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A refined regional modeling approach for the Corn Belt – Experiences and recommendations for large-scale integrated modeling

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SUMMARY

Nonpoint source pollution from agriculture is the main source of nitrogen and phosphorus in the stream systems of the Corn Belt region in the Midwestern US. This region is comprised of two large river basins, the intensely row-cropped Upper Mississippi River Basin (UMRB) and Ohio-Tennessee River Basin (OTRB), which are considered the key contributing areas for the Northern Gulf of Mexico hypoxic zone according to the US Environmental Protection Agency. Thus, in this area it is of utmost importance to ensure that intensive agriculture for food, feed and biofuel production can coexist with a healthy water environment. To address these objectives within a river basin management context, an integrated modeling system has been constructed with the hydrologic Soil and Water Assessment Tool (SWAT) model, capable of estimating river basin responses to alternative cropping and/or management strategies. To improve modeling performance compared to previous studies and provide a spatially detailed basis for scenario development, this SWAT Corn Belt application incorporates a greatly refined subwatershed structure based on 12-digit hydrologic units or 'subwatersheds' as defined by the US Geological Service. The model setup, calibration and validation are time-demanding and challenging tasks for these large systems, given the scale intensive data requirements, and the need to ensure the reliability of flow and pollutant load predictions at multiple locations. Thus, the objectives of this study are both to comprehensively describe this large-scale modeling approach, providing estimates of pollution and crop production in the region as well as to present strengths and weaknesses of integrated modeling at such a large scale along with how it can be improved on the basis of the current modeling structure and results. The predictions were based on a semi-automatic hydrologic calibration approach for large-scale and spatially detailed modeling studies, with the use of the Sequential Uncertainty Fitting algorithm (SUFI-2) and the SWAT-CUP interface, followed by a manual water quality calibration on a monthly basis. The refined modeling approach developed in this study led to successful predictions across most parts of the Corn Belt region and can be used for testing pollution mitigation measures and agricultural economic scenarios, providing useful information to policy makers and recommendations on similar efforts at the regional scale.

1. Introduction

Elevated concentrations of Nitrogen (N) and Phosphorus (P) contribute to the water quality impairment of many streams and rivers in the United States. In addition to local impairments, these nutrients contribute to eutrophication in downstream lakes, bays and estuaries, and are primarily responsible for hypoxia in the Gulf of Mexico (USEPA, 2000, 2007). Under recommendations of the Clean Water Action Plan in 1998, the US Environmental Protection Agency (USEPA) developed a national strategy for establishing water body-specific nutrient criteria for all water bodies (USEPA, 1998) to reduce nutrient concentrations and improve the beneficial ecological uses of surface waters. The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (2008) established a goal to reduce the size of the hypoxic zone in the Gulf of Mexico to 5000 km^2, which has been documented to form on a

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seasonal basis in most years since 1985 (Rabalais et al., 2007; Turner et al., 2008). This will require substantial reductions in nutrient loadings from the Misssissippi/Atchafalaya River basin (MARB) and especially from its most upstream and intensively cultivated region, the 492,000 km^2 Upper Mississippi River Basin (UMRB) and the 528,000 km^2 Ohio-Tennessee River Basin (OTRB), which form the 'Corn Belt' Region of the US extended across 12 States of the Midwest. The level of nutrient reduction from these basins required to achieve the goal of 5000 km^2 hypoxic zone has been estimated at 45% (EPA-SAB, 2007).

Agricultural nonpoint source pollution is the main source of N and P discharged to the UMRB and OTRB stream systems, primarily via fertilizer and/or livestock manure applied to cropland or pasture, although point sources are also important nutrient sources. Specifically, these two basins contribute about 82% of the nitrate–N (NO_3–N), 69% of the total Kjehdahl nitrogen (TKN), and 58% of the total P fluxes to the Gulf despite representing only 31% of the total drainage area (EPA-SAB, 2007). On the other hand, the UMRB and OTRB areas are the primary agricultural landscapes of the country with substantial importance for both the regional and national economies. Apart from the required food and feed production from the growing of corn and soybean, there is an ambitious target of biofuel production to be achieved by 2022, either as grain-based ethanol or from cellulosic feedstock, which will further increase the economic importance of the region (USDA Biofuels Strategic Production Report, 2010). Obviously, within this large area, trade-offs between the interdependent goals of food and feed production, sustainable biofuel production, and improved water quality will have significant implications for commodity groups, individual producers and other stakeholders in the region. These implications should also be investigated by considering possible future changes in climate, which will influence management planning.

Within this context, the appropriate use of process-based ecohydrological models for the evaluation of agricultural management options with socio-economic and environmental impacts under climate variability is crucial. A great advantage of such models is their distributed nature, which is considered indispensable in identifying and prioritizing cost-effective management actions toward multiple targets. In order to reliably address what-if scenarios, however, extensive calibration of these models using measured data at multiple locations is necessary. The development and validation of these models become even more challenging at the regional scale, because of the considerably large input data and computational resource requirements. Although calibration and validation guidelines are increasingly developed to facilitate the use of such models (Moriasi et al., 2012), manual calibration of a distributed watershed model such as the Soil and Water Assessment Tool (SWAT) watershed-scale water quality model (Arnold et al., 1998; Williams et al., 2008), is difficult and time consuming for large-scale applications (Arnold et al., 2012).

SWAT has proven to be an effective tool for evaluating agricultural management simulations for complex landscapes and varying climate regimes (e.g., see Gassman et al., 2007, 2014; Douglas-Mankin et al., 2010; Tuppad et al., 2011). To date, SWAT has already been applied for several studies in the UMRB and to a lesser extent in the OTRB, including studies describing model performance evaluations and calibration/validation approaches (Kannan et al., 2008; Srinivasan et al., 2010; Santhi et al., 2008, 2014), climate change effects on hydrology and water quality (Jha et al., 2006, 2013; Wu et al., 2012a) and evaluation of land use, best management practice (BMP) scenarios and conservation practices (Rabotyagov et al., 2010; Santhi et al., 2014; Secchi et al., 2011; Demissie et al., 2012; Wang et al., 2011; Wu et al., 2012b; White et al., 2014). To maintain modeling efficiency at the regional scale and the feasibility of manual calibration in particular, the delineation of existing UMRB and OTRB SWAT models into subwatersheds was based on 8-digit Hydrologic Unit Codes (HUCs) or "8-digit watersheds" (USGS, 2012, 2014a). Given the relatively large average area of an 8-digit watershed in these regions (~3600 km^2) and the fact that only one set of climate data can be input per subwatershed in SWAT, such an approach needs climate adjustments for each 8-digit watershed, resulting in data inaccuracies with respect to climate spatial variability, the major driving force of hydrological processes, water balance and subsequently water quality estimations across the basin. On the other hand, the use of 12-digit subwatersheds (USGS, 2012, 2014a), which average roughly about 85 km^2 in area (each 8-digit watershed is comprised of about 40–45 12-digit watersheds – see Fig. 1 as an example) provides the opportunity to more directly and accurately capture meteorological inputs from the thousands of available stations in the Corn Belt, which could not be used in the model with a coarse 8-digit delineation. Any adjustments of the available climate data to derive the 'average' climate of a virtual station for a particular 8-digit watershed in this case is not as representative as using directly all the available information across the basin and assigning it to smaller areas of increased hydrologic homogeneity. A great advantage of using a large number of smaller subbasins in a SWAT project is also the consideration of topography in the calculations. SWAT calculates a single slope for each subbasin based on the elevation layer inserted at the beginning of a model's setup and uses this value by default for all HRUs within each subbasin. By using the more detailed 12-digit watershed delineation, slope differentiation is more accurate across the basin with positive expected impact on the estimation of water balance components (e.g. surface and lateral flow), erosion calculation and water quality predictions. Moreover, such a 12-digit delineation approach in this large modeling system would obviously allow in the future for increased flexibility in defining reservoirs, wetlands and other hydrologic elements close to their real locations, improved representation of river water routing processes at a small time step (daily), more accurate targeting of practices across the landscape as well as linkages to climate data and downscaled Global Climate Model (GCM) projections across a dense grid in a given SWAT simulation.

To be able to address all these issues in an extensive future scenario research in the Corn Belt, we have constructed a SWAT-based modeling system using 12-digit subwatersheds, which can estimate nutrient loads from the UMRB and OTRB regions. The system has already provided the flexibility to analyse a wide range of alternative cropping, management strategies, and/or future climate change scenarios and their impacts on water quality and the hypoxic zone in the northern Gulf of Mexico (Panagopoulos et al., 2014; Kling et al., 2014). The objectives of this specific study are:

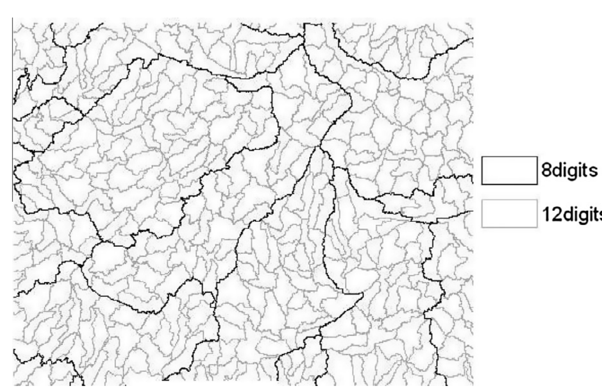

Fig. 1. 8-Digit and 12-digit Hydrologic Unit Codes (HUCs) or watersheds within a small part of the study region within the US Corn Belt.