RECLAMATION

Managing Water in the West

Technical Report No. SRH-2014-41

Modeling Delta Erosion with a Landscape Evolution Model

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

September 2014

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Bureau of Reclamation

Technical Service Center, Denver Colorado

Sedimentation and River Hydraulics Group

Technical Report No. SRH-2014-40

Modeling Delta Erosion with a Landscape Evolution Model

Prepared by:

D Nathan Bradley   10/6/2014

D. Nathan Bradley, Ph.D., Physical Scientist   Date

Sedimentation and River Hydraulics Group, Technical Service Center

Report Peer Reviewed by:

10/6/2014

Jennifer Bountry, P.E., M.S., Hydraulic Engineer   Date

Sedimentation and River Hydraulics Group, Technical Service Center

Table of Contents

1.0 Introduction

The Elwha and Glines Canyon Dams were removed from the Elwha River between 2011 and 2014. The rate of removal of Glines Canyon Dam was established based on hydraulic and sediment study findings in the early 1990s. Phased notches of approximately 15 feet followed by 2 week to 2 month hold periods were planned. When dam removal was started in September 2011, field monitoring was used to track sediment erosion rates and numerical modeling was used to forecast sediment erosion rates. The integrated monitoring and modeling information was used to provide recommendations for adjusting the rate of dam removal. The rate could be increases if sediment erosion objectives had been met for a given notch, or decreased to ensure the rate of river erosion kept pace with the rate of dam removal.

Modeling was required on a quarterly basis during dam removal to inform the adaptive management program. Traditional numerical models, either 1D, 2D, or 3D were not utilized because of limitations in capturing the complexities associated with rapid and extensive vertical incision and lateral erosion of the delta during drawdowns. Another challenge was that the erosion was affected by sediment properties in the delta that varied both vertically and laterally from non-cohesive to cohesive, and had multiple layers of organics. Additionally, computation time required posed a risk to accomplishing routine prediction runs with multiple hydrologic and removal scenarios in a real-time framework that could be used to manage the pace of removal. Instead, a GIS-based model was generated that relied on empirical relationships informed by monitoring data to make predictions of sediment erosion volumes. The volumetric output from the GIS model for a given dam removal period (weeks to months) was then "routed" with daily hydrographs to produce concentration predictions for downstream sediment levels. The routing also required empirical relationships on how to weight sediment distribution based on the time delay from each notch and hydrology. At first, the GIS-model utilized simplified geometric representations of longitudinal slope and channel width tied to discharge to make predictions of erosion volumes. As more monitoring data became available, the GIS-model was able to integrate more complex channel width and slope measurements and not only peak discharge but factors such as number of days above a given flow level. The advantage of the GIS model was that it could easily integrate complex real-time measurements and new information about empirical relationships. In terms of computation resources, it took about 1 day to run each hydrologic or dam removal scenario. The disadvantage was the model relied on being informed by the user of key variables of slope and erosion width.

Research funding was provided by the Reclamation Science and Technology office to explore application of SRH-2D with bank erosion modules on the Lake Mills delta erosion during removal of Glines Canyon Dam. As part of the research effort, we reviewed an alternative modeling approach that would incorporate utilization of a landscape evolution model. This approach may offer components that would be valuable to incorporate in future model testing and development for complex projects like the Lake Mills drawdown with variable sediment properties and rapid rates of incision and lateral migration.

2.0 Landscape Evolution Models

An alternate approach to modeling the erosion of the Mills Delta is to use a landscape evolution model (LEM). The removal of the Elwha river dams is a man-made "natural experiment" [*Tucker*, 2009] and the subsequent erosion of the Lake Mills delta and the response of the river channel is a unique opportunity to apply and test a LEM. Landscape evolution models have been used to simulate topographic evolution at a wide variety of spatial and temporal scales. Relevant examples include modeling the response of a river flowing across a normal fault in Italy to an increase in the fault slip rate [*Attal et al.*, 2008] and the formation of gully networks in Colorado [*Istanbulluoglu et al.*, 2005]. Landscape evolution models differ from coupled hydraulic and sediment transport models such as SRH-2D in that the simulation of the hydraulic flow field is less detailed. Either the shallow water flow equations are simplified (for example, by using the kinematic wave approximation) or water is routed between model elements based on the topographic slope [*Tucker and Hancock*, 2010]. The advantage of a simplified representation of the flow field is that it is less computationally intensive.

The Channel-Hillslope Integrated Landscape Development (CHILD) model [*Tucker et al.*, 2001] is one example of a LEM that could be used to simulate the evolution of Mills Delta. The lowering of the Lake Mills outlet as the dam was removed is similar to a river flowing across a normal fault. When the fault slips, the channel on foot wall block sees a base level drop as the hanging wall subsides and it responds by incising. A CHILD simulation of a channel network developing on the footwall of a normal fault and depositing a delta on the subsiding hanging wall can be seen at http://www.youtube.com/watch?v=4DUsEDUEc2E.

Modeling the delta evolution with CHILD requires a model mesh that represents the initial topography of the Mills Delta, the pilot channel, and the bathymetry of the reservoir. The required boundary conditions include a base level lowering schedule (the dam removal schedule), a representation of the delta stratigraphy, a time series of river discharge, and a time series of sediment flux into the model domain. The last can probably be ignored if the sediment contribution from the basin upstream of Lake Mills is small compared to that sourced from the delta itself. Repeated topographic surveys of the evolving delta and a time series of sediment flux out of Lake Mills would be useful for model calibration and validation. Many, if not most, of these data sets are available.

CHILD drives landscape evolution with a stochastic series of precipitation events (storms). Since the evolution of the Mills Delta evolution appears to be driven almost entirely by migration of the Elwha channel migration, some tuning of the model precipitation patterns would be required to match the model river discharge to observed river discharge at the top of the delta. This might require modeling all or part of the basin, which would have the advantage of representing the effects of the tributaries in addition to the effect of the main stem Elwha River.

CHILD treats the erosion and transport of sediment in a manner similar to SRH-2D (essentially, an erosion rule based on shear stress or stream power and a geomorphic transport law [*Dietrich et al.*, 2003] coupled with continuity of mass), but it makes no distinction between a channel element and a hillslope element. In principle, this means that a laterally moving channel can be simulated without the difficulty associated with tracking bank cells and re-meshing on the fly as bank material is eroded. In practice, however, lateral channel motion and the associated erosion of banks and deposition of bars is difficult to simulate and is an area of ongoing research.

3.0 Discussion

Part of the difficulty in simulating bank erosion is that overhanging or vertical structures such as steep cohesive banks are not naturally represented by a model mesh that treats topographic elevation as a function of the horizontal coordinates z = f(x,y). *Istanbulluoglu et al.* [2005] addressed this problem to implement a slab failure model for gully head migration in CHILD.

A second issue is that models such as CHILD that use the kinematic wave approximation to route water have no explicit representation of channel width and therefore the water depth and velocity for a given discharge depends on the how width is calculated. One option is, to treat the channel width as an integer multiple of the mesh cell size, which tends to underestimate erosive power because in reality the channel width is often smaller than the resolution of the model mesh [*Tucker and Hancock*, 2010]. An alternative is to use a scaling relationship for channel width, typically based on discharge. However, discharge-width relationships developed for steady state rivers may not apply to transient cases [e.g. *Attal et al.*, 2008] or extremely dynamic systems like the Mills delta. Field measurements noted that channel width was tied to discharge peak, but two other important processes needed to be incorporated in predictions. When the river was eroding through non-cohesive sediment, sequential peak discharges of similar magnitude could result in increasing channel width for a given base level at the dam. There appeared to be a relationship between channel width and number of days over a discharge threshold in which the river was capable of mobilizing sediment. Given enough time, field measurements observed the channel kept widening until it was nearly valley wall to valley wall, or another increment of dam removal and base level lowering occurred. Another important process was the lag effect in headcut migration that often resulted in both migration and incision during single storm events.

A larger issue is that the physics of flow, sediment transport, and bank erosion along river bends are complex and not fully understood [*Darby et al.*, 2002; *Dietrich*, 1987]. Consequently, there is no universally accepted model for the inception and evolution of river meanders and channel migration by bank erosion [*Camporeale et al.*, 2007], though there has been much recent progress [e.g. *Limaye and Lamb*, 2013; *Parker et al.*, 2011]. CHILD includes a meander module [*Lancaster and Bras*, 2002] that produces realistic patterns of channel migration [*Bradley and Tucker*, 2013], but it is not entirely physically-based [*Camporeale et al.*, 2007] and it is unknown if it would be able to simulate the erosion of the Mills delta.

It is also far from clear that the relevant processes of bank erosion are fully captured by the models in the literature [e.g. *Darby et al.*, 2002; *Duan and Julien*, 2005; *Parker et al.*, 2011; *Raven et al.*, 2011]. In general, excess shear stress is assumed to erode the bank toe, which eventually undermines the bank, causing it to collapse. This is likely an oversimplification.

Irregularities in bank material (common in fluvially deposited sediment) and vegetation that are much smaller than a model mesh element may create variations in geotechnical properties that are not represented at the scale of the numerical model. In nature, these small scale features may quickly grow into large scale features (analogous to a Rayleigh–Taylor thermal instability) in a way that present models do not capture. Current models also neglect to consider how geotechnical properties of the banks change when saturated. It is likely that saturated banks are more prone to failure than dryer banks, so precipitation rates and precipitation history also likely plays a role.

4.0 Summary

In summary, the erosion of the Lake Mills delta as the Glines Canyon Dam was removed is an appropriate target for simulating with a landscape evolution model. The sizes of the basin and the delta are tractable and are similar to other landscapes simulated using LEMs. The lowering of the river's base level as the dam was removed is similar to a river flowing across a normal fault, a classic natural experiment that has been simulated successfully with a LEM [e.g. *Attal et al.*, 2008]. However, the lateral motion of channels is not entirely understood and the processes that affect bank erosion may not be well represented at the scale of a numerical model.

5.0 References

Attal, M., G. Tucker, A. Whittaker, P. Cowie, and G. P. Roberts (2008), Modeling fluvial incision and transient landscape evolution: Influence of dynamic channel adjustment, *Journal of Geophysical Research: Earth Surface (2003–2012)*, *113*(F3).

Bradley, D. N., and G. E. Tucker (2013), The storage time, age, and erosion hazard of laterally accreted sediment on the floodplain of a simulated meandering river, *Journal of Geophysical Research: Earth Surface*, *118*(3), 1308-1319.

Camporeale, C., P. Perona, A. Porporato, and L. Ridolfi (2007), Hierarchy of models for meandering rivers and related morphodynamic processes, *Reviews of Geophysics*, *45*(1).

Darby, S. E., A. M. Alabyan, and M. J. Van de Wiel (2002), Numerical simulation of bank erosion and channel migration in meandering rivers, *Water Resour. Res.*, *38*(9), 2-1-2-21.

Dietrich, W. (1987), Mechanics of flow and sediment transport in river bends, *River channels: Environment and process*, *134*, 179-227.

Dietrich, W. E., D. G. Bellugi, L. S. Sklar, J. D. Stock, A. M. Heimsath, and J. J. Roering (2003), Geomorphic transport laws for predicting landscape form and dynamics, *Prediction in geomorphology*, 103-132.

Duan, J. G., and P. Y. Julien (2005), Numerical simulation of the inception of channel meandering, *Earth Surface Processes and Landforms*, *30*(9), 1093-1110.

Istanbulluoglu, E., R. L. Bras, H. Flores-Cervantes, and G. E. Tucker (2005), Implications of bank failures and fluvial erosion for gully development: Field observations and modeling, *Journal of Geophysical Research: Earth Surface (2003–2012)*, *110*(F1).

Lancaster, S. T., and R. L. Bras (2002), A simple model of river meandering and its comparison to natural channels, *Hydrological Processes*, *16*(1), 1-26.

Limaye, A. B. S., and M. P. Lamb (2013), A vector-based method for bank-material tracking in coupled models of meandering and landscape evolution, *Journal of Geophysical Research: Earth Surface*, *118*(4), 2013JF002854.

Parker, G., Y. Shimizu, G. Wilkerson, E. Eke, J. Abad, J. Lauer, C. Paola, W. Dietrich, and V. Voller (2011), A new framework for modeling the migration of meandering rivers, *Earth Surface Processes and Landforms*, *36*(1), 70-86.

Raven, E. K., R. Ferguson, and S. N. Lane (2011), A coupled sediment routing and lateral migration model for gravel-bed rivers, *Hydrological Processes*, *25*(12), 1887-1898.

Tucker, G. E. (2009), Natural experiments in landscape evolution, *Earth Surface Processes and Landforms*, *34*(10), 1450-1460.

Tucker, G. E., and G. R. Hancock (2010), Modelling landscape evolution, *Earth Surface Processes and Landforms*, *35*(1), 28-50.

Tucker, G. E., S. Lancaster, N. Gasparini, and R. Bras (2001), The channel-hillslope integrated landscape development model (CHILD), *Landscape Erosion and Evolution Modeling*, 349-388.