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3D GEOVISUALIZATION AS A COMMUNICATION AND ANALYSIS TOOL IN FLUVIAL GEOMORPHOLOGY

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Abstract

The fields of hydrology and fluvial geomorphology get more and more attention in the general public. The reason for this is changed climate patterns with increased frequencies of storms and river flooding and as a result changed geomorphology and living conditions for the inhabitants of the area. With the development of 3D geovisualization, hydrological and geomorphological processes can be better simulated and visualized. Thus not only the domain specialists, but also the general public can appreciate very complex hydrological processes and resulting geomorphology. This is of great value since a high frequency of storms and flooding has been a big issue for politicians, planners, and the general public. It is in this sense that 3D geovisualization can be an important tool for analysis and communication. Complex hydrological and geomorphological processes can be effectively simulated and analyzed by the domain specialists while efficient and effective visualization provides a common platform for communication among domain specialists and the general public. This paper will discuss and illustrate these issues using a case study of geomorphology along the Reventazón River, downstream from the Cachí Reservoir in Costa Rica, due to the release of extreme amounts of sediment during flushing of the reservoir.

INTRODUCTION

Over the last few years, extreme hydrological events have received increasing amounts of attention, and with regular intervals news broadcasters report of floods from all over the world. One explanation for this is that media now have access to, or can obtain reports from, most areas in the world. Other explanations can be that global warming now is present and we now see the first results of that, i.e. increased frequency of flood events as well as increased magnitudes of the events, or that the increased usage of riverine environments for housing automatically leads to problems.

Since most people now are more or less aware of the extreme hydrological events, a big pressure is placed on for example physical planners and politicians to take precautions and actions against these events. Examples of this include risk consideration when planning new city areas close to rivers, construction of river margin dykes and utilization of areas for temporary storage of excess water. In this respect, geographic information system (GIS) has a particular application in the sense that it can help to capture all kinds of environment data, to build up models and to provide intuitive presentations for various users concerned with these extreme events. This kind of GIS can be characterized as environmental GIS (Brimicombe, 2003). Despite various efforts made in using GIS to predict, prevent and risk assessment, current GIS still lacks in efficiency in terms of its visualization capacity. This is due to the fact that existing GIS is based on map metaphor, which is essentially 2D based. We believe that with 3D geovisualization such risks or hydrological consequences can be described and communicated in a more efficient and effective way and thus to contribute to better decision making and planning.

This paper will address various visualization issues in the context of fluvial geomorphology. We will show how an environmental GIS will be improved through introduction of more powerful visualization capabilities. This paper serves as a working paper for our ongoing project, which targets to develop an environmental GIS at the University of Gävle. As an example of how 3D geovisualization can contribute to communication, between hydrologists, planners and citizens, and to the analysis of river processes, an area in Costa Rica is described with respect to prevailing hydrological conditions and what can be made with it within the framework of a 3D GIS.

STUDY AREA

The area of interest is situated downstream from the Cachí Reservoir along the Reventazón River which drains part of the eastern slopes of Costa Rica to the Caribbean Sea. The Reventazón River has a mean water discharge of about 100 m^3s^{-1} and drains an area of almost 3000 km^2.

The upstream areas from the Cachí Reservoir suffers from severe soil erosion. Most of the eroded sediments finally end up in the reservoir. To avoid the reservoir being filled up with sediments, every year or two, the bottom gates are opened and the river can flow freely through the reservoir and dam gates, and pick up previously deposited sediments and flush them to the downstream river. During the reservoir flushing of 1996 about one million tons of sediment were flushed out, most of it during a time period of five hours (Brandt and Swenning, 1999). This leads to extremely high sediment concentrations where values over 20% are common.

About half of the year’s sediment transport in the river can be attributed to this single event. Consequently, the downstream river reaches are affected by heavy sedimentation and geomorphological changes during the flushing period.

METHODS

To visualize the geomorphological changes next to the river during flushing, a digital elevation model was constructed. Areas were surveyed with a total station both before and after the flushing. Grids with interpolated values were then produced and volumes of the deposited sediments were calculated by subtracting post-flushing sediment surfaces from pre-flushing sediment surfaces.

To be able to relate the sediment depositions to sediment transport processes, also hydrological and suspended sediment transport data were needed. This data was provided by the Instituto Costarricense de Electricidad, which has several hydrological stations along the river. Also sediment samples, for e.g. grain size analysis, were taken at the surveyed sites.

More and complete information about the methods used during the flushing have been described by Brandt (1999) and Brandt and Swenning (1999).

HYDROLOGICAL PROCESSES

The hydrological processes, and hence consequences, during reservoir flushing differ from processes during normal conditions. Therefore, good ways to present the geomorphological effects are essential, both to analyze and understand the processes as well as to present them to physical planners and the general public.

The flushing wave released from the reservoir actually consists of two parts: water and sediment. The water part determines how much of the surrounding areas that will be flooded and how much sediment that can be eroded and transported. The sediment part is, on the other hand, dependent on the water for its future fate.

When looking at a cross section of the river flow from a sedimentological perspective, the section can be divided into two parts: the river bed and the river banks. A commonly used indicator on how large particles that can be transported by the water is the bed shear stress, τ [N m^{-2}], usually expressed as $\tau=\rho gDS$ where ρ is flow density [kg m^{-3}], g is gravity acceleration [m s^{-2}], D is depth of flow [m] and S is slope [m m^{-1}]. The bed shear stress describes the force exerted over an area of the channel bed, which is compared to the critical shear stress, τ_c, needed for incipient movement for different sizes of particles. Julien (1995) presented the equation $\tau_c=0.785d_{50}$ where d_{50} [mm] is the median grain size of bed material (valid for particles larger than 0.3 mm). From these two equations, it can be seen that larger particles need higher shear stresses to start moving, and that deeper waters are able to transport larger particles in the downstream direction than are shallow waters. Note, however, that cross-sectional movement in shallow waters may start due to the side slope being relatively great.

Similarly, the rates of deposition can be explained as the reverse. Where water flow is deep, only coarser material can be deposited due to high shear stress, and where water flow is shallow, also fine-grained material can deposit on the bed. Figure 1 shows schematically the relationships between water and sediment in a channel cross section.

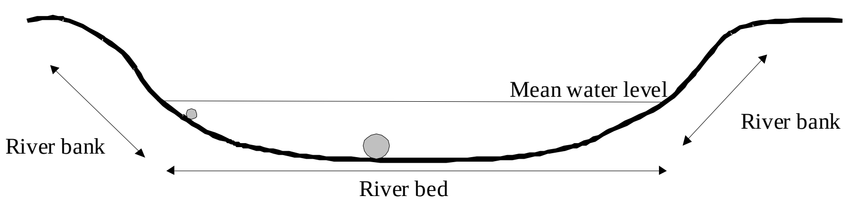

Figure 1: Schematic illustration of distribution of grain sizes at different locations in a channel cross section.

During flushing, the amounts of sediment released are so extreme such that the flow cannot transport it at all, i.e. the water flow’s sediment-transport capacity is not sufficient compared to the sediment load produced during erosion in the reservoir. The load exceeding the transport capacity will deposit at different locations in the cross section, depending on the grain sizes of the transported material. A schematic figure of where the depositions take place, as well as the terminological difference between bed and banks that is used in this article, can be seen in Figure 2.

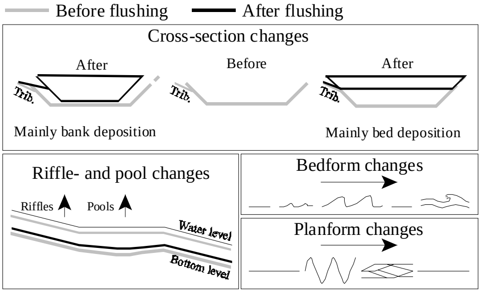

Figure 2: Schematic illustration of plausible geomorphological effects in the downstream river during reservoir flushing. Bedforms change from flat bed over ripples, dunes and plane bed to antidunes. Planforms change from straight over meandering and braided to straight (Brandt, 2000).

The same relationships between water and sediments are valid for the hydrological processes in the longitudinal direction. Due to the extreme concentrations close to the reservoir, much of the sediment load will fall out and deposit. The flow, therefore, slowly approaches an equilibrium condition where the sediment-transport capacity equals the transported sediment load the farther downstream the flow travels. Figure 3 shows how deposited depths decrease in the downstream direction. The general decrease in depth is only offset at 45 km, which can be attributed to a change in channel slope at 30 km.

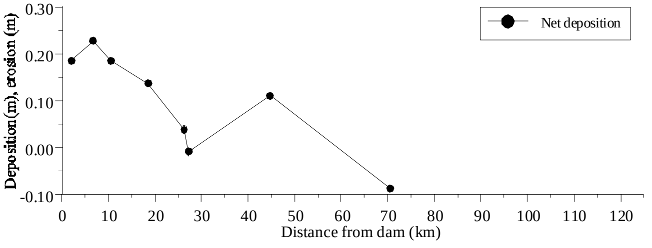

Figure 3: Deposition depths at investigated sites downstream from the Cachí Reservoir (Brandt, 1999).

Local conditions also influence deposition of sediments. Irregularities of the bed, e.g. dunes and boulders, make the flow converge and diverge, thereby changing the flow's velocity. On top of dunes, the flow velocity will increase, due to compressed flow, and erosion may occur if the critical values for sediment entrainment are exceeded. At least this leads to fine-grained material not being able to deposit on the dune crests. Behind the dunes, deposition will occur, due to reduced water velocity and possibly backward flow (Figure 4).

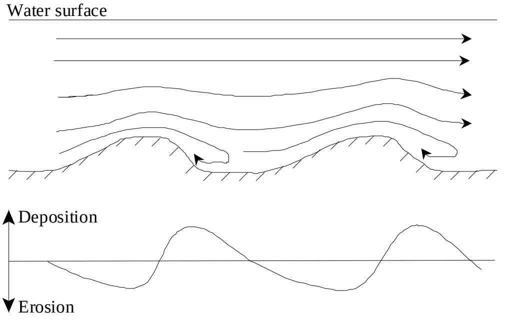

Figure 4: Water flow pattern and related deposition and erosion in a longitudinal section of the river.

Another characteristic of flushing is that water and sediment move at different velocities. Since the sediment wave moves at a slower pace, soon it will lag behind the water peak, and hence be carried by rapidly decreasing sediment-transport capacities. Figure 5 shows how water discharge, sediment concentration and transported suspended load varies with time at a station 10 km downstream from the reservoir. Note the abrupt decrease in transported load, even though the sediment concentration is still high, when the water discharge peak has passed the station. Also note that this is not the case in the two smaller water discharge peaks, which can be attributed to local rainfall.

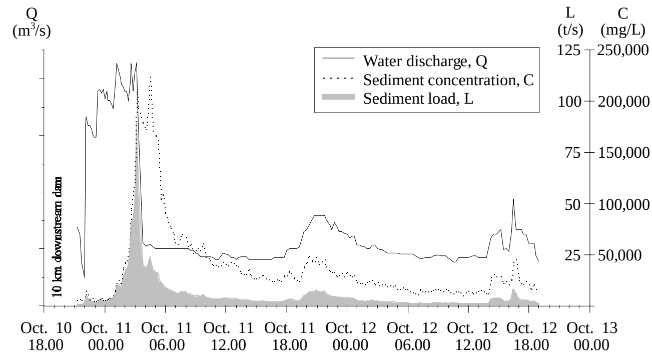

Figure 5: Water discharge, suspended sediment concentration and suspended sediment load during flushing 1996 at a hydrological station 10 km downstream from the Cachí Reservoir (Brandt and Swenning, 1999).

The phase lag between water and sediment also leads to that deposition on the river banks (see Figure 1) will decrease with downstream distance, since the raised water levels have already passed with the peak in water discharge. The time period when river bank deposition is possible is shown in Figure 6 when water discharge is greater than the mean water discharge. On the other hand, deposition on the river bed is still possible.

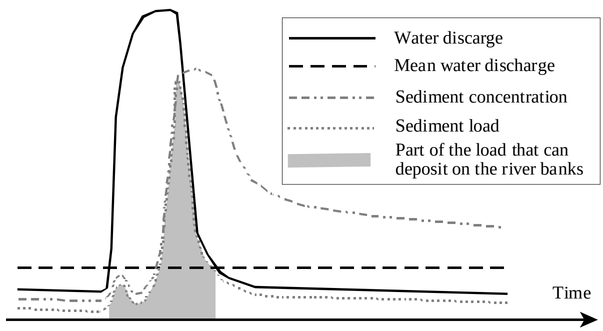

Figure 6: Time period when deposition on the river banks can occur during flushing (Brandt, 1999).

3D VISUALIZATION

If the resulting geomorphology is shown in 3D, the underlying processes and effects get much easier to comprehend. To illustrate the usefulness of 3D geovisualization an area at the river about one kilometer downstream from the dam will serve as an example. Photos of the area before and after the flushing can be seen in Figures 7. These clearly show that there has been substantial deposition during the reservoir flushing.

Figure 7: The site 1 km downstream from the dam. (a) Upstream view before the flushing. (b) Downstream view after the flushing.

Figures 8 and 9 show two different ways of illustrating the area before the flushing as 3D and the deposition depths as 2D. The combination of 3D and 2D makes it easy to recognize where in the terrain erosion and deposition take place. If two 3D maps had been used, the differences between them would be very difficult to see. Another advantage is that the interpretation of the hydrological processes gets much easier. The deposited depths can be directly linked to the variation of the terrain before the flushing. Raised bed levels mean converging flow and less deposition or even erosion. Lowered bed levels mean diverging flow and better opportunities for deposition (see Figure 4).

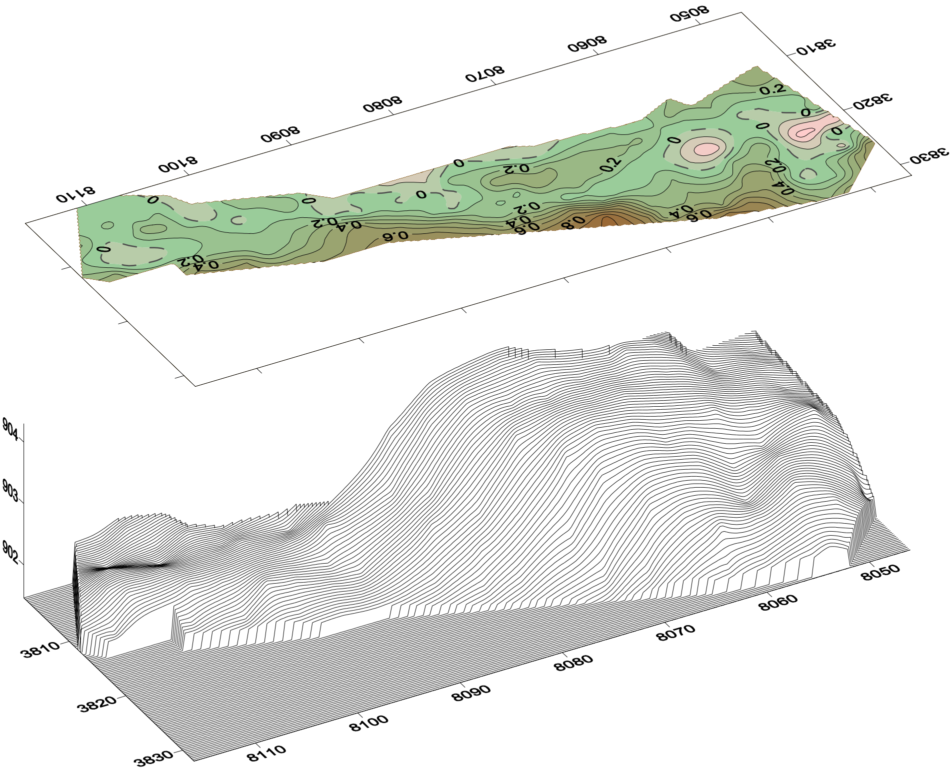

Figure 8: The site 1 km downstream from the dam. Erosion and depositional depths [m] are shown as separate 2D map.

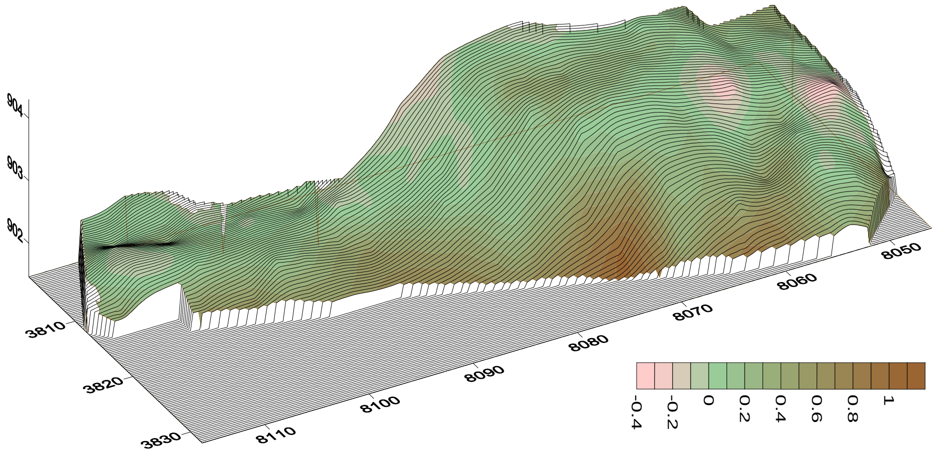

Figure 9: The site 1 km downstream from the dam. Erosion and depositional depths [m] are shown as an overlay on the 3D map.

The relation between hydrology and sedimentation is clearly seen in Figure 9. The water flow enters from the right. First the flow is forced upward and some erosion take place. When the bed level is lowered, deposition occurs. Local depressions also show signs of increased deposition. A general pattern of decreasing amounts of deposition can be seen the farther away from the stream channel it gets. This is in accordance with Figure 6 which shows that the highest terrain on the banks only are flooded with high sediment loads during a relatively short period of time. The lower lying bank areas can receive larger deposits, since they are flooded during longer periods of time.

DISCUSSION

The outline followed in this article can be used for any hydrological problem that needs to be communicated. First a digital elevation model may be constructed to generate hydrological drainage features. Then simulation of water and sediment movement is carried out. The results are analyzed and then visualized in a GIS as overlays on the elevation model. A new analysis session can take place and then conclusions can be drawn .

In the case of flushing operations, the results from the hydrological analysis can be used to show the extent of the flooded area as well as the changes in geomorphology and grain-size distribution of the flooded areas. This can be of importance for e.g. farmers with agricultural fields next to the river. With the fine-grained material from the flushing, lots of nutrients, but possibly also pollutants, are supplied to the fields. Others who can have interest in this may be e.g. tourist agencies, which use the river banks for recreation or camping, and biologists who are concerned about spawning areas for fish.

An area where visualization will be of even greater use is hydrological studies of floods. Similarly, hydrological analysis is made where the result is shown simultaneously on a digital elevation model. If sediment transport and geomorphological changes are neglected, results of flooded areas can be shown rapidly and different scenarios can be evaluated.

Today, much of the planning relies on water levels related to different recurrence intervals, e.g. the 100-year flood. There is, however, a big problem with these intervals. They are on most occasions, if lucky, based only on some decades of hydrological data. Quite often the 100-year flood turns out to be only the 50-year flood or even lower when new data are gathered. Also, these intervals are based on statistics for a certain area in a certain climatic setting. If the climate changes, as it may do due to global warming, the statistical base is not the same anymore and all prior recurrence intervals are useless.

In addition to 3D visualization elaborated above, there is another trend which should draw our attention, i.e. agent-based simulation. The emerging technology has special application of various dynamics of geographic phenomena (Gimblett, 2002). Since it is a kind of bottom-up approach, it has some advantages over the conventional methods in understanding the geomorphological processes. For instance, watershed dynamics can be understood as a self-organising process between water drops and topographic environments (Jiang and Gimblett, 2002).

It is also important to note that besides integration of analytical models with visualization for the understanding of complex geomorphological processes in reality, it can be used to conduct so called “what if” modelling.

CONCLUSION

In the fluvial-geomorphological and hydrological literature, generally there are only separate before and after images or just plain text. The aim with this article is, however, to show that by visualizing fluvial geomorphological effects in 3D, both the interpretation of hydrological processes gets better, as well as it facilitates communication with non-hydrologists. That is, “When you see – you understand why!”.

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