Modeling the Impacts of Hydromodification

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Abstract

Hydromodification is caused by anthropogenic activities driven by human population growth and resource consumption that alter watershed hydrologic responses. These activities include urbanization, channel modification, flow regulation by water impoundments, water withdrawal, and climate change. Hydromodification is a major source of integrated stressors that disrupt ecosystem functions and consequently the ecosystem services that watersheds provide. Stressors associated with hydromodification include flow alteration, water quality degradation, habitat degradation, and loss of aquatic life and biodiversity. Hydromodification is one of the leading sources of water quality impairment. Under the Clean Water Act, it is a regulatory requirement to develop total daily maximum loads (TMDLs) for streams and rivers affected by hydromodification. However, modeling approaches that address the complexities of hydromodification are not well established. Specifically, quantifying stressor levels associated with different hydromodification activities and assessing their impacts on aquatic ecosystems is a major challenge. In this paper, we propose Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) as a modeling framework suitable for forecasting anthropogenic-induced stressors and their effects on aquatic ecosystems.

Introduction

Rivers and river-fed lakes are valuable natural resources that provide about 61 percent of the nation's drinking water and serve as riverine habitats to an estimated 40 percent of the fish species and about half of the birds in North America (Whiting, 2002). In addition, rivers store floodwaters for groundwater recharge and provide recreational amenities such as boating, fishing, and swimming (Whiting, 2002) as well as navigation, irrigation, power generation, and waste load transport and assimilation (Poff et al., 1997). Resource extraction projects such as land development for agriculture, energy, mining, forestry, transportation, urban development, and water resources development threaten valuable ecosystem services. For example, urban development and efforts to use rivers for transportation, water supply, flood control, irrigation, and power generation often result in altered flow regimes, which in turn affect the sustainability of the ecosystem services that rivers and river-fed lakes provide (Poff et al., 1997).

Understanding anthropogenic-induced stressor levels and their effects on aquatic ecosystems requires the development and application of integrative modeling approaches. Integrative modeling approaches are rarely used to quantify anthropogenic-induced stressor levels and their integrated effects on aquatic ecosystems. A number of factors contribute to the lack of development and application of integrative modeling approaches that address multiple stressor-response relationships. First, watersheds, which are the basic environmental management units, do not usually coincide with jurisdiction boundaries where decisions on urban development and management are often made. Second, water quantity and water quality are regulated by various federal and state agencies (Karr, 1991).

Forecasting environmental consequences of urbanization and water resources development projects is a fundamental challenge to science, especially as water demand increases in the next two to three decades (Naiman et al., 2002). Current pressing demands on water use and continuing alteration of watersheds are important research topics that require scientists to help develop management protocols that can accommodate economic uses while protecting ecosystem functions (Poff et al. 1997). The need for comprehensive water resource management at the watershed scale was also highlighted in two recent federal government reports on water research and data collection across federal agencies (The National Research council, 2004, and the General Accounting Office, 2004).

Integrative modeling approaches are capable of simulating multiple stressors (i.e. nutrients, pathogens, suspended solids, metals, flow alterations, and habitat alterations) and their cumulative effects on aquatic ecosystems. A suitable hydromodification approach enables resource managers to forecast the stressor levels and their combined effects on aquatic ecosystems before land and water resources development plans are implemented in a watershed. The objective of this study is to explore the applicability of the BASINS modeling framework as the basis of an integrative modeling approach that forecasts anthropogenic stressor levels and their impacts on aquatic ecosystems. The paper does not present application examples that demonstrate the capabilities of the BASINS modeling framework.

Hydromodification: Source of Integrated Stressors

Hydromodification describes land and water resources development activities that are driven by human population growth and resource consumption. These activities often produce direct or indirect changes to water quantity and quality. USEPA (1993) defines hydromodification as the "alteration of the hydrologic characteristics of coastal and non-coastal waters, which in turn could cause degradation of water resources." According to USEPA (2007), hydromodification consists of channelization and channel modification, construction of dams and impoundments, and streambank and shoreline erosion. Hydromodification has also been narrowly defined as flow hydrograph modification elsewhere in the literature.

USEPA (2007) presents hydromodification as a leading source of water quality impairment of streams, lakes, estuaries, and aquifers in the United States. The National Water Quality Inventory Report to Congress (2004) that was released in 2009 identified agricultural nonpoint source (NPS) pollution as the primary (48%) water quality impairment of assessed streams and rivers followed by hydromodification (20%), and habitat alteration (14%) (USEPA, 2009). Figure 1 shows the top ten sources of impairment in assessed rivers and streams in the United States. They are closely linked to human activities that alter the physical structure or the natural function of a water body. Water quality degradation caused by hydromodification includes increased sedimentation, higher water temperature, lower dissolved oxygen, degradation of aquatic habitat structure, and loss of fish and other aquatic populations.

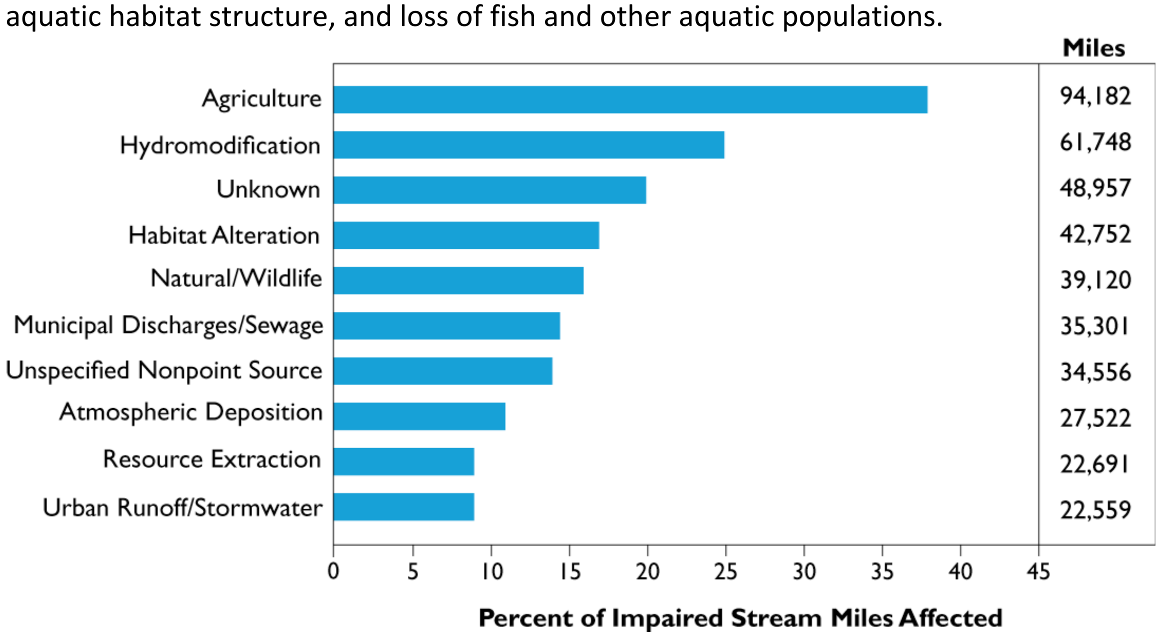

Figure 1. Top 10 sources of impairment in assessed rivers and streams in the United States (Source: USEPA, 2009)

Adding to USEPA's definition of hydromodification, we define hydromodification more broadly to include urbanization, climate change, water withdrawal, and inter-basin transfers. Our intention is to use the term for a wide range of anthropogenic watershed disturbances that alter natural flow regimes and degrade water quality. Addressing the impacts of integrated stressors is more effective than addressing stressors individually because multiple stressors can have integrated effects that are not independent. Furthermore, integrated stressors impair many watersheds and resource managers are unable to identify the cause of impairment. Despite being a major source of impairment in assessed water bodies, modeling approaches that adequately address the complex nature of hydromodification-induced stressors and impacts are not available.

Types of Hydromodification Activities

Urbanization

Urbanization alters natural flow regimes by directing water away from subsurface flow pathways to surface flow. As the percent of impervious cover area increases in a watershed, peak flow rates and flow volumes increase (Arnold and Gibbons, 1996; Tang et al., 2005) and baseflow and groundwater recharge decrease (Rose and Peters, 2001). These hydrologic disturbances may lead to serious economic and environmental consequences. For example, many incidences of water supply shortages have been reported for communities in water-rich areas of the world (Okun, 2002). In the United States, frequent and severe droughts and urbanization-induced water shortages have been observed in some areas of New England, in the Southeast (Atlanta), and areas in the west coast (Seattle and Portland) (Sehlke, 2004). Urban development causes redistribution of surface and baseflow, which makes it difficult to balance water availability and water demand particularly for municipal water supply and in-stream flow needs or balance upstream and downstream water needs.

Channel Modification and Streambank Erosion

Streams and rivers, which are important habitats to many aquatic organisms, are affected by channel modification. Channel modifications include direct channel operations such as dredging, widening, and straightening, or indirect modifications caused by flow alteration. Anthropogenic-induced stressors such as flow alteration, unsanitary discharge, and channelization projects degrade many streams and rivers (Leblanc et al., 1997). A number of investigators have examined the ecological impacts of hydromodification by assessing the biotic integrity of streams using multi-metric indices, such as the indices of biotic integrity (IBI) (Karr 1991) or bioindicator approaches (Adams, 2005). To link urbanization-induced stressors to stream habitat degradation, a number of investigators have examined relationships between total impervious area (TIA) and biological integrity (Morse et al., 2003; Booth et al. 2004) of urban streams. Other investigators have related hydrologic metrics (estimated from simulated or observed streamflow data) to biological integrity. For example, Richter et al. (1996) identified flow magnitude, frequency, duration, timing, and rate of change as ecologically relevant hydrological indicators.

The approach proposed to simulate the impacts of channel modification on stream habitat is to use simulated hydrologic, hydraulic, and water quality metrics that link anthropogenic-induced stressors to stream habitat quality. In addition to development of hydromodification metrics, hydromodification impacts on stream habitat can be evaluated by coupling HSPF to a habitat suitability model such as PHABSIM (Milhous et al. 1984) or an ecological risk assessment model such as AQUATOX (Park et al. 2008).

Water Withdrawal

In most cases, water rights are simulated using state-specified water allocation models. These models include the Water Rights Allocation Program (WURP) developed for Texas (Wurbs, 2005) and the MODSIM model for Colorado (Labadie, 2005). Zariello and Reis (2000) used HSPF to examine the effect that water withdrawals have on streamflow using eleven water management alternatives for a period of 35-years. Anthropogenic activities that affect water availability have tremendous impact on in-stream and municipal water rights. Balancing changing water availability and demand for watersheds affected by anthropogenic disturbances is becoming a major challenge to resource managers. Although these modeling challenges are widely recognized, approaches that address the integrated anthropogenic-induced stressors and their effects on aquatic ecosystems are not available. A suitable modeling approach is to link water quality and water allocation models (Azevedo et al. 2000).

We propose to simulate water withdrawal by using HSPF in a stepwise fashion. First, HSPF is used as a simulation model to simulate water availability (streamflow) and water quality for a given scenario. Second, HSPF is used as a water allocation or water accounting model that assigns simulated available water to competing water users. An important feature of HSPF is its ability to run as a simulation model and as a water accounting model.

Flow Regulation by Dams and Impoundments

In past decades, trends in urbanization and population growth increased water demand and has led to extensive damming of rivers and streams. In the United States, more than 85% of the inland waterways are now artificially controlled (NRC, 1992), including nearly 1 million km of rivers that are affected by impoundments (Echeverria et al. 1989). Water impoundments are the most obvious direct modifiers of river flow because they capture high flows to control floods, generate electric power, and provide irrigation, navigational, and municipal water needs. Impoundments have number of environmental impacts that include inundation of wetlands, riparian areas, reduction or elimination of downstream flooding, blocking fish migration routes, increased turbidity and sedimentation at the construction stage, and flow alteration. Flow regulation profoundly alters natural flow regimes resulting in degraded river ecosystems (Power et al., 1996). Fishery managers have long argued that maintaining the natural flow regimes observed before development is essential to the composition and structure of native riverine ecosystems and associated biodiversity (Richter et al. 2000). Elliot and Parker (1997) have studied the impacts of impoundments on flow and sediment regimes using before and post-development analysis, but methods to evaluate the combined and cumulative effects of impoundments, flow diversions, and urbanization are lacking.

Climate Change

Our approach to modeling climate change impacts on water quantity and quality is to use GCM temperature and precipitation projections. Model users can select scenarios that are similar to mean GCM projections for the United States or scenarios that differ from mean GCM projections. For example, one can select a scenario that has a 10% increase in annual precipitation, with a 10% increase in the frequency of high precipitation events, and increased return frequency of storms of particular magnitudes. For temperature increases, a modeler could select a corresponding scenario with two degrees increases during the cool season months, and four degree increases during the warm months. Note that climate change is only one driver of hydromodification, and it can be addressed separately or concurrently with urbanization, flow regulation, and channel modification. For more discussion on generating climate change scenarios for the HSPF model in BASINS, interested readers can refer to the Climate Assessment Tool (CAT) manual, which can be accessed at http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=203460.

BASINS Modeling Framework: A background

The Clean Water Act was established to restore and maintain the chemical, physical, and biological integrity of the nation's waters. In the 1970s and 1980s, EPA successfully regulated point source pollution through the National Pollutant Discharge Elimination System (NPDES) permit program. However, managing nonpoint source pollution from terrestrial ecosystems has proven to be more difficult. To manage this problem efficiently, EPA adopted an approach that makes the watershed the unit of regulatory focus (USEPA, 1998; Whittemore and Beebe, 2000). Adoption of the watershed approach as the management and regulatory unit has created a need for watershed models and modeling approaches. Today, watershed models are widely used to manage nonpoint source pollution, particularly through the development of TMDL plans for water quality impaired water bodies. To manage land and water resources in a sustainable manner, resource managers need modeling approaches that forecast the impact of hydromodification on water quantity and quality. In 2007, EPA released a guidance document on managing nonpoint source pollution caused by hydromodification (USEPA, 2007). This document listed a number of models applicable to hydromodification modeling, but did not present specific hydromodification modeling guidance. HSPF and AQUATOX, which are part of the BASINS modeling framework, were among the models listed.

In 1996, USEPA released BASINS ver. 1.0 modeling and decision support system (EPA, 1996a). BASINS integrates Geographic Information System (GIS) tools, national databases (elevation, hydrography, meteorology, land use, and soil), assessment tools (target, assess, and data mining), data management and graphing programs (WDMUtil and GenScen), models (HSPF, SWAT, PLOAD, and AQUATOX), and analysis tools including the Climate Analysis Tool (CAT).

Figure 2 matches BASINS' modeling capabilities with hydromodification drivers, stressors, and impacts. As shown in Figure 2, using GIS tools and databases, BASINS provides access to information about soils, topography, and land use and land cover of a watershed. In addition, BASINS provides information on hydromodification projects already present in the watershed and their distribution in the landscape. Resource managers can use BASINS to identify priority areas for preservation and development. As stated earlier, hydromodification activities are driven by population growth and the accompanying need for resource extraction and consumption. The watershed management goal is to minimize the impacts of economic development projects on water quantity and quality by reducing anthropogenic-induced stressors to levels that can be assimilated by the watershed or mitigated through BMPs. Here, we briefly discuss some of the models available in BASINS that apply to modeling hydromodification.

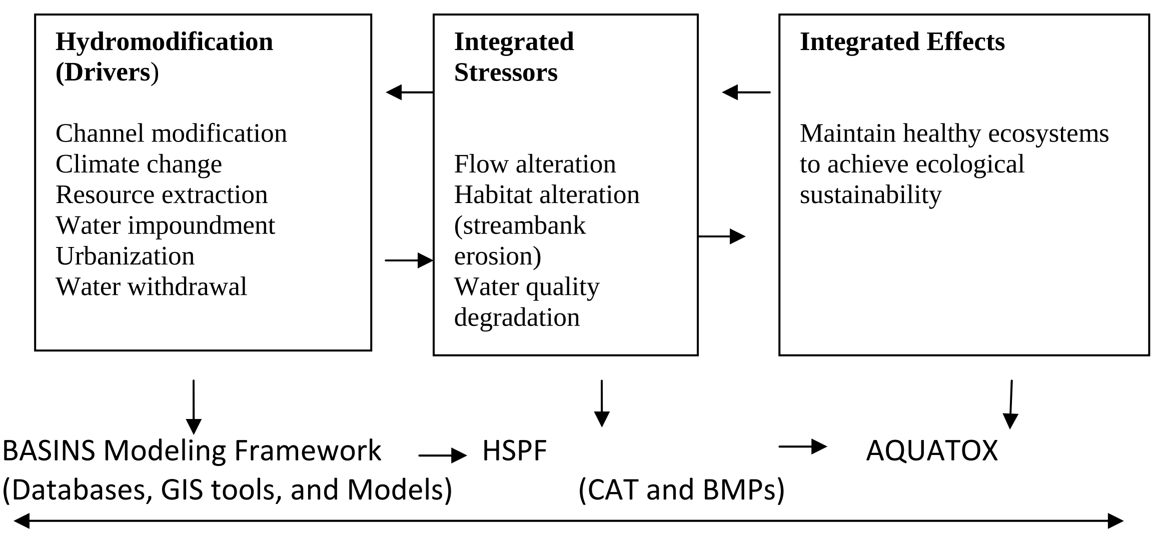

Figure 2. Matching framework modeling capabilities with hydromodification drivers, integrated stressors, and integrated effects.

HSPF is EPA's premier watershed hydrology and pollutant transport model (Whittemore and Beebe, 2000) and is the core watershed model in BASINS. In addition to water quality and hydrologic process simulations, HSPF has been used to assess the effects of land use change on streamflow (Brun and Band, 2000), effects of water withdrawal on streamflow (Zariello and Reis, 2000), and effects of climate change on water quantity (Goncu and Albek, 2009). Furthermore, HSPF has been used for developing hydrological and biological indicators of flow alteration in the Puget Sound low land streams (Cassin et al. 2005).

Conclusion

BASINS and its core watershed model, the Hydrological Simulation Program- FORTRAN (HSPF), provide a framework for modeling hydro modification. Specifically, HSPF simulates flow alteration, water quality degradation, and water allocation under alternative future scenarios. For each scenario, HSPF allows resource managers to forecast scenario-specific anthropogenic-induced stressors. To link these anthropogenic-induced stressors to ecosystem impacts, we recommend the use of AQUATOX, a general ecosystem assessment model in BASINS. The proposed modeling approach enables resource managers to evaluate different alternative scenarios and select those that meet the objectives of sustainable land and water resources development.

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