Catena 150 (2017) 87–99

Contents lists available at ScienceDirect

Catena

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

Using multiple watershed models to assess the water quality impacts of alternate land development scenarios for a small community

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ARTICLE INFO

Article history:
Received 20 April 2016
Received in revised form 25 October 2016
Accepted 6 November 2016
Available online 14 November 2016

Keywords:
Watershed modeling
Multiple model comparisons
SWAT
GWLF
CBP-CWM
Chesapeake Bay

ABSTRACT

Chesapeake Bay, the largest estuary in North America, is impaired by excess nutrient discharges, especially from urban and agricultural land. Watershed simulation models have provided key insights to understanding land-to-water connections, but rarely are these models applied to guide local land management to explore and communicate uncertainty in the model predictions. In this study, three watershed simulation models; the Soil and Water Assessment Tool (SWAT), the Generalized Watershed Loading Function (GWLF) model, and the Chesapeake Bay Program's Chesapeake Watershed Model (CBP-CWM) were implemented to predict water, total nitrogen, and total phosphorus discharges from small tributaries in the town of Queenstown, Maryland, USA. Based on our evaluation metrics, none of the models consistently provided better results. In general, there was a good agreement on annual average water flow between the SWAT and CBP-CWM models, and the GWLF and CBP-CWM models predicted similar TN and TP loads. Each model has strengths and weaknesses in flow and nutrient predictions, and predictions differed among models even when models were initialized with the same data. Using multiple models may enhance the quality of model predictions and the decision making process. However, it could also be the case that the complexity of implemented watershed models and resolution of our understanding currently are not yet suited to provide scientifically credible solutions.

1. Introduction

Coastal zones provide valuable ecosystem services to human society worldwide (Agardy and Alder, 2005; Barbier et al., 2011), but coastal zones have also been foci of urban development. In some US coastal areas, the rate of development has considerably exceeded the population growth rate (Nagy et al., 2012). Population growth is accompanied by land conversion, mostly into urban land uses, which can threaten the integrity of coastal waters through multiple negative effects on water quality (Grimm et al., 2008; Tu, 2009). Urbanization increases impervious area, resulting in quicker and larger pulses in storm flow, geomorphic changes in stream channels, and higher sediment yields (Arnold et al., 1982; Wahl et al., 1997). Urban lands are also potential sources for heavy metals, nutrients, and bacteria (Rose, 2002; Schoonover et al., 2005). Excessive loads of nitrogen (N) and phosphorus (P) in urban streams can trigger undesirable effects in the receiving water bodies, such as algal blooms, eutrophication, and hypoxia. In addition to urbanization, agricultural activities are also major contributors to coastal eutrophication (Boesch et al., 2001).

Chesapeake Bay, the largest estuary in North America, is ecologically degraded, largely because of excessive nutrients received from urban and agricultural discharges. In 1970, Chesapeake Bay was one of the first estuaries found to contain marine dead zones (Kemp et al., 2005). The Bay and its tidal tributaries were later listed as impaired water bodies under section 303(d) of the Clean Water Act. Since 1980, management efforts to reduce nutrient loads to the Bay have intensified, but the loads from urban land have actually increased by 15% since 1985 (Chesapeake Bay Program, 2010). Increased loads from population growth and new suburban sprawl have outweighed load reductions achieved from stormwater management practices. Current efforts to reduce urban loads emphasize site-scale practices (i.e., stormwater management) and watershed-scale planning, such as directing low impact development to designated areas adjacent to a municipality.

Since 1983, the Chesapeake Bay Program (CBP); a regional partnership including local, state, and federal agencies, has worked to protect and restore the Bay and its 167,000 km^2 watershed (Chesapeake Bay Program, 2010). To develop policy recommendations, the CBP uses simulation models of the Chesapeake Bay watershed (CBP-CWM) and

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http://dx.doi.org/10.1016/j.catena.2016.11.009
0341-8162/

estuary to set the regulatory limits for total maximum daily loads (TMDLs) to Chesapeake Bay and to evaluate the likely effects of possible management actions on nutrient loads (Linker et al., 2013). However, land management plans are implemented at much smaller spatial units than those considered by the CBP-CWM model. Furthermore, when assessing the impacts of alternative land management plans, the intrinsic uncertainty of watershed process modeling and the potential impacts of climate change on surface water quality and quantity are often overlooked. Land management plans for improving water quality may fail if the plans are based on models that do not consider the spatial patterns of land use, model uncertainty, or climatic variability (Weller et al., 2011, Weller and Baker, 2014).

Watershed models are essential tools for summarizing knowledge of watershed processes and forecasting the effects of different land use or climate scenarios on water quantity and quality. However, imperfect model representations of key hydrologic and biogeochemical processes reduce confidence in model predictions (Sharifi et al., 2016; Yen et al., 2014b). Combining results from a group of models (ensemble modeling) instead of relying on a single model can improve predictions and enhance confidence when applying the models to identify optimal development scenarios (Beven and Freer, 2001; McIntyre et al., 2005). Assessing model structural uncertainty is a common objective among many studies that have employed multiple watershed models (Breuer et al., 2009). Most of these studies focused only on parameter uncertainty within a single model, without much consideration to structural uncertainty (i.e., the choice of underlying model algorithms) or input uncertainty (i.e., the choice of and errors in land use, land cover, and other input data) (Yen, 2012). Furthermore, most studies focus primarily on flow prediction (Reed et al., 2004; Goswami et al., 2005; Breuer et al., 2009); and fewer studies considered model uncertainty in predicting sediment (Kalin and Hantush, 2006; Shen et al., 2009), phosphorus (Nasr et al., 2007) nitrogen (Amiri and Nakane, 2009; Grizzetia et al., 2005), or multiple materials (Boomer et al., 2013).

A multi-model ensemble (MME) goes beyond model comparison by integrating the predictions of individual models into an ensemble average. MME often has better average performance than single models and increases the credibility of model predictions by accounting for uncertainty in model structure (Georgakakos et al., 2004; Boomer et al., 2013). Ensemble model averaging provides alternatives in addition to a single model, especially when there is not enough information to identify the best model or when the data do not favor a particular model (Kadane and Lazar, 2004). Several studies have applied the MME approach to flow prediction or flood forecasting (Renner et al., 2009; Zhao et al., 2011) and one study demonstrated that combining nitrogen predictions of five models gave better predictions than the individual models (Exbrayat et al., 2010). In addition, the LUCHEM study applied an ensemble of 10 watershed models to assess the effects of land use and land cover (LULC) change on hydrology and water quality (Breuer et al., 2009; Huisman et al., 2009; Viney et al., 2009).

It was mentioned in literature that varying spatial resolution of a single modeling project in the same study area may cause direct impact upon model predictions for flow and water quality outputs (Chaubey et al., 2005). In this study, it was further investigated if the modeling results could be inconsistently affected by alternative watershed simulation models even initialized by the same data resolution. Three watershed models were used to evaluate and compare the impacts of three alternative future land development scenarios for Queenstown, MD; a small (37 km^2) coastal community located on the Chesapeake Bay's Eastern Shore (Fig. 1). The models were the Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012), the Generalized Watershed Loading Function (GWLF) model (Haith and Shoemaker, 1987) and the Chesapeake Bay Program's Chesapeake Watershed Model (CBP-CWM) (Linker et al., 2013). It was stated in literature that the SWAT model is slightly better than GWLF in terms of nutrient predictions. However, both models performed similarly in hydrological processes (Niraula et al., 2013). In this study, model predictions of flow, total nitrogen (TN), and total phosphorus (TP) under different LULC configurations were compared; and model predictions were combined into ensemble averages, which were also compared to the predictions of the individual models.

2. Materials and methods

2.1. Study area

Queenstown is located within the Chesapeake Bay drainage, in Coastal Plain physiographic province of Maryland (Fig. 1). The study site has relatively flat terrain with elevations ranging from 0 to 10 m above mean sea level (AMSL). Because of the affordable land, low taxes, and proximity to the Washington DC and Baltimore metropolitan

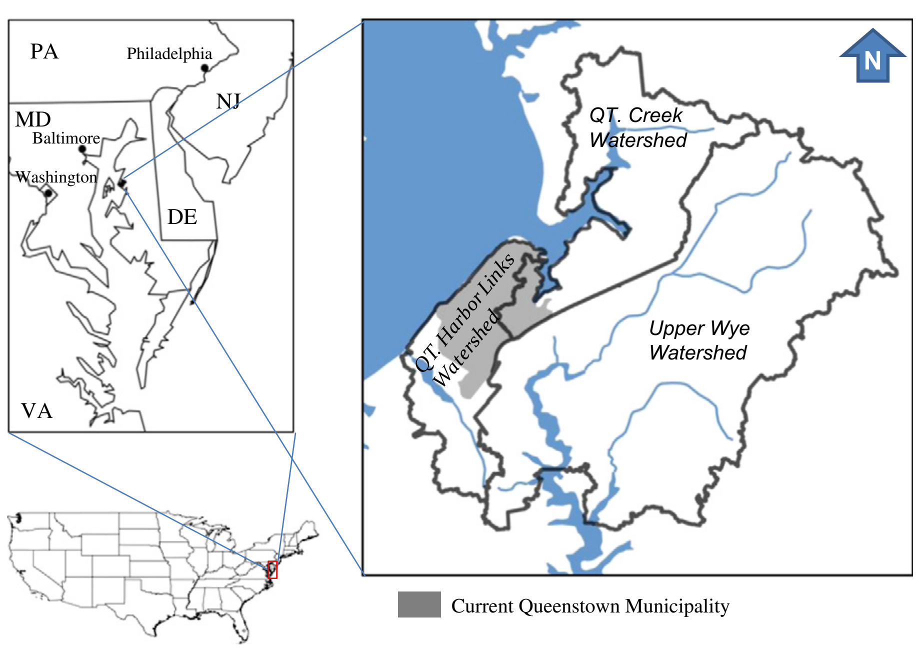

Fig. 1. Three watersheds comprising the Queenstown study area on the eastern shore of Chesapeake Bay. Current development is mostly in the gray area.