Journal of Hydrology 537 (2016) 322–333

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A framework for modeling contaminant impacts on reservoir water quality

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ARTICLE INFO

Article history:
Received 28 March 2015
Received in revised form 6 February 2016
Accepted 21 March 2016
Available online 31 March 2016
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Bibhash Nath, Associate Editor

Keywords:
Reservoir management
Contaminant spills
Hydrodynamic and water quality models
Water quality
Drinking water

SUMMARY

This study presents a framework for using hydrodynamic and water quality models to understand the fate and transport of potential contaminants in a reservoir and to develop appropriate emergency response and remedial actions. In the event of an emergency situation, prior detailed modeling efforts and scenario evaluations allow for an understanding of contaminant plume behavior, including maximum concentrations that could occur at the drinking water intake and contaminant travel time to the intake. A case study assessment of the Wachusett Reservoir, a major drinking water supply for metropolitan Boston, MA, provides an example of an application of the framework and how hydrodynamic and water quality models can be used to quantitatively and scientifically guide management in response to varieties of contaminant scenarios. The model CE-QUAL-W2 was used to investigate the water quality impacts of several hypothetical contaminant scenarios, including hypothetical fecal coliform input from a sewage overflow as well as an accidental railway spill of ammonium nitrate. Scenarios investigated the impacts of decay rates, season, and inter-reservoir transfers on contaminant arrival times and concentrations at the drinking water intake. The modeling study highlights the importance of a rapid operational response by managers to contain a contaminant spill in order to minimize the mass of contaminant that enters the water column, based on modeled reservoir hydrodynamics. The development and use of hydrodynamic and water quality models for surface drinking water sources subject to the potential for contaminant entry can provide valuable guidance for making decisions about emergency response and remediation actions.

1. Introduction

Protecting surface drinking water sources from point and non-point sources of contamination is an important element to maintaining high drinking water quality and minimizing treatment costs. However, if contaminants enter a drinking water source, it is important to have an understanding of their fate and transport in the surface water body and how they may impact drinking water quality. Hydrodynamic modeling studies are typically carried out after a contamination incident to guide operational response, data collection, or remedial action, while few contaminant modeling studies have been published that help to understand contaminant transport in anticipation of incidents (Clark et al., 1989; Grayman and Males, 2002; Gullick et al., 2003). Hydrodynamic and water quality models are useful tools for determining contaminant plume behavior and impacts to water quality at a drinking water intake, making simulations especially useful for accessing multiple scenarios and proactively developing response plans for rapid and appropriate action in the event of an actual contaminant event in a drinking water reservoir (DiGiano and Grayman, 2014; Henderson-Sellers, 1991).

Water quality models can be used to simulate hydrodynamics, heat transfer, and water quality processes in water bodies in order to predict the fate and transport of water quality constituents or contaminants. Models simulate concentrations of nutrients, pathogens, microbes, and other constituents in the water body based on analytical or numerical solutions to equations describing physical, chemical, and biological processes of importance. Simulating conservative constituents is important for confirming that a model adequately describes the hydrodynamics of a system. Reactive water quality constituents are affected by both fluid transport processes and reactions, which may result in degradation and lower concentrations at a location of interest such as a drinking water intake. Contaminants which may be of concern to reservoir operators include natural substances (natural organic matter (NOM)) and inorganic species, pathogens and other microorganisms, as well as the accidental release of anthropogenic substances (e.g. pesticides, pharmaceuticals, industrial compounds).

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http://dx.doi.org/10.1016/j.jhydrol.2016.03.041
0022-1694/

A contaminant may enter a water body from point and non-point sources. Point sources of contaminants are inputs occurring at a single location and may include inflows such as those from a tributary, discharges from a wastewater treatment plant, or an accidental contaminant spill. For example, in the year 2011, Hurricane Irene in the Northeastern US, a 200-yr event, caused discharge and dissolved organic matter concentrations in the Esopus Creek to increase 330 and 4-fold, respectively (Yoon and Raymond, 2012). The Esopus Creek drains 16,500 ha of the Catskill Mountains and eventually discharges into the Ashokan Reservoir, a primary drinking water source for New York City. The inflows from this tributary are closely monitored, since high stream flows from large events are associated with large point sources of nutrients, sediment, and pollutant transport to the reservoir. A recent anthropogenic point source contaminant input to a drinking water supply was the West Virginia chemical spill into the Elk River in January 2014 from an industrial source located 1.61 km (1 mile) upstream from the Kanawha Valley Water Treatment Plant, the drinking water supply to the Charleston, WV (Bahadur and Samuels, 2014). An estimated 37,854 L (10,000 gal) of 4-methycyclohexane methanol (MCHM) and propylene glycol phenyl ether (PPH), organic solvents used in coal processing, spilled into the river, which shortly overwhelmed treatment capacity of the drinking water treatment plant and led to a water ban for an estimated 300,000 West Virginia residents (Bahadur and Samuels, 2014).

Nonpoint sources of contaminants can include distributed runoff from a watershed, subsurface flow, atmospheric inputs, or roosting waterfowl. Diffuse pollution in agricultural watersheds from cropland and livestock are often significant sources of nutrients and pesticides to a surface water body resulting in impaired water quality (Sharpley et al., 1994; Wauchope, 1978). Field studies of roosting gulls on the Quabbin Reservoir, a drinking water supply reservoir for metropolitan Boston, MA, investigated this non-point source of fecal coliform to understand how gull roost location impacts coliform concentration at the drinking water intake (Garvey et al., 1998). Water from the Quabbin Reservoir has a filtration waiver from the Surface Water Treatment Rule (SWTR). Therefore, managers have chosen to conduct studies to understand the fate and transport of contaminants, like fecal coliform, and develop source water management plans to deal with nighttime roosting of gulls on the reservoir to maintain water quality. The field study, in conjunction with hydrodynamic and water quality modeling efforts, later described, helped reservoir management understand the importance and impact of their gull harassment program.

Hydrodynamic and water quality models are commonly used for simulating the response of a water body to changes in nutrient loads or contaminant inputs from both point and non-point sources. Selection of an appropriate water quality model depends of the geometry of the water body and the transport process of interest. In temperate climates the fate and transport of contaminants in drinking water reservoirs are influenced by seasonal thermal stratification. Impacts of thermal stratification on the transport of an inflow containing a contaminant of concern is of particular interest to reservoir operators because studies indicate that thermally stratified water bodies significantly decrease vertical mixing, causing contaminants to spread laterally, potentially leading to higher contaminant concentrations at a drinking water intake compared to well mixed conditions (Chung and Gu, 1998; Gu et al., 1996; Jeznach et al., 2014; Marti et al., 2011).

Hydrodynamic and water quality modeling can be used to evaluate various contaminant scenarios and impacts of management response decisions specific to a particular water body. Contaminant types and sources of potential contaminants in a reservoir will depend on hydrologic and watershed characteristics. Although a drinking water treatment plant can have a robust treatment system to deal with variations in water quality characteristics, source water protection is an important barrier to water quality impairment from contaminants.

2-D models have been used in many applications to simulate constituent fate and transport and to evaluate management responses. Garvey et al. (1998) used CE-QUAL-W2 in conjunction with field studies, previously described, to simulate the fate and transport of fecal coliforms from gull roosting in the Quabbin Reservoir, an oligotrophic drinking water source in Massachusetts. The model results suggested that the gull roost location, wind speed, and wind direction impact the magnitude and variability of the outlet coliform concentration. Chung and Gu (1998) used the two-dimensional generalized longitudinal-vertical hydrodynamics and transport model (GLVHT) to simulate the transport and mixing of a spill of conservative contaminant methyl isothiocyanate (MITC) in Shasta Reservoir in California. GLVHT was developed from the laterally averaged reservoir model (LARM), which was later used to develop CE-QUAL-W2. The CE-QUAL-W2 model was modified to include a toxics sub model to better simulate the fate and transport processes of toxic contaminants, including sorption, desorption, photolysis, hydrolysis, oxidation, biotransformation, volatilization, diffusive exchanges between the sediments and water column, and sediment transport and deposition in the reservoir (Gu and Chung, 2003). The same modified model was used to simulate the herbicide atrazine in the Saylorville Reservoir in Iowa from agricultural runoff (Chung and Gu, 2009). The results from the study were useful in developing reservoir operation strategies to minimize contaminant concentration in the intake water (Chung and Gu, 2009).

Hydrodynamic and water quality models used in conjunction with a Spill Management Information System (SMIS) can help to effectively manage the risks of a potential spill into a water body (Martin et al., 2004). The GIS based system incorporates CE-QUAL W2 V3.1 as its surface water contaminant transport model and Computer-Aided Management of Emergency Operations (CAMEO) to model atmospheric dispersion. The SMIS application was designed to evaluate the short-term impacts of a chemical spill and to facilitate the development of a comprehensive response plan. This application was tested on the Cheatham Reach, a part of the Cumberland River, where the model simulated a 50,000 L spill of benzene that occurred over 1 h. The combination of model results from CE-QUAL-W2 and CAMEO, and information from GIS layers, provides real-time planning and analysis capabilities for first-responders, facility operators, and emergency response organizations (Martin et al., 2004).

Knowledge of potential contaminant types and sources in combination with knowledge of the hydrodynamics and transport specific to surface water reservoirs can lead to more informed management decisions in the event of an actual contamination scenario. The use of models to simulate scenarios and evaluate management responses can be a critical exercise for developing appropriate and timely responses to emergency situations, guiding measurements of a contaminant plume as it travels, and reducing short and long term impacts to drinking water supplies. This paper presents a framework for using models to understand the hydrodynamics and transport of potential contaminants in a surface drinking water source and an example case study applying the framework to assess contaminant impacts on the Wachusett Reservoir, in central Massachusetts.

2. Framework

Fig. 1 lays out a framework for assessing contaminant impacts on reservoir water quality and developing management response plans. Although the framework is presented in a linear order, the