; Transport; Deposition

1. INTRODUCTION

The interest for reservoir flushings has continuously grown during the last century. In the beginning, it was focused on the flushing efficiencies, i.e. how much sediment can be removed using as small amount of water as possible. When routing the flow through the sluice gates to the downstream reaches, this research showed how the physical characteristics of the reservoirs and sediment properties influenced the degree of success in releasing sediments. Detailed descriptions on the effects and processes in the reservoirs during flushing can be found in e.g. Morris & Fan (1997), Brandt (1999, 2000a), Batuca & Jordaan (2000), and White (2001). This need to preserve the reservoir volume capacity often leads to flushing flows having extreme sediment concentrations released to the downstream reaches. Therefore, although much later in time, an interest for studying these downstream impacts has emerged. Not only do water-quality parameters change drastically, affecting the biota in the rivers,

In: Byong-Ho Jun, Sang-Il Lee, Il Won Seo and Gye-Woon Choi, Editors.
XXXI International Association of Hydraulic Engineering and Research Congress,
Water Engineering for the Future: Choices and Challenges.
September 11-16, 2005, Seoul, Korea.

sedimentation rates increase rapidly leading to fine-grained deposition coats on coarser river bed material, and a shifting of sediment problems from one reservoir to another downstream reservoir may occur. Reviews on these downstream matters are few, but can be found in e.g. Brandt (1999, 2000a).

In this paper, I will try to conceptualize the hydraulic and sedimentary processes downstream from dams during flushing. Through an understanding of the hydrology and sedimentary processes, physical effects can be anticipated and also aid in understanding e.g. biological effects, i.e. hydraulic and sedimentary effects serve as reference frame for other processes and effects. In the next section, the geographical setting of the case study is presented. Different downstream responses to dams, responses during flushing, and the methods used to study them are presented in section 3. In section 4, the importance of visualizing these mattes are looked into and in the final section conclusions and future perspectives are given.

2. THE CACHÍ AND THE REVENTAZÓN – PHYSICAL SETTING AND FLUSHING OF THE RESERVOIR

To illustrate hydraulic and sedimentary processes during flushing, the Reventazón River downstream from the Cachí Dam and Reservoir in Costa Rica is used. The river basin is almost 3000 km^2 and drains the eastern slopes of Costa Rica to the Atlantic Ocean (Fig. 1).

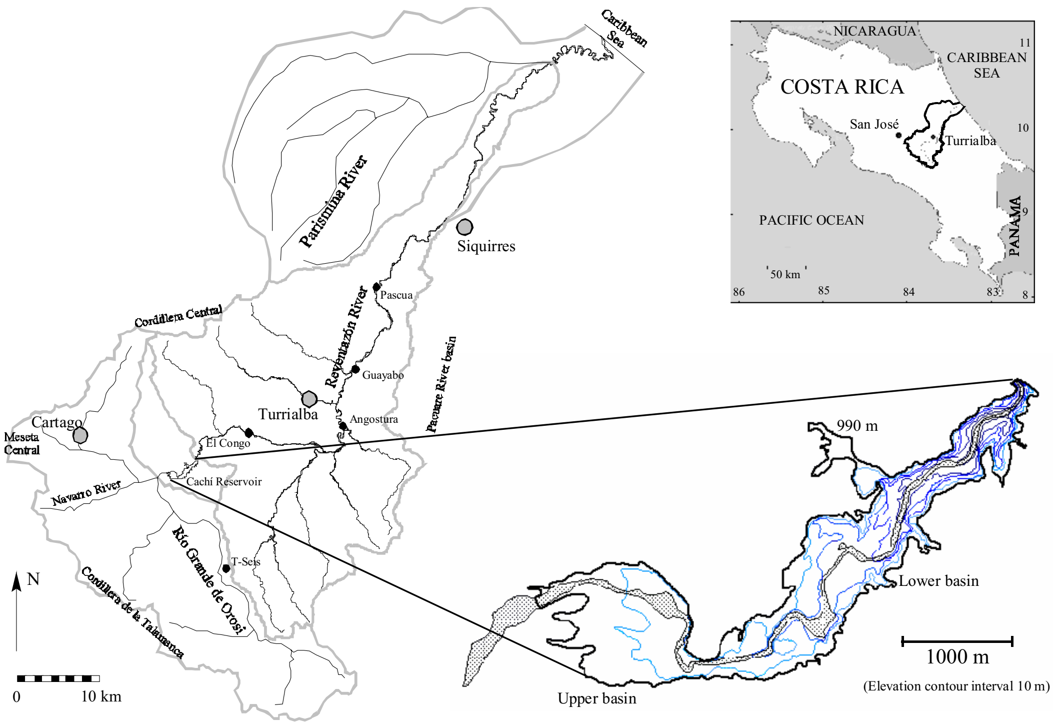

Fig. 1 The Reventazón River Basin (derived from Brandt, 1999) and the Cachí Reservoir (derived from Jansson & Rodríguez, 1992).

Rainfall in the area averages 3780 mm yr^{-1}, but varies greatly, from 1329 mm yr^{-1} in the Cartago area to 7556 mm yr^{-1} in the mountains southeast of the Cachí Reservoir (station T-seis) (Vahrson, 1992). Surrounding the drainage area to the north is the volcanic mountain range, Cordillera Central, with peaks up to 3432 m a.s.l. To the west there is a drainage divide on the high plateau, Meseta Central, at about 1400 m a.s.l. that drains to the Pacific Ocean, to the south there is the high mountain range, Cordillera de la Talamanca, with peaks up to 3491 m a.s.l. consisting of sedimentary rocks, and to the east there is the Pacuare River basin (see Fig. 1). Upstream from the Cachí Reservoir there are two sub-drainage basins, Navarro and Río Grande de Orosi. The southern basin, Río Grande de Orosi, mainly drains virgin rain forest areas, while the northern basin, Navarro, drains the densely populated and cultivated area around the city of Cartago. Due to insufficient soil erosion countermeasures together with high rainfall rates, the Navarro basin suffers from severe soil erosion. Hence, most of the sediment delivered to the Cachí Reservoir originates from that area.

The Cachí Dam impounds the Reventazón River at 921.5 m a.s.l. and has an upper storage level at 990 m (Ramírez & Rodríguez, 1992). The Cachí reservoir consists of one narrow lower basin and one wider upper basin (see Fig. 1). Much of the coarser material that enters the reservoir, deposits in the upper basin or is transported with density currents in the old river thalweg to the lower basin. The fine-grained material is, however, spread out more evenly in the reservoir. Although most of it is deposited in the old river thalweg, some is deposited on the terraces above the sides of the thalweg. Hence, flushing operations are not totally successful in removing all of the incoming sediments. Much will remain on the terraces and some will remain in the upper basin.

The flushing process starts with 25 days of lowering the reservoir water table, from 990 m with one meter per day until the level of 965 m is reached. The next emptying phase consists of rapid release of the remaining water during 5 hours, and the last phase consists of two to three days of free-flowing river water (Ramírez & Rodríguez, 1992). The total amount of flushed-out sediments usually varies between 500000 tons to 1000000 tons, where most of it is released during the end of the final lowering of the reservoir water level and during the beginning of the free-flowing water phase (Jansson, 1992). Detailed descriptions on the erosional and geomorphological effects in the Cachí Reservoir can be found in Jansson & Rodríguez (1992), Brandt (1999), Brandt & Swenning (1999) and Jansson & Erlingsson (2000).

3. ACTIVE PROCESSES IN DOWNSTREAM REACHES

The main focus of this paper is to look into the hydraulic and sedimentary processes in the downstream reaches during flushing. However, before dwelling into flushing issues, it is important to know the "normal" effects in reservoirs downstream from dams as well as implications of the methods used to study the processes and effects.

3.1 NORMAL DOWNSTREAM EFFECTS OF DAMS

Downstream effects of dams during flushing should not be confused with "normal" effects downstream from dams. In fact, there are no normal conditions downstream of dams. The effects depend on the purpose of the reservoir, released water flow and sediment characteristics as well as the physical characteristics of the river (see Brandt, 2000b). A typology, or classification, consisting of nine different cases of the geomorphological effects after river impoundment can be found in Brandt (2000b). The classification is based on how water discharge has changed after impoundment and on how the relationship between sediment load input to the downstream reach and the sediment transport capacity of the flow has changed. Prior to dam construction, the sediment load and the transport capacity are thought to be of equal magnitudes, as is the case in alluvial rivers at equilibrium conditions. The water discharge is considered to be the channel forming discharge, i.e. the dominant discharge, which often is equated with bankfull flow. The load can be measured at any sediment sampling station and the transport capacity can be calculated using any sediment transport equation that has been proven to work well in the pre-dam river system.

Of the nine cases described in Brandt (1999), Case 1, with decreased water discharge and a relative change where the transported sediment load is less than the flow's transport capacity, and Case 4, where the water discharge is unchanged while the load has become less than the transport capacity, are the most common (see Fig. 2). This is because the water in the reservoir either is used for e.g. agricultural purposes (i.e. water loss for Case 1) or is released at certain times to generate electricity (i.e. no water loss for Case 4). Very seldom does the water flow released to the downstream reaches increase in magnitude (although this is possible due to river diversions from other watersheds). In both cases, a reduction in sediment load is expected due to sedimentation in the reservoir. Hence, the transport capacity is greater than the load, leading to erosion of the downstream river bed and banks. Only if the water discharge has been so much reduced that incipient motion of river bed and bank material cannot occur (for Case 1), there will be no erosion, and only reduced cross-sectional areas of flow will occur. Schematic changes can be seen in Fig 2. If erosion will be downward or sideward depends on e.g. substrate material and the river slope. Further discussions on cross-sectional effects as well as longitudinal effects can be found in Brandt (2000b).

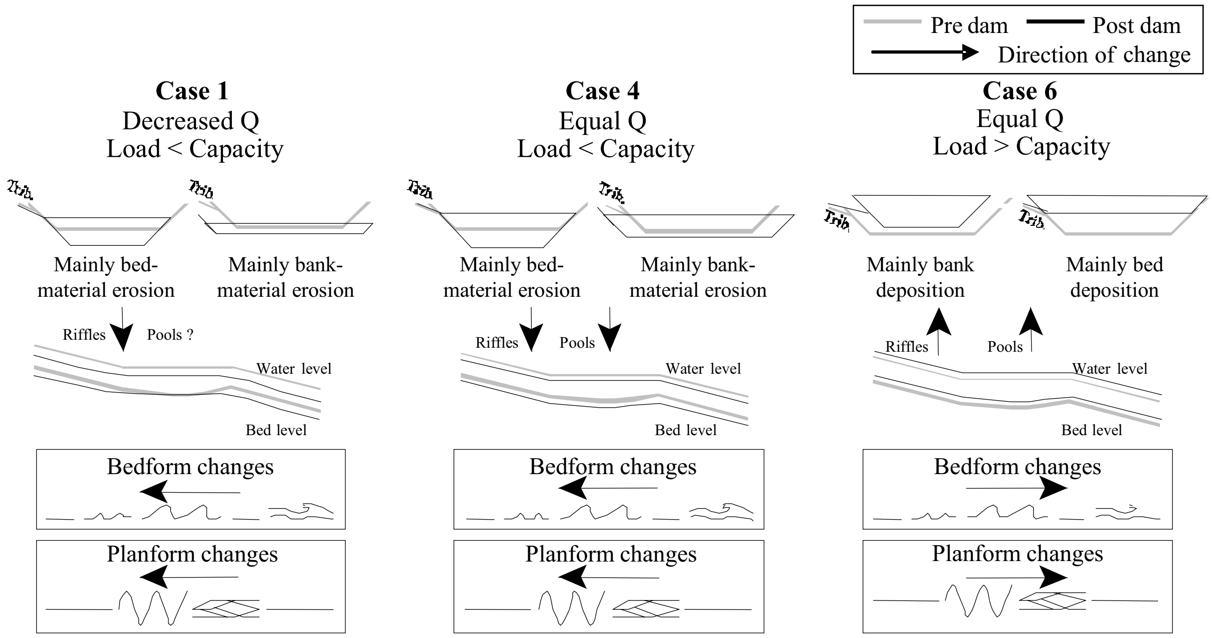

Fig. 2 Different types of commonly occurring geomorphological responses downstream of dams (Cases 1 and 4) and response downstream from reservoirs during flushing (Case 6), depending on change in water discharge, Q, and change in the relationship between sediment-load input and the flow's sediment-transport capacity (cases according to Brandt, 2000b).

3.2 METHODS USED TO STUDY FLUSHING PROCESSES AND EFFECTS

The methods used to study the flushing effects in the Reventazón River will not be presented here, but can be found in Brandt (1999) or Brandt and Swenning (1999). Instead, some problems and uncertainties experienced during the field work and analysis are treated.

Predicting the sedimentological effects during flushing is difficult due to the altered hydraulic and sedimentary conditions that exist, where the release of extreme sediment concentrations to the downstream reaches is the most apparent. As soon as sedimentation starts, the water discharge estimates may be erroneous due to the altered friction coefficients, i.e. Manning's n, that occur. A fine-grained coat on the coarse-grained material deposited during flushing drastically changes the friction factor. To get correct water discharges from stage measurements the change in n must be changed as soon as sedimentation occurs. Either special stage-discharge calibrating campaigns should be made during flushings or, as suggested by Simons et al. (1979), the product of water discharge, calculated from the original stage-discharge rating curve, and the ratio of Manning's n of original gravel bed to deposited sand bed should be used. The friction change is usually greatest in the upstream reaches, where pre-flushing processes have eroded the fine-grained material in the river bed by selective erosion, and possibly created an armour layer (see Cases 1 and 4 in Fig 2). Farther downstream the downstream effects usually diminish, wherefore only slight changes of the friction factor are expected.

Measuring water discharge may, however, be the easy part. Far more difficult is the measurement of sediment transport. During the water discharge peak, the flow may be so high that the sediment sampler may not move through the water column as it should. Also, the high sediment content increases the viscosity of the flow. Hence, heavier equipment than usual should be used. Other problems may occur if the nozzle of the sediment sampler becomes clogged, and of course, if the bottles become overfilled. Jansson (1992) tried to use turbidimeters, but concluded that it is associated with many practical problems. They may, however, be useful for indicating when sediment concentration peaks occur. Studies on how much of the total sediment transport that is transported as bottom load are scarce. Some estimates have been made by AB Hydroconsult (1995), but no real sampling was made. What is clear, is that most of the material is transported as suspended load during the last phase of the lowering of the reservoir water level and during the beginning of the free flow in the reservoir. The percentage bedload will then depend on the water discharge and wherefrom in the reservoir the material has been eroded.

Measuring sedimentation depths along the river banks has also been difficult. The use of total stations can produce relatively good results, especially in flat areas with large sedimentation depths, but in areas with many blocks and big stones, where sedimentation occurs in between them, the results are uncertain. This effect will be further enhanced farther downstream where sedimentation depths are small. Another problem area is surveying of sedimentation depths on the river bed, since it is occupied by the water. In large rivers, echo-sounding equipment can be used, but in smaller rivers manual surveying techniques probably are better. Another option is to use signals with water surface penetrating capabilities. Finally, since the deposits from the flushing are more fine grained than the normal bed material, they are more prone to be eroded than the normal material. Therefore, as soon as new water releases from the reservoir take place or if heavy rains lead to increased flow in the river, the deposited sediment will be eroded and shifted downstream.

3.3 DOWNSTREAM EFFECTS OF DAMS DURING FLUSHING

Flushing operations will in most cases result in opposite effects compared with those most commonly occurring downstream from dams, since heavy sedimentation is expected to occur (see Case 6 in Fig. 2). Fig. 3 shows typical water discharge, sediment concentration, and sediment load curves for three gauging stations downstream from the Cachí Dam. At first glance, these curves may not look very different from other water discharge and sediment transport curves, but in fact they do. The only normal looking behaviors in Fig. 3 are the small sediment peaks at 21:00 and 15:00, more than 24 hours after the flushing was begun. These peaks are attributed to rainfall and subsequent sediment transport in the river. As will be described next, sediment peaks from the flushing do not show this appearance.

The first, or main, difference is the extreme sediment concentration. During a short time in 1993, the gauging station 10 km downstream from the dam experienced almost 50% sediment in the flow. This alone explains why there may be severe environmental impacts.

The second difference, that must be emphasized, is the different times when the water flow peak and the sediment concentration peak occur at a downstream station. In rivers flowing on alluvium, changes in sediment concentration follow changes in water discharge, i.e. an increase or decrease in sediment carrying capacity of the water will instantly change the amount of sediment transported. During flushing, however, the water is loaded with an extra amount of sediment that the flow cannot sustain or transport for any longer distances (see Figs 2 and 3). These sediments can be considered as a point source input to the downstream reaches, compared with the non point source input from the river bed. Furthermore, due to the sediments released from the reservoir not traveling with the same velocity as the water, there is an increasing lagging behind of the sediment concentration peak compared with the water discharge peak (Fig. 3). If scrutinizing the curves carefully, it is possible to see that both normal alluvial-condition processes and the special flushing conditions take place during the passage of the flushing wave. During the rising limb of the water discharge peak, a small concentration peak is visible, where the sediments come from the river alluvium, while during the peak, an extreme second sediment concentration peak is visible which mainly consists of material flushed from the reservoir.

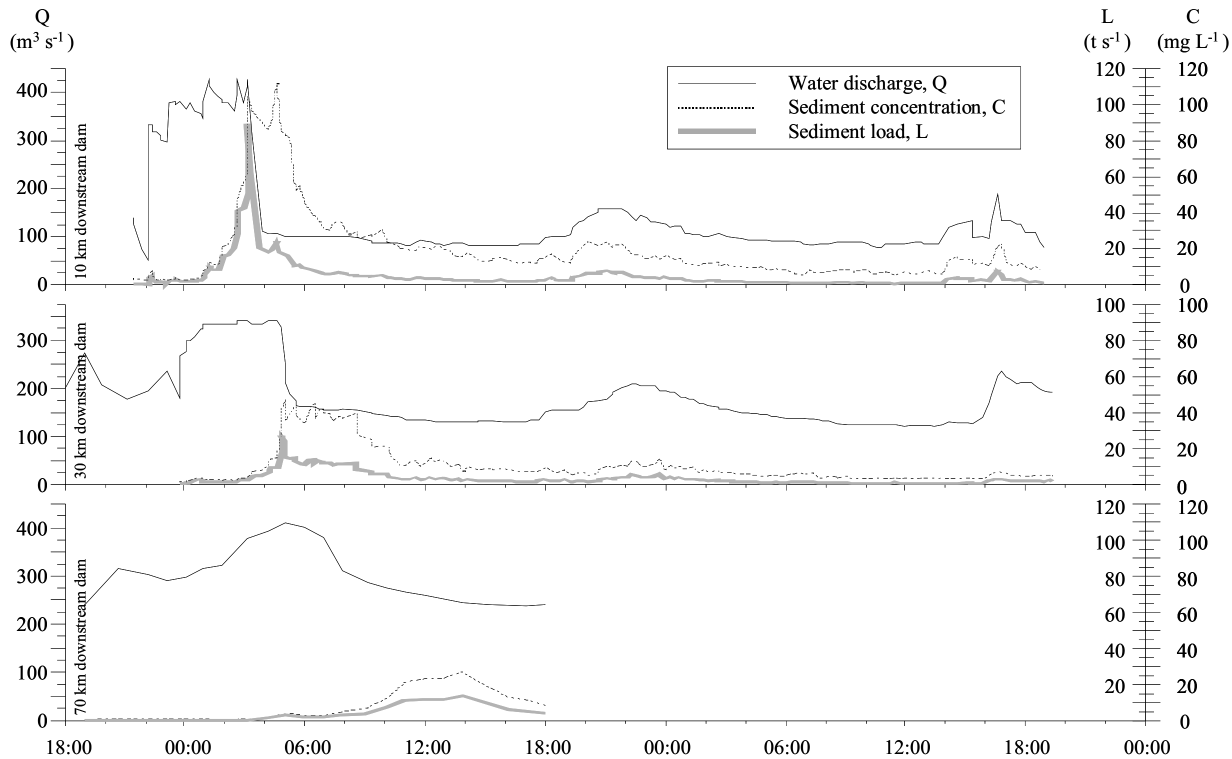

Fig. 3 Water discharge, sediment concentration and load for three gauging stations, 10, 30, and 70 km downstream from the Cachí Dam during the flushing in 1996 (From Brandt, 1999).

The time lag between the water discharge peak and the sediment concentration peak will affect the sedimentation rate. Without a time lag, sediments would deposit with a slightly decreasing rate the farther downstream the flushing wave passes, i.e. the “overloading” of the flow due to the point source input will gradually decrease. Since the overloading is greatest close to the dam, it is also where the sedimentation rate would be greatest. During flushing, however, at some distance the sediment concentration peak is lagging behind so much that the water peak has already passed, leaving only a fraction of the sediment transport capacity of the peak discharge to transport the sediments. Therefore, during the rapid recession of the water discharge peak, large amounts of sediment will be deposited on the river bed. This can be seen in Fig. 3 for the gauging station 10 km downstream from the dam, where even though the sediment concentration is high during the recession part of the water discharge peak, the sediment load transported decreases drastically.

Since the water discharge peak may arrive earlier than the sediment concentration peak, actually there may be some erosion of the river bed, something that is not directly associated with reservoir flushings. Results from the 1996 flushing of the Cachí Reservoir indicate that some erosion took place, with increasing amounts farther downstream, before sedimentation processes dominated (see Fig. 4). This is in accordance with the increasing time lag between water and sediments.

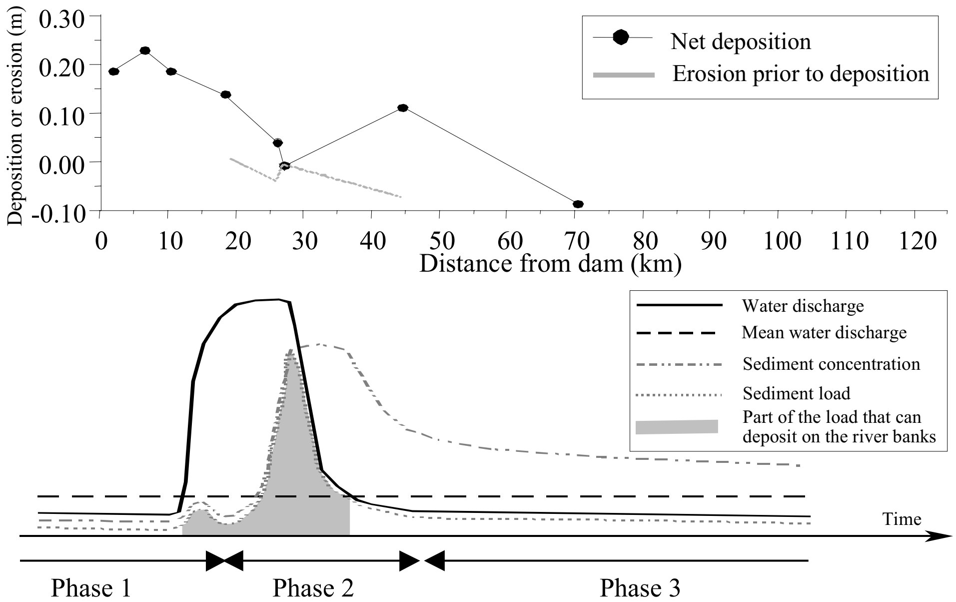

Fig. 4 Erosion and deposition in the Reventazón River during flushing in 1996 (above), and schematic illustrations on water discharge, changes in sediment transport with time, and flushing phases in the downstream reaches (below).

The time lag between water and sediments also has an impact on where the deposition of sediments will occur. During the water discharge peak, usually water levels in the river are higher than normal flow levels, although they may be lower than bankfull flows. During this peak, sediment can deposit on both the river bed as well as on the banks (Fig. 4). Probably relatively coarser material will deposit on the bed and relatively finer material on the banks. After the water discharge peak has passed, sedimentation can only occur on the river bed. Therefore, decreasing amounts of bank deposition can be expected when going in the downstream direction. After the time period of much sedimentation, the sediments will be transported without erosion or deposition. No erosion due to insufficient water discharges, and no deposition due to that all coarser-grained material that could have been deposited already has deposited in the upstream reaches while the finer-grained material behaves as wash load. See Fig. 4 for schematic illustrations. It should be noted that the deposition increase at 45 km in Fig 4, depends on local slope changes and, therefore, does not show the general decrease in sedimentation depth. Brandt & Swenning (1999) defined three phases in the downstream reaches: Phase 1 is the time period before the flushing-induced sediment concentration peak, when the sediment concentration depends on water discharge and is limited by sediment supply. Phase 2 includes the flushing-induced sediment concentration peak, when the sediment concentration does not depend on water discharge, but rather on the point source input of sediments from the reservoir flushing. Finally, Phase 3 is the time period when sediment concentration, again, depends on water discharge, ending when the sediment supply pertaining to the reservoir flushing is depleted (Fig 4).

Another difference between normal flows and flushing flows is the different appearances of hysteresis loops. Positive, or clockwise, hysteresis occurs when water discharge increases and sediment is eroded from the river bed. During flushing, however, the sediments do not come from the river bed, but originate from the reservoir and arrives later than the water discharge peak, leading to negative, or anti-clockwise, hysteresis (Brandt, 1999).

Downstream effects may occur all the way to the river outlet in the sea if no other dams and reservoirs hinder the flow. At the Reventazón River outlet, the sediment concentration of the flow in 1996 was estimated to 0.02 g cm^{-3} in the sediment concentration peak. This yields a density of 1.009 g cm^{-3} at 25ºC. The seawater has a density of 1.023 g cm^{-3} which means that the river flow will spread out on the seawater surface and sediment particles will start settling as soon as the water velocity approaches zero. If, however, the sediment concentration had been 0.05 g cm^{-3}, as it was some 50 km upstream from the coast, the density would have been 1.028 g cm^{-3}, leading to a plunging current beneath the sea surface (Brandt, 1999). These matters may have great influence on for example coral reefs along the coasts.

For detailed discussions on how sedimentation rates and grain-size variations in transported and deposited material varies during the different phases of flushings, as well as how changes in river slope affect the sedimentary processes, see Brandt (1999), and for predictions and discussions on the quantitative amounts of channel changes, see Brandt (2000c).

4. VISUALIZATION OF EFFECTS

Since the studies on downstream effects only have begun relatively recently, it is important to make existing knowledge and new findings interesting and easy-to-understand for others (Brandt & Jiang, 2004). They can be politicians or physical planners that want to make plans for riverine environments, civil engineers that are constructing new dams and reservoirs, but have insufficient knowledge of the sedimentary processes, or biologists that are studying or trying to preserve the fauna and flora in the downstream rivers. The hydrologic and hydraulic software usually come handy if they have visualization capabilities, but the use of

Geographical Information Systems (GIS) is probably even better to visualize the effects of flushings. To illustrate that both erosion and deposition take place during flushing, digital elevation modeling was used for an area relatively close to the Cachí Reservoir. To illustrate the 1996 flushing, photos before and after the flushing are shown in Fig. 5.

Fig. 5 The Reventazón River at 2 km downstream from the dam. Left photo is an upstream view taken before the flushing and right photo is a downstream view after the flushing.

Fig. 6 shows a 3D elevation model of the pre-flushing surface over the area shown in Fig. 5, as well as a 2D-dimensional map with resulting deposition depths due to the flushing on top of the 3D map. Just by looking at the combination of the 3D and 2D map, a hydrologist can interpret processes, such as that even erosion takes place on high-lying ground exposed to the flow and that the heaviest deposition take place in the low-lying areas not directly exposed to the flow. Without this 3D/2D combination, interpreting the processes would be much more difficult. Therefore, both to enhance the analyses and to explain this to a non specialist will be much easier if using the proper tools, e.g. 3D terrain models (Brandt & Jiang, 2004).

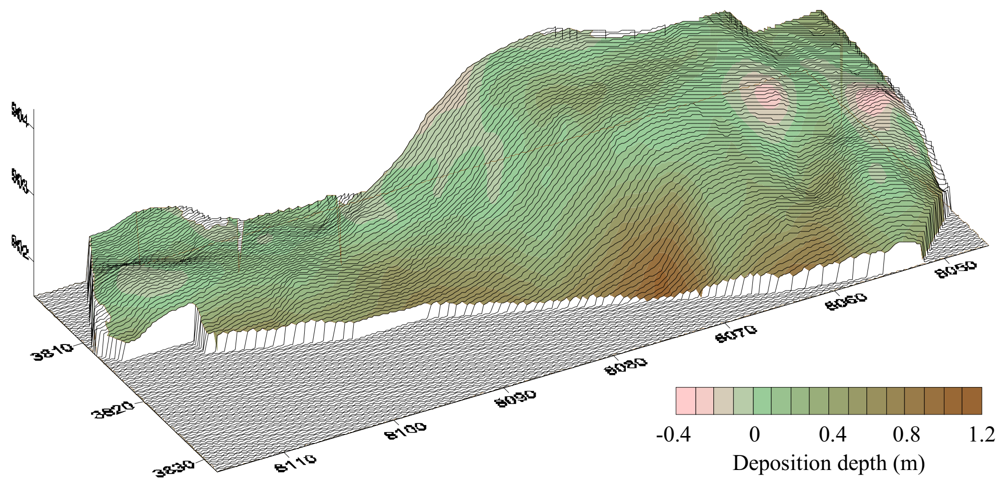

Fig. 6 The Reventazón River at 2 km downstream from the dam. The 3D map shows elevations before flushing and the 2D map overlain on the 3D map shows deposition depths. Water is flowing from right to left (From Brandt & Jiang, 2004).

5. CONCLUSIONS AND FUTURE PERSPECTIVES

This paper has shown the difference of hydraulic and sedimentary processes and resulting geomorphology between rivers during flushing of upstream reservoirs, and rivers downstream from reservoirs not subjected to flushings. During flushing of a reservoir, a wave will be released to the downstream reaches. This wave can be divided into one water part and one sediment part. Initially they are in phase with each other, but with increased distance downstream from the dam, the transported sediment lags behind the water due to different traveling velocities. When and where sedimentation occurs can be predicted if knowledge of magnitudes of released water and sediment and velocities are known. The problem today is that only a few case studies have been made, meaning that results from these cannot be considered generally applicable. For example may one way to get better deposition results be to use terrester laser scanners, something that have come into use during the last years. Then millions of points are generated over small areas giving superb possibilities of terrain modeling. The only problem then is to reduce the number of points by filtering algorithms, so the points can be practically handled. Especially where sedimentation depths are small, this technique will improve the results. Airborne laser scanners are getting popular for building terrain models for flooding studies, but they have too poor vertical resolution to be of use other than close to dam sites where sedimentation depths are very deep.

Finally, sediment transport equations especially developed for flow overloaded with sediments must be developed or adjusted to these conditions. The equations in use today are based on the assumption that water discharge, or velocity, etc. determines the sediment concentration.

REFERENCES

AB Hydroconsult, 1995. Sedimentation and Erosion Processes Related to the Hydropower Projects Angostura, Guayabo and Siquirres. Part 1, Aim 1: Prediction of Reservoir Sedimentation. Uppsala, 135 p.

Batuca, D.G., Jordaan, J.M., 2000. Silting and Desilting of Reservoirs. A.A. Balkema, Rotterdam, xiii+353 p.

Brandt, S.A., 1999. Reservoir Desiltation by Means of Hydraulic Flushing: Sedimentological and Geomorphological Effects in Reservoirs and Downstream Reaches As Illustrated by the Cachí Reservoir and the Reventazón River, Costa Rica. Geographica Hafniensia A8, Copenhagen, 231 p.

Brandt, S.A., 2000a. A review of reservoir desiltation. Int. J. Sediment Research, vol. 15(3), pp. 321-342.

Brandt, S.A., 2000b. Classification of geomorphological effects downstream of dams. Catena, vol. 40(4), pp. 375-401.

Brandt, S.A., 2000c: Prediction of downstream geomorphological changes after dam construction: a stream power approach. Int. J. Water Resources Development, vol. 16(3), pp. 343-367.

Brandt, S.A., Jiang, B., 2004. 3D geovisualization as a communication and analysis tool in fluvial geomorphology. In: Brandt, S.A. (Ed.), 2004. Geoinformatics 2004: Proceedings of the 12th International Conference on Geoinformatics - Geospatial Information Research: Bridging the Pacific and Atlantic. University of Gävle, Sweden, 7-9 June 2004. Gävle University Press, Gävle. Volume 1, pp. 339-346.

Brandt, S.A., Swenning, J., 1999: Sedimentological and geomorphological effects of reservoir flushing: the Cachí Reservoir, Costa Rica, 1996. Geografiska Annaler, vol. 81A(3), pp. 391-407.

Jansson, M.B., 1992. Suspended sediment outflow from the Cachí Reservoir during the flushing in 1990. In: Jansson, M.B., Rodríguez, A. (Eds). Sedimentological Studies in the Cachí Reservoir, Costa Rica: Sediment Inflow, Reservoir Sedimentation, and Effects of Flushing. UNGI Rapport 81, Uppsala University, Department of Physical Geography, pp. 127-136.

Jansson, M.B., Erlingsson, U., 2000. Measurement and quantification of a sedimentation budget for a reservoir with regular flushing. Regulated Rivers: Research and Management, vol. 16, pp. 279-306.

Jansson, M.B., Rodríguez, A. (Eds), 1992. Sedimentological Studies in the Cachí Reservoir, Costa Rica: Sediment Inflow, Reservoir Sedimentation, and Effects of Flushing. UNGI Report 81, Uppsala University, Department of Physical Geography, 217 p.

Morris, G.L., Fan, J., 1997. Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use. McGraw-Hill, New York, xxiv+805 p.

Ramírez, C., Rodríguez, A., 1992. History of the Cachí Reservoir. In: Jansson, M.B., Rodríguez, A. (Eds). Sedimentological Studies in the Cachí Reservoir, Costa Rica: Sediment Inflow, Reservoir Sedimentation, and Effects of Flushing. UNGI Report 81, Uppsala University, Department of Physical Geography, pp. 27-30.

Simons, D.B., Al-Shaikh-Ali, K.S., Li, R.-M., 1979. Flow resistance in cobble and boulder riverbeds. J. Hydraulics Division, vol. 105(HY5), pp. 477-488.

Vahrson, W-G., 1992, Tropische Starkregen und ihre Verteilung - das Beispiel des Einzugsgebietes des Río Reventazón, Costa Rica. Die Erde, vol. 123, pp. 1-15.

White, R., 2001. Evacuation of Sediments from Reservoirs. Thomas Telford, London, 280 p.