ASSESSING POST-DAM REMOVAL SEDIMENT DYNAMICS USING THE CONCEPTS COMPUTER MODEL

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Abstract  Dam removal will impact stream morphology not just locally, but both far upstream and downstream. There is a critical need for tools to predict the rates, magnitudes, and mechanisms by which sediment is removed from a reservoir following dam removal, as well as for tools to predict where this sediment will be deposited downstream and how it will impact downstream channel morphology. Channel forming processes upstream of the dam are similar to those of channelized or incised streams. The US Department of Agriculture, Agricultural Research Service has developed the channel evolution computer model CONCEPTS to simulate the evolution of such channelized streams. CONCEPTS is therefore suitable to evaluate post-dam removal sediment dynamics. Further, the model contains features specific to dam removal studies, such as progressive lowering of the water surface elevation in case of phased dam removal and the consequent effects of dewatering of the stream bank/reservoir materials on bank material shear-strength. Application of CONCEPTS to evaluate dam removal consequences on the Kalamazoo River, Michigan, and the Klamath River, California, demonstrate the model’s performance.

INTRODUCTION

Across the United States (US) more than a thousand dams have been removed or are planned to be removed in the near future, often to improve habitat or due to decommissioning. Dam removal will impact stream morphology not just locally, but both far upstream and downstream. The sediment stored behind the dam will be eroded due to increased boundary shear stresses caused by the lowering of the water level. A new channel will form within the reservoir deposit. The location and rate at which the channel forms are controlled by reservoir topography, sediment properties, their distribution, and the imposed stream flow. The transported sediment is generally much finer than the stream bed material downstream of the dam, making prediction of downstream sediment transport rates difficult. Therefore, detailed studies are required to minimize the downstream impact of the eroded sediments on stream habitat, water quality, and flood elevations. Channel forming processes upstream of the dam are similar to those of channelized or incised streams. Before attaining a new quasi-equilibrium, the evolving channel proceeds through stages of degradation, degradation with channel widening, and aggradation with channel widening. The US Department of Agriculture, Agricultural Research Service has developed the channel evolution computer model CONCEPTS to simulate the temporal adjustment of such evolving streams. CONCEPTS is therefore suitable to evaluate post-dam removal sediment dynamics. The model contains features specific for dam removal studies. For example, the model is capable of simulating the effects of water level drawdown in the case of phased dam removal and the consequent effects of dewatering of the stream bank/reservoir materials on bank material shear-strength. This paper presents these features and two model applications.
CHANNEL EVOLUTION AFTER DAM REMOVAL

A computer model of post-dam removal sediment dynamics must be capable of simulating both upstream and downstream geomorphic adjustments. These adjustments are briefly described below.

**Upstream Geomorphic Adjustment** Because dam removal represents a large change in local base level, Doyle et al. (2002) postulated that the reservoir will respond in a similar fashion as incising channels. They derived a conceptual model of channel development in a reservoir after dam removal using conceptual channel evolution models of incising streams (see Figure 1). Stage A is the initial, predisturbed reservoir condition with the dam in place, and Stage B is the reservoir condition after the removal of the dam but before any disturbance of the sediment surface. Rapid degradation of the channel bed is dominant during Stage C, as upstream degradation begins to flatten the channel gradient. During this period of degradation the critical height of the channel banks is often exceeded, inducing channel widening via mass wasting (Stage D). In Stage E aggradation becomes dominant downstream as upstream degrading reaches provide substantial quantities of sediment to downstream reaches. Aggradation during Stage E decreases bank heights, reducing the amount of bank widening. As deposition continues at a more limited rate, often accompanied by the establishment of vegetation on the deposited sediment, a new dynamic equilibrium is established, Stage F.

**Downstream Geomorphic Adjustment** Transport of the sediment stored behind a dam is analogous to the translation and dispersion of a sediment slug (Doyle et al., 2002). The migration and dispersion of the sediment wave greatly depends on sediment size, watershed hydrology, and large-scale channel and floodplain characteristics (Nicholas et al., 1995). Migrating sediment waves can substantially impact local channel morphology, including: initiation of channel
CONCEPTS COMPUTER MODEL

General Overview  CONCEPTS is capable of simulating the upstream and downstream geomorphic channel adjustment post-dam removal. It has shown to correctly simulate the evolution of incising streams (Langendoen et al., 2009b). The main processes simulated by CONCEPTS are streamflow hydraulics, sediment transport, streambed evolution, and streambank erosion. This section briefly discusses the characterization of these processes in CONCEPTS. For more details see Langendoen and Alonso (2008) and Langendoen and Simon (2008).

Hydraulics  CONCEPTS models stream flow as one-dimensional along the channel’s centerline. Hence, it is limited to fairly straight channels; it cannot predict bar formation and channel migration. CONCEPTS simulates gradually-varying flow (described by the Saint-Venant equations) as a function of time along a series of cross sections representing stream and floodplain geometry. The governing system of equations is solved using the generalized Preissmann scheme, allowing a variable spacing between cross sections and large time steps conducive to long-term simulations of channel evolution. The implementation of the solution method contains various enhancements to improve the robustness of the model, particularly for flashy runoff events.

Sediment Transport and Streambed Evolution  Alluvial streambanks are typically composed of deposits containing clays, silts, and fine sands, which may overlay coarser relic point bars. Streambeds are more commonly composed of sands and gravels, resistant clay layers or bed rock. Therefore, the range in particle sizes being transported in alluvial streams may be quite large and the composition of the sediment mixture in transport may be quite different from the bed-material composition because a majority of the sediments are fines transported in suspension. CONCEPTS therefore calculates sediment transport rates by size fraction for 14 predefined sediment size classes ranging from 10 μm to 64 mm.

CONCEPTS uses a total-load evaluation of bed-material transport and treats movement of clays and fine silts (<10 μm) as pass-through background wash load. The differences in transport mechanics of suspended and bed load movement are accounted for through non-equilibrium effects. The composition of bed surface and substrate is tracked, enabling the simulation of vertical and downstream fining of the bed material.

Streambank Erosion  CONCEPTS simulates channel width adjustment by incorporating the two fundamental physical processes responsible for bank retreat: fluvial erosion or entrainment of bank-material particles by flow, and bank mass failure due to gravity. Bank material may be cohesive or non-cohesive and may comprise numerous soil layers.

The detachment of cohesive soils is calculated following an excess shear-stress approach. An average shear-stress on each soil layer is computed. If the critical shear stress of the material is
exceeded, entrainment occurs. CONCEPTS is able to simulate the development of overhanging banks.

Streambank failure occurs when gravitational forces that tend to move soil downslope exceed the forces of friction and cohesion that resist movement. The risk of failure is expressed by a factor of safety, defined as the ratio of resisting to driving forces or moments. CONCEPTS performs stability analyses of wedge-type failures and cantilever failures of overhanging banks. The effects of pore-water pressure and confining pressure exerted by the water in the stream are accounted for.

**Riparian Processes** Riparian vegetation has well-known beneficial effects on bank stability, biological diversity, and water temperature of streams (e.g., Karr and Schlosser, 1978). The use of riparian buffer systems has become an increasingly popular means of improving habitat and streambank stability in stream restoration. Riparian vegetation controls streambank stability in two ways: (1) hydrologically by affecting soil water, and (2) mechanically through root reinforcement of the soil (Simon and Collison, 2002). To evaluate these controls CONCEPTS has been integrated with the Riparian Ecosystem Management Model (REMM). REMM has been developed as a tool to aid natural resource agencies and others in making decisions regarding management of riparian buffers to control nonpoint source pollution (Altier et al., 2002). REMM is also intended as a tool for researchers to study the complex dynamics of hydrology and water quality functions of riparian ecosystems. At present, a daily feedback of several parameters has been established between CONCEPTS and REMM to calculate, among others, the effects of pore-water pressure and root biomass on streambank stability (Langendoen et al., 2009a).

**Dam Removal Features** CONCEPTS contains the following specific features to assess the downstream and upstream impact of dam removal: (1) phased water level drawdown, (2) bed and width adjustment of an evolving channel within the reservoir deposit, and (3) progressive dewatering of the reservoir deposit with the lowering of the water surface.

Water level drawdown associated with phased dam removal is simulated by imposing the time series of water surface elevation at the dam location. The time series comprises the starting and ending time and water surface elevation of each drawdown segment.

Bed and width adjustment is simulated by calculating the divergence of the bed-material transport by grain size, and the fluvial erosion and mass wasting of streambank materials (Langendoen and Alonso, 2008; Langendoen and Simon, 2008).

Lowering of the water surface in the reservoir may greatly affect streambank erosion rates. The initial loss of confining pressure destabilizes the streambank. However, the dewatering of the streambank materials enhances the apparent shear strength of the bank soils by increasing matric suction. The enhanced shear strength and reduced bulk density increases streambank stability. In CONCEPTS the relation between water surface elevation and groundwater elevation is:

\[
\frac{d \Delta H}{dt} = \beta \Delta H
\]  

(1)
where \( t \) is time, \( \Delta H = H_s - H_g \) is the difference between surface water elevation \( (H_s) \) and groundwater elevation \( (H_g) \), and \( \beta \sim K_s/L \) is a coefficient proportional to the ratio of saturated conductivity \( (K_s) \) of the bank soil and a length measured normal to the stream over which the bank is dewatered \( (L) \). The elevation difference \( \Delta H \) at time \( t_2 = t_1 + \Delta t \) is related to that at time \( t_1 \) as

\[
\Delta H(t_2) = \Delta H(t_1) \exp(-\beta \Delta t)
\]

(2)

The new groundwater table is then used to update the pore-pressure distribution in the streambank and resulting apparent shear strength.

**APPLICATIONS**

**Kalamazoo River, Michigan** Between the mid 1800s and the early 1900s, four dams were constructed on the Kalamazoo River between Plainwell and Allegan, Michigan (see Figure 2). Three hydroelectric dams (Trowbridge, Otsego, and Plainwell) were decommissioned as power generators in the mid 1960s. The Otsego City Dam still remains in operation. The impoundments have been the depositories of upstream sediment and industrial waste materials. Between 1957 and 1971, Kalamazoo area paper mills recycled carbonless copy paper containing polychlorinated biphenyls (PCBs) as ink solvent and incorporated these PCBs in their waste discharge. The paper wastes also included kaolinite clays, which were found in the impoundment sediments (streambank and floodplain) to contain concentrations of PCBs as high as 94 mg per kg.

The state of Michigan is interested in removing the dams while minimizing impacts to the study reach and downstream reaches, and to provide for improved fisheries. Concerns over the fate of PCB-laden channel sediments in the Kalamazoo River between Plainwell and Otsego, especially its release by bank erosion, resulted in the US Geological Survey supporting a study by NSL to simulate sediment loads and channel changes in the reach (Wells et al., 2007). To estimate volumes and rates of sediment transport within the study reach and to address specific objectives of the study, three modeling scenarios were evaluated over a 38-year period (2000-2037) to determine the response of the Kalamazoo River between Plainwell (rkm 91.2) and Otsego (rkm 82.4) to current channel conditions (Dams In, DI), instantaneous removal of two low-head dams (Dams Out, DO), and a design channel without the low-head dams (Design, D).

Flows for all three-simulation scenarios are based on a 17.7-year discharge record (October 1984 to June 2002) from the USGS gage on the Kalamazoo River at Comstock, Michigan (04106000). The 17.7-year flow record was created using daily data from 1984 to 1989 and hourly data from 1989 to June 2002 to account for changing hydraulic conditions and instantaneous peaks. The Gunn River flows into the study reach from the north between cross-sections G5 and G6 (Fig. 2). Because there is no flow data for this tributary, the flow from the Gunn River was estimated using a drainage area comparison from the flow record at the Kalamazoo River at Comstock. The resulting flow from the Gunn River is 17% of that at the Kalamazoo River at Comstock.
Figure 2 Map of Kalamazoo River study reach showing modeled cross sections and locations of the Plainwell and Otsego City Dams.
The modeling reach of the Kalamazoo River extends 8.8 km from approximately 82.4 km above the confluence with Lake Michigan (cross section OC8), to cross section P3, approximately 91.2 km above the confluence with Lake Michigan (Figure 2). The study area can be separated into three distinct sub-reaches based on location relative to the Plainwell and Otsego City Dams: (1) the Otsego (OC) reach below the Otsego City Dam, (2) the Plainwell-Otsego (POC) reach between the Otsego City and Plainwell Dams, and (3) the Plainwell (P) reach above the Plainwell Dam.

Sediments eroded from the channel boundary and downstream sediment load are similar and fairly low for the DI and D scenarios, indicating a stable stream system (Table 1). Removal of the low-head dams induces severe channel bed and streambank erosion upstream of the former dam locations, significantly increasing sediment load. However, most of these sediments are eroded in the first three years (Table 1). The quantities of fine-grained material (< 63 μm) transported past the downstream boundary over the last 35 years of the simulation are similar to those of the DI and D scenarios. Therefore, most of the channel adjustment due to dam removal occurs in the first three years of the simulation.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Sediment yield in kilotonnes/yr</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 63 μm</td>
</tr>
<tr>
<td>Dams In (DI)</td>
<td>10.4</td>
</tr>
<tr>
<td>Dams Out (DO)</td>
<td>8.9</td>
</tr>
<tr>
<td>Dams Out (DO, year 1-3)</td>
<td>43.7</td>
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<tr>
<td>Dams Out (DO, year 4-38)</td>
<td>6.5</td>
</tr>
<tr>
<td>Design (D)</td>
<td>8.4</td>
</tr>
</tbody>
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For the DO scenario, Fig. 3 shows that the channel upstream of the Otsego City Dam rapidly incises to the coarse, pre-dam bed-material and widens consequently. The simulated morphology upstream of the Otsego City Dam progresses through Stages B, C, and D of Doyle et al.’s (2002) conceptual channel evolution model (cf. Fig. 1). The coarser eroded sediments initially deposit immediately downstream of the former dam location to form a lump, which disperses and migrates slowly. Streambank erosion in the POC reach is an order of magnitude greater for the DO scenario (3,000 T/y) than the DI (157 T/y) and D (272 T/y) scenarios.

**Klamath River, California** The Klamath River flows from its headwaters near Crater Lake, Oregon to its confluence with the Pacific Ocean at the town of Klamath, California (Fig. 4). The Klamath River Project is a hydroelectric facility comprising seven dams and appurtenant facilities. Six of these dams are located on the main stem of the Klamath River. The Klamath River Project is undergoing relicensing proceedings before the Federal Energy Regulatory Commission. Outside of the traditional relicensing process, many interested parties have met to discuss future management options for the project, including the feasibility of dam removal (e.g., GEC, 2006).
GEC (2006) conducted a study to investigate the potential for removal of the four most downstream dams of the Klamath River Project: Iron Gate, Copco 2, Copco 1, and J.C. Boyle. Two of the dams, Iron Gate and Copco 1, have large reservoirs that have trapped significant amounts of sediment that may adversely impact downstream stream function when removed. GEC (2006) concluded that erosion of sediment would occur as the reservoirs are drawn down. The small sediment particle size and high water content of the sediment will result in nearly instantaneous erosion of sediment in the path of flowing water. GEC (2006) recommended drawdown rates ranging from 1 to 3 feet per day, which would result in highly elevated suspended sediment concentrations lasting approximately 120 to 40 days, respectively. Timing of reservoir drawdown is a big problem. It affects concentrations and duration of elevated concentrations, ability of structure demolition and removal activities to accomplish the required work before high flows refilled reservoirs, and effects of subsequent high flows on water quality. Review of the timing of fish runs in the river suggests that optimum timing to avoid fish impacts
would be sometime starting in October. Starting the drawdown in October would provide reliable higher flows to erode sediments and avoid impacts to many of the species. Starting drawdown in late spring of the year would allow more construction flexibility. If drawdown were to begin before June, Iron Gate Dam could be removed before winter high flow events occur. Overbank revegetation could also proceed without concern over loss of efforts due to inundation of the sediment. However, the following winter flows could be expected to erode a wider channel and cause intermittent pulses of elevated sediment as banks eroded.

Figure 4 Klamath River Basin and Dam Location Map
Philip Williams and Associates Ltd of San Francisco, California performed a study for the California State Coastal Conservancy using CONCEPTS to assess changes in stream morphology upstream of the Iron Gate and Copco 1 Dams caused by 1- and 3-ft/day drawdown scenarios, and a series of winter storms. Results of a 3 feet per day drawdown and a series of four hydrographs of the wettest year (hydrograph duration is approximately five months and hydrograph peak discharge is about 225 m$^3$/s) for the Iron Gate Dam removal modeling study are presented below. The study section is located approximately 4.8 km upstream of the dam location and has a length of about 2.5 km. The flow depth before drawdown at the downstream end of the study reach is approximately 14 m. The drawdown duration is 13 days, after which the flow depth at the downstream end of the study reach has been reduced to approximately 1.5 m.

In the case of the drawdown scenario, Figs. 5 and 6 show that fluvial shear stresses remain small enough to inhibit fluvial erosion of the reservoir deposit. Sands delivered from upstream form a downstream migrating delta front. The smaller flow depths and resulting larger fluvial shear stresses cause mobilization of silts and clays to start at the upstream end of the study reach. The mobilized silts and clays deposit on the floodplain because the pre-dam (historic) channel is submerged for almost the entire drawdown duration. This may not be realistic, but is caused by the method used in CONCEPTS to simulate transfer of in-stream suspended sediments onto the floodplain. This method assumes that sediment transport capacity of the flow on the floodplain is negligible.

![Simulated changes in thalweg elevation upstream of the Iron Gate Dam caused by: (1) 3 ft/day drawdown, and (2) a series of winter hydrographs from the wettest year on record.](image)

Figure 5 Simulated changes in thalweg elevation upstream of the Iron Gate Dam caused by: (1) 3 ft/day drawdown, and (2) a series of winter hydrographs from the wettest year on record.

The large winter runoff events storms cause significant erosion of the streambed and streambank materials (Figs. 5 and 6). Results show rapid erosion of the bed with accompanying erosion of the banks. The first runoff event exposes the pre-dam bed material, which is eroded down to bed rock during the following runoff events. The rate of channel widening is controlled by fluvial erosion. The rate of channel widening is reduced as the channel widens.
Figure 6 Simulated changes in cross section geometry of a cross section located approximately 19,000 ft upstream of the Iron Gate Dam for: the drawdown scenario (left) and a series of winter hydrographs (right).

Figure 5 shows that the modeling results are affected by the chosen location of the downstream boundary. The very fine streambed material is not being eroded by the flow. To improve the modeling results the downstream boundary of the study reach should be located downstream of the Iron Gate Dam. Also, the simulation of fine sediment transport on the floodplain needs to be improved.

CONCLUSIONS

The channel evolution computer model CONCEPTS originally developed to simulate the temporal adjustment of incising streams was enhanced with the following features specific to post-dam removal sediment dynamics: prescribed drawdown of the water elevation at the dam location and the effects of dewatering of the reservoir deposit on its resistance to erosion. Evaluating the impact of removing the Otsego City and Plainwell Dams on the Kalamazoo River, Michigan shows that CONCEPTS satisfactorily simulates both upstream and downstream geomorphic adjustment. Upstream geomorphic adjustment progresses through Stages B to F of the conceptual model of Doyle et al. (2002). Downstream geomorphic adjustment shows a very slowly migrating sediment wave. Dispersion of the sediment wave controls long-term downstream sediment loads. Application of the model to the removal of the Iron Gate Dam on the Klamath River shows deposition onto the downstream floodplain within the reservoir of large quantities of silts and clays mobilized at the upstream end of the reservoir, which may be unrealistic. Hence, improvements of CONCEPTS are required to more accurately simulate the transport of silts and clays on the floodplain.

REFERENCES


