Forecasting the effects of Dam Removal on river form and process: an analysis of progress in modelling forecasts 2002-2012

Abstract

The process of dam removal is becoming recognised as a necessary action in the restoration of many hydrological systems, particularly in the USA. Dam removal science is rapidly developing. This literature review outlines the key concepts regarding dam removal, before analysing progression in the effectiveness and refinement of modelling techniques over the last decade. Modelling techniques analysed include conceptual modelling, numerical, physical and digital monitoring, integrated process modelling and comprehensive studies. Conclusions are drawn on the progress made in modelling techniques, with suggestions made for further model improvement and literature study, and the concept of a dam removal study database, complete with modelling methods, is introduced.

Keywords
Dams, Dam removal, Modelling

Introduction

The study of dam removal on river form and process is becoming increasingly important due to the large amount of dams either being removed, or considered for removal. The science has emerged in recent years, with modelling techniques being used to forecast hydrologic, geomorphic and ecological effects (Doyle, Harbor and Stanley 2003:453). The area provides a unique and testing challenge within hydrological modelling. Dam structures affect hydrologic regimes widely, so their removal has noticeable impacts. Dam removal can influence water discharge, sediment loading, sediment grain size and river slope topography, consequently affecting ecological systems. Impacts often occur both above and below the dam site, due to the presence of reservoir storage systems behind dams. Pizzuto (2002:683) observed that current site specific forecasting methods were unreliable, producing inaccurate results. Cui *et al*. (2005) identified a lack of understanding concerning the impacts of reservoir stored sediments, and their release following dam removal. It could be suggested that a robust scientific foundation is lacking, given the substantial development of the practice. Doyle, Harbor and Stanley (2003) recommended that a minimum level of critical analysis is required through conceptual understanding with a need for numerical data and simulation modelling methods.

Forecasting Methods and Models

Conceptual Modelling

Conceptual modelling of dam removal is outlined by Pizzuto (2002) as a key step in creating numerical models, highlighting a lack of understanding of geomorphic conceptual processes as a past problem in numerical modelling development. The semi-quantitative study of a variety of dam removal projects is encouraged, providing the critical knowledge for conceptual models, in order to make subsequent numerical models more reliable. Leroy and Hart (2002) identify the importance of study at a conceptual level of a variety of dams, with differing structures and functions. Similarly to Pizzuto (2002), Doyle, Harbor and Stanley (2003) also identified a lack of scientific understanding in critical analysis.

Large proportions of conceptual dam removal studies have focused on researching sedimentary processes of transport and deposition. Cui and Wilcox (2008) summarise understanding of sediments released from reservoirs in the dam removal process, analysing sediment transport theories and citing the importance of the size of sediment. It was suggested that current conceptual models required refinement in such areas, particularly geomorphological head-cut theory. A later study considering channel adjustments and responses (Sawaske and Freyberg 2012) included head cut theory in a conceptual channel evolution model.

A study by Kibler, Tullos, and Kundolf (2011) of a small gravel filled dam found that results differed from previous studies due to the presence of coarse sediments, leading to the promotion of a refined conceptual model for gravel sediments. However, a study by Wildman and MacBroom (2005) with similar sedimentary conditions found results to be relatively accurate when compared with fine grain sediment studies. This could lead to the assumption of suggested improvements in the accuracy of semi-quantitative conceptual studies in recent years; however Sawaske and Freyberg (2012) indicate that sedimentary processes in small dam removals can be highly specific depending on local conditions. This reinforces the statement of a need for a variety of conceptual studies in differing situations.

Recent geomorphological studies have included research of a dam removal in ephemeral stream conditions (Neave, Rayburg and Swann 2009), and studies with a focus on sediment and nutrient dynamics (Ahearn and Dahlgren 2005). Another recent small dam study by Skalak, Pizzuto and Hart (2009) used semi-quantitative geomorphic characterisation to understand pre-dam environments below the dam, using flow regime data from upstream of the river reservoir. It is clear that a variety of conceptual studies are being carried out.

Numerical Modelling

Advancing from conceptual modelling, numerical modelling is required to improve the quantitative forecasting of geomorphological processes, as the impacts of dam removal are likely to reach far enough downstream for a one- dimensional longitudinal scale to be of use (Pizzuto 2002). Doyle, Harbor and Stanley (2003), and Lorang and Aggett (2005) recognised the significance of conceptual understanding, but also the need for numerical modelling to refine scientific studies, including one dimensional numerical models.

An example of a study utilising a one dimensional numerical model is that of Konrad (2009), researching dam removal in the Elwha River in Washington State, USA. The model was used to measure daily time periods, calculating changes in river bed elevation, sediment particle size distributions and concentrations of suspended sediment, in a three year removal and four year recovery period. However the movable boundary sediment transport model employed neglects large scale geomorphological changes, and is therefore not robust (Konrad 2009)

Numerical studies by Lorang and Aggett (2005), and Snyder *et al*. (2004) also focused on quantifiable variables of sediment storage, using bathymetric surveys to measure total volumes of sediment. Bathymetric surveys are often expensive and time consuming (Snyder *et al*. 2004), therefore not realistically a feasible option for every dam removal project. Further numerical studies (Downs *et al*. 2009, Cheng 2005, and Cui and Wilcox 2008) analysed sediment transportation and deposition downstream of dam removal, an important area in the related studies of ecology and geomorphology. Cheng (2005) used a one-dimensional hydrometric model, calibrated with observational data to measure the timing of the flood wave following removal of the dam, leading to analysis of bed level adjustments (2005). The importance of particle size and distribution of sediments was once again highlighted.

The main limitations of one-dimensional numerical models are outlined by Cui and Wilcox (2008):

1. Mitigation of channel morphology changes following erosion
2. Large spatial and temporal scales required
3. Questions in reliability of sediment transport equations.

Cui and Wilcox (2008) suggest that numerical modelling techniques can be beneficial in making predictions, where various dam removal projects are able to be compared, however more comparison with observations and data collection is required to aid refinement.

Physical and Digital Modelling

Physical modelling is the process whereby physical and conceptual models are tested in varying, variable controlled circumstances (Pizzuto 2002). This can involve the use of flumes in scale models, which in past studies of fluvial morphology produced comparative and reliable results (Pizzuto 2002). Expanding on the points made by Pizutto (2002), Doyle, Harbor and Stanley (2003) state that physical simulation modelling is a necessary addition to conceptual and numerical methods in the study of dam removal.

Cui *et al*. (2005) were responsible for the development of the Dam Removal Express Assessment Models (DREAM). Two one-dimensional, cross sectional sediment transport models were produced; one, applicable to locations where non-cohesive sand and silt sediments were present (DREAM 1), and the other to gravel-based reservoir deposits (DREAM 2). DREAM 1 was tested using physical models in lab conditions, whereas DREAM 2 was first tested using field data, before similar physical sample runs were carried out to validate assumptions (Cui *et al*. 2006). Physical models were used in this instance to give feedback on the accuracy of initial quantitative research, allowing for contributions to be made in identifying necessary methods of dam removal. A similar physical model was utilised by Downs *et al*. (2009) to model coarse sedimentary pulse release into river bed pool-bar sediment deposition sequences.

However, the influence and use of physical modelling appears to have declined through the last ten years, due to certain limitations. Pizzuto (2002) mentioned the difficulty in producing models that reflected the process of surface chemistry in fine sediments, as well as creating physical models with accurate geometry to represent geomorphic landscapes. The process of physical modelling is also a lengthy (Snyder *et al*. 2004), and seemingly an unsustainable process.

The decline of physical modelling could be directly related to improvements in digital monitoring by computing methods. Pizzuto (2002) cited limitations in computer storage capacity to be preventing the production of 2D and 3D modelling; however there have been major technological advances in computing systems. Evans *et al*. (2002) were able to use Geographical Information Systems (GIS), in combination with sediment routing, to calculate the volume of sediments stored in a reservoir, whilst Cheng (2005) used high resolution Digital Elevation Models (DEMs), to compare erosion and deposition in pre-dam removal and post-dam removal environments. Following observations, it was found that the DEM overestimated transport rates, but to a degree of magnitude (Cheng 2005). Similarly, Berrios *et al* .(2007) used ArcGIS Spatial Analyst software to create 3D images for timescale river bed monitoring, creating estimations for non- sample point from sample points. Within the last decade, the use of digital modelling has largely now replaced physical modelling, seemingly, due to ease of use and advances in computing technology.

Integrated process modelling

Integrated process modelling in the case of dam removal covers geomorphic, hydrologic and ecological processes (Pizzuto 2002). Conceptual ecological models should be coupled with such models described earlier in the review, so these variables can be factored into decisions and policy making for dam removal (Konrad 2009), as ecology is widely affected by river geomorphology (Pizzuto 2002). Pizzuto (2002: 690) states that previous one-dimensional longitudinal models are not of an appropriate scale to be used for ecological studies; therefore the use of digital 2D and 3D geomorphic models is important within the integrated modelling process, especially for ecological studies (e.g. Stanley and Doyle 2002). The concept of eco – hydromorphology, introduced by Vaughan *et al*. (2009) makes progress in describing these processes of integrated study. A general concept for river science and management, eco-hydromorphology focuses on the combination of ecology, hydrology, and fluvial geomorphology studies at their interface, with large scale catchment projects focusing on certain organisms as focal research points. Expertise is described as fragmented at the interface, thus hindering individual progress in all three studies (Vaughan *et al*. 2009:114). Stanley, Leubke and Marshall (2002) identified a lack of understanding of the impacts of dam removal upon riverine ecosystems. Vaughan *et al*. (2009) also recommended the study of eco-hydromorphic mechanisms over correlations.

Over the last ten years, there are very few examples of integrated process modelling at dam removal sites. Downs *et al*. (2009) produced a study using robust physical and numerical modelling, implemented for a fine sediment dam removal site. The study is not integrative, however does highlight the need for a specific evaluation of the environmental impacts of sediment management techniques that are described (Downs *et al*. 2009:440). Hendrix (2011) carried out a combined study on short term changes in channel form and macroinvertebrate communities in two rivers, whilst a study by Bartholow, Campbell and Flug (2005) calibrated a thermal numerical model, integrated with conceptual ecological models of fish stocks using computing systems.

The most comprehensive integrated study reviewed was carried out by Tomsic *et al*. (2007). A coupled eco-hydrodynamic model (a Habitat Sustainability Index (HSI) and an ArcGIS hydromorphic model using 45 cross sections across a longitudinal area of the river pre- and post dam removal) was used, predicting the habitat of a target species, Greater Redhorse, a water quality sensitive fish (Tomsic *et al*. 2007:220). The ArcGIS environments pre- and post-dam gave clear indications of HSI, which was mainly affected by changes in river bed depth. Such studies show progress in integrated modelling, particularly the integration of ecological variables.

Comprehensive Studies

Comprehensive studies are described as site-specific quantitative and multi-disciplinary studies (Pizzuto 2002:689). Studies should include thorough quantification of physical and biological conditions, and are said to be the only means by which a thorough evaluation can be carried out. Dam removal is also described by Leroy and Hart (2002:667) as “an excellent opportunity for comprehensive, cross discipline studies of riverine ecosystems”.

Possibly due to the timescale and monetary issues of such studies, no studies researched with the last ten years were found to comprehensively meet the criteria described above, but there is evidence of significant progress to provide a foundation. This is largely due to the increased use of GIS and remote sensing in digital modelling, replacing physical modelling. An integrative and detailed study of habitat suitability for Walleye fish in the Sandusky River, Ohio, employing such robust digital methods, cited HSI and other ecological model levels of accuracy as limitations, however (Gillenwater, Granata and Zika 2006:322); such studies need be comprehensive in all areas of the eco-hydromorphic interface. From this example it appears ecological modelling requires improvements, however a more comprehensive review of the literature is required to validate this assumption.

Progress towards comprehensive studies requires the collaboration of different research areas and organisations associated with dam removal. Berrios *et al*. (2007) present the opportunity for such a study with river bed monitoring of the Marmot Dam, on the Sandy River in Oregon, with dam removal consultation involving 23 different associated bodies, including state and federal resource agencies, and local businesses. The complex nature of comprehensive studies on riverine form and process requires a joint approach at the eco- hydrogeomorphic interface, with inclusion of social and economic impacts as recommended additions (Roberts *et al.* 2007).

Conclusion and considerations for the future

From the literature reviewed, it is clear that progress has been made in models forecasting the effects of dam removal within the last decade. A number of conceptual studies examining various variables have taken place over a wide selection of differing dam case studies, key to effective forecasting. However, there still appears to be gaps in the knowledge base and theories that require continuous refinement. Conceptual observations have also aided the adjustment of numerical models measuring a wide range of variables. One-dimensional physical modelling has widely been replaced by digital modelling, with 2D and 3D capabilities, following improvements in computer systems. These advances have allowed for advance in integrated modelling, particularly the integration of ecological variables, and developing progress in eco-hydrogeomorphic studies. However, there is little evidence showing the development of fully comprehensive studies.

A broader, more refined review of the literature should be considered to further analyse recent advances in the capability of modelling methods. Also the construction of a database, containing findings from all dam removal studies would be useful in creating a refined comprehensive model. If advances in computing systems and storage continue, progress could be directed towards the creation of a comprehensive computer forecasting model with inclusive variable data entry. Any advances towards a comprehensive eco-hydrogeomorphic digital model of this type would be beneficial, to allow the comprehensive analysis of the effects of dam removal on river form and process.

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