EVALUATION OF FLOOD MITIGATION STRATEGIES IN AN AGRICULTURAL WATERSHED IN IOWA USING PHYSICALLY-BASED MODELING

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Abstract

Each one of Iowa’s 99 counties has been impacted by flooding events that exceeded the state’s capacity to respond and that ultimately led to flood-related presidential disaster declarations (FRDD). In the last three decades, the total number of FRDD in Iowa counties has exceeded 900, making flooding one of the most prominent environmental challenges that Iowa faces. Physically-based watershed modeling was used to evaluate the flood reduction benefits expected from both nature-based and structural mitigation strategies. Model baseline conditions were determined using a 15-year continuous simulation. The model was forced with hourly climatological data and simulated streamflow hydrographs were compared against measurements taken at USGS stations. The model was able to reproduce satisfactorily the measured hydrographs as well as seasonal and annual trends. Model baseline parameters were modified to simulate implementation of cover crops and native vegetation (e.g. tall-grass prairie) in the study area. In addition, the watershed model was used to evaluate the flood reduction benefits associated to a system of distributed storage built with ponds located in the watershed’s headwater catchments. This work presents quantifications of changes in watershed’s hydrology as well annual peak flow reductions.

Introduction

Each one of Iowa’s 99 counties has been impacted by flooding events that exceeded the state’s capacity to respond and that ultimately led to flood-related presidential disaster declarations (FRDD). In the last three decades, the total number of FRDD in Iowa counties has exceeded 900, making flooding one of the most prominent environmental challenges that Iowa faces. (Figure 1). In January 2016, the state of Iowa received a $97 million award for the Iowa Watershed Approach project (IWA, https://www.iowawatershedapproach.org/). The grant was part of the U.S. Department of Housing and Urban Development’s (HUD) National Disaster Resilience Competition, which funds cutting-edge projects to address unmet needs from past natural disasters and reduce Americans’ vulnerability to future disasters. The IWA project will accomplish six specific goals: reduce flood risk; improve water quality; increase community flood resilience; engage stakeholders through collaboration, outreach, and education; improve quality of life and health for Iowans, especially for vulnerable populations; and develop a program that is scalable and replicable throughout the Midwest and United States. This project will end in September 2021. The eight watersheds selected to participate in the IWA project are presented in Figure 1.
Within the work of the IWA project, physically-based hydrologic modeling was used to evaluate the flood reduction potential of different land use changes and structural Best Management Practices (BMPs). Model results were used to quantify the potential effects of three different flood mitigation strategies: 1) conversion of 100% of the rowcrop acres to native vegetation, 2) adoption of both no-till and cover crops in 100% of the rowcrop acres, and 3) a distributed storage system built with ponds located in the headwater catchments. This paper presents results of the hydrologic analyses performed in the Upper Iowa River watershed (see watershed in red in Figure 1).

![Flood-related FEMA Disaster Declaration 1988-2016](https://www.fema.gov/)

**Figure 1.** Number of flood-related federally declared disasters in Iowa counties (1988–2016). Data source: https://www.fema.gov/.

**Study Area**

The Upper Iowa River Watershed (UIRW) is located in North-East Iowa and South-East Minnesota. UIRW encompasses approximately 1,000 square miles and it drains into the Mississippi River at the Iowa and Wisconsin border. The watershed boundary falls within seven counties; however, most of the watershed area lies within Allamakee, Winneshiek, Howard Counties. Elevations range from approximately 1,500 feet above sea level to 600 feet above sea level in the downstream portion of the watershed. Land use in the UIRW is mainly agricultural, dominated by cultivated crops (corn/soybeans) at approximately 44.3% of the acreage, followed by grass/pasture at approximately 25.7%. The remaining acreage in the watershed is about 20.5% forest, 5% developed land, 3.7% crops other than corn/soy and 0.4% open water and/or wetlands, per the 2017 USDA/NASS Cropland Data Layer (Figure 2).
Hydrologic Model Description

The modeling activities described in this paper were performed using Generic Hydrologic Overland-Subsurface Toolkit (GHOST) which is a physically-based integrated model recently developed by IIHR-Hydroscience & Engineering. This model considers Iowa’s varied topography, soils, and land use and simulates the hydrologic responses at watersheds over time periods in the order of decades. GHOST is based on the open source hydrologic code MM-pihm (Qu and Duffy 2007, Yu et al. 2013), which fully couples surface and subsurface water systems to predict streamflow and groundwater movement for normal and extreme rainfall and snowmelt events. Figure 3 presents the major hydrologic processes modeled in GHOST. Specific modules were developed at IIHR and incorporated into the code to properly predict water budgets for the long-term simulations required for the large-scale IWA watersheds. Publicly available data on land use, soil type, and surface elevations were used to spatially describe surface and subsurface domains. Stage IV radar rainfall estimates (NCEP/EMC 4KM Gridded Data (GRIB) Stage IV Data) were used as the precipitation input for simulation. Other meteorological data such as air temperature, relative humidity, wind speed, shortwave/longwave radiation and surface pressure were obtained from North American Land Data Assimilation System Phase 2 (NLDAS-2) products. The temporal resolution of all the used forcing data was hourly. The ground surface was discretized using 8,185 triangular elements and the river network captured by the model is made of 1,653 linear segments. A view of the mesh is presented in Figure 4. The same figure shows the approximately 180 points (see red points) at which hourly climate data were available.
Figure 3. Hydrologic processes modeled in GHOST.

Figure 4. Computational mesh and rainfall/climate pixels.
Hydrologic Model Calibration and Validation

Model calibration was carried out for a nine-year period (2002-2010) and during the validation process the model performance was evaluated using measurements taken between 2011 and 2016. Simulated flows were compared against observed flows at two USGS stream-gage stations: Upper Iowa River at Decorah: USGS 05387500 and Upper Iowa River near Dorchester: USGS 05388250 (see Figure 5). For 2002, measured data at Decorah have significant gaps therefore those data were omitted from the analysis presented below.

Figure 5 shows observed and simulated time series for both the calibration and validation periods at Dorchester. Overall, model predictions match the measurements adequately. This figure displays both periods where the simulated values follow measured data closely, and others when they do not. Given that a hydrologic model is a simplified representation of the actual watershed, some level of mismatch between the simulation results and measured data is to be expected. Based on Moriasi et al., (2007) model simulations can be judged as satisfactory if Nash-Sutcliffe efficiency (NSE) > 0.50, Percent bias (PBIAS) ± 25% for streamflow, and the coefficient of determination (R²) values are close to 1. Table 1 presents common metrics used in hydrologic model performance evaluation. The UIRW model results for both the calibration and validation periods display metrics that meet those criteria.

In the UIRW monthly runoff depths display a marked seasonal cycle with the window between April and August showing the highest runoff depths (Figure 6). Model results show a slight tendency to underestimate runoff at Decorah for the wettest months (May-July). This trend is less apparent when making comparison between simulated and observed flow near Dorchester. Figure 6 shows that simulated runoff during the winter and fall is also slightly underestimated by the model. Overall, simulated monthly runoff values match observations closely with values of R²>0.95.

To assess the model ability to predict flood characteristics in the Upper Iowa River simulated and observed annual peak flows were compared at Decorah and near Dorchester (see Figure 7). Model results show no bias and annual peaks are both slightly under-predicted and over-predicted (data on both sides of the one-to-one line).

Table 1. Hydrologic model evaluation metrics for both the calibration and validation periods. Nash-Sutcliffe efficiency (NSE), Percent bias (PBIAS), and coefficient of determination (R²).

<table>
<thead>
<tr>
<th></th>
<th>NSE Cal</th>
<th>NSE Val</th>
<th>PBIAS Cal</th>
<th>PBIAS Val</th>
<th>R² Cal</th>
<th>R² Val</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decorah</td>
<td>0.82</td>
<td>0.81</td>
<td>4.89</td>
<td>8.81</td>
<td>0.90</td>
<td>0.91</td>
</tr>
<tr>
<td>Dorchester</td>
<td>0.77</td>
<td>0.82</td>
<td>-0.40</td>
<td>2.25</td>
<td>0.89</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Scenarios

The GHOST model of the UIRW was used to investigate the potential impacts of alternative flood mitigation strategies in the watershed as well as the consequences of projected increases in heavy downpours in Iowa and the Midwest for the mid and late 21st century described in the latest Climate Science Special report (see Figure 8). The main focus of these scenarios was placed on understanding the impacts of (1) increasing infiltration/transpiration in the watershed and (2) implementing a system of distributed storage projects (ponds) across the landscape. In this section, we examine two different alternatives to reduce runoff through land use changes and soil quality improvements. One hypothetical land use change would be the conversion of row crop agriculture back to native tall-grass prairie. Another possible land use change would be improvements to agricultural conditions that would result from planting cover crops during the dormant season as well as adoption of no-till in 100% of the rowcrop acres. These are hypothetical examples and are only meant to illustrate the potential effects on flood reduction. The examples are also not project proposals; they are either economically undesirable or not practically feasible. Still, these hypothetical examples provide valuable benchmarks on the limits of flood reduction benefits that are physically possible with broad-scale land cover changes. Modifications to baseline model parameters to represent land use changes (e.g., native vegetation and cover crops/no-till) were based on information reported by several studies: Baschle, (2017); Mohamoud, (1991); VanLoocke et al., (2012); Kang et al. (2003); Baron et al. (1993), Bharati et al. (2002); Yimam et al. (2015), and Cronshay, (1986).
Figure 6. Observed and simulated average monthly runoff depth (in inches) for the Upper Iowa River Watershed. Results are shown for both the calibration and validation periods. Top: Decorah (USGS 05387500) and bottom: Dorchester (USGS 05388250).

Figure 7. Simulated versus observed annual maximum peak daily discharges (cfs). Top: Decorah (USGS 05387500) and bottom: Dorchester (USGS 05388250).
Increased Precipitation and Index Points

A simple approach was followed to generate forcing data for simulations with increased precipitation (IP). Daily rainfall accumulations for each one of the rainfall pixels (see Figure 4) were calculated using observed hourly data from 2002 to 2016. The days were ranked and hourly precipitation values for the wettest 5% of the non-zero-rain days were increased by 10%. No other meteorological data were modified for the IP simulations. For the 15 years of available data, precipitation for approximately 95 days was altered.

The hydrologic model made predictions at approximately 1,600 locations along the stream network. Six index points were selected to present the results of different watershed scenarios (Table 2). These points were chosen based on several criteria including the location of the existing USGS gauging stations, areas with high risk potential and/or proximity to a community, and to demonstrate the model results at different spatial scales.

<table>
<thead>
<tr>
<th>Index Point</th>
<th>Represents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Upper Iowa River at Lime Springs</td>
</tr>
<tr>
<td>2</td>
<td>Upper Iowa River at Kendallville</td>
</tr>
<tr>
<td>3</td>
<td>Upper Iowa River into Decorah</td>
</tr>
<tr>
<td>4</td>
<td>Near outlet of Trout Creek (HUC 12 near Decorah/Freeport)</td>
</tr>
<tr>
<td>5</td>
<td>Canoe Creek (HUC10)</td>
</tr>
<tr>
<td>6</td>
<td>Upper Iowa River at Dorchester</td>
</tr>
</tbody>
</table>
Mitigating the Effects of High Runoff with Native Vegetation

One of the proposed scenarios was to replace all current rowcrop acres with native tall-grass prairie. The simulation results from this scenario are not intended to be a recommend flood mitigation strategy; rather these results are meant to provide the theoretical maximum of the flood reduction benefits that can be expected from land use changes.

A flood frequency analysis was conducted at the index points for three different simulations: baseline, native vegetation, and native vegetation plus increased precipitation. Figure 10 shows the 15 annual maximum peak discharges and a sample estimate of the exceedance probability. Results show that for all the 15 years and under both historic and increased precipitation conditions, the adoption of native vegetation significantly reduces peak discharges at all six locations. We mapped average peak reductions at the chosen index points in Figure 9.

In each one of the panels in Figure 10, the average peak flow reduction is reported for both Baseline vs. Native Vegetation and Baseline vs. Native Vegetation + IP. Peak flow reduction along the Upper Iowa River mainstem (points 1, 2, 3, and 6) decreases as one moves downstream. The highest average peak flow reductions were found at the index point 1 and the lowest at point 6. Under historic precipitation conditions, the average peak flow reduction in the Upper Iowa River at Decorah (index point 3) is 46% whereas in the IP simulations is 33%.

The transformation of rainfall into runoff is known to be a highly non-linear process and therefore increases in precipitation volumes by a given percentage are not expected to result in similar increases in peak flow magnitudes. In other words, a 10% increase in heavy precipitation does not necessarily create floods with 10% larger peaks. Model predictions show that for the most severe floods (see Figure 10, exceedance probabilities < 20%, scenario vs. scenario + IP), increases in peak discharges due to increases in heavy precipitation are up to approximately 40%.

Mitigating the Effects of High Runoff with Cover Crops/Soil Health/No-Till

The purpose of this hypothetical scenario is to investigate the impact of improved agricultural management practices could have on reducing flood peak discharges throughout the watershed. Planting cover crops across all agricultural areas in the watershed during the dormant (winter) season is hypothesized to lower the runoff potential of these same areas during the growing season (spring and summer) due to increased soil health and fertility. This scenario does not represent the conversion of the existing agricultural landscape to cover crops. Rather, the existing agricultural landscape is kept intact, but its runoff potential during the growing season has been reduced by planting cover crops in all rowcrop acres.

Based on the model results, cover crops/no-till practices reduce peak discharges for all the years at all index points when using measured precipitation data (Figure 11, green circles below the blue squares). This is largely true for the model results of the simulations with cover crops/no-till plus increased precipitation. However, at all index points the maximum annual peak discharge values for the simulations with increased precipitation is larger than those of the baseline condition (black circles above the blue squares). The largest and the smallest average peak flow reductions were found at points 1 and 6, respectively.
For this analysis, 735 ponds were simulated in the UIRW (Figure 12). A “typical” pond was developed for use for the Upper Iowa River Watershed using the existing data on farm ponds in Iowa and NRCS Technical References as guidance. The geometry of this typical pond consists of a 6-inch pipe outlet as the principal spillway with a 10-foot wide emergency spillway set at an elevation above the pipe inlet to provide a flood storage of 20 acres-feet. Site topography will actually dictate the placement of the emergency spillway and the potential dam height. The stage-storage relationship of a pond also depends on local topography and is highly variable from site to site. There certainly are opportunities to design and construct ponds at locations in subbasins that have not been used in this analysis. Furthermore, some of the locations selected for ponds may be far from ideal. Therefore flood reductions presented below do not represent the theoretical maximum of the flood reduction benefits that can be expected from construction of ponds throughout the watershed.
Figure 10. Sample probability distribution of annual maximum peak discharges for the baseline, native vegetation, and native vegetation plus increased precipitation simulations. Results are shown at the six index points displayed in Figure 9. Baseline corresponds with the calibrated model.
Figure 11. Sample probability distribution of annual maximum peak discharges for the baseline, cover crops/no-till, and cover crops/no-till plus increased precipitation simulations. Results are shown at the six index points displayed in Figure 9. Baseline corresponds with the calibrated model.
Information on annual peak discharge reduction is presented in Table 3 and Figures 13. The 735 ponds result in average peak flow reductions at all index points, under historic precipitation conditions, that range between 5% and 11%. However, these reductions are smaller than those of the cover crops/no-till and native vegetation scenarios. As expected, reductions for the index points along the Upper Iowa River mainstem decrease in the downstream direction (Index Points 1, 2, 3, and 6).

Simulation results with increased precipitation conditions show no positive average peak flow reductions at any of the index points (Table 3). In other words, on average the ponds are insufficient to keep the peak flows below the baseline conditions (under IP conditions). However, for the highest annual streamflow peaks the model predicts a lower peak flow value (under increased precipitation conditions with the ponds) at all points except at index point 4 (Figure 13). It is worth mentioning that for index point 4 the ratio between the total drainage area and the area regulated by the ponds (Table 3, DAR/DA) is just 0.04 and a higher level of protection can be expected by increasing the number of ponds upstream from this point.

**Table 3.** Average peak flow reduction at the index points.

<table>
<thead>
<tr>
<th>Index Point</th>
<th>Drainage Area (DA) (mi²)</th>
<th>Number of Ponds</th>
<th>Drainage Area Regulated (DAR) (mi²)</th>
<th>DAR/DA</th>
<th>Avg. Peak Reduction (%)</th>
<th>Avg. Peak Reduction under IP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>182</td>
<td>249</td>
<td>74</td>
<td>0.41</td>
<td>10</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>281</td>
<td>353</td>
<td>102</td>
<td>0.36</td>
<td>9</td>
<td>-3</td>
</tr>
<tr>
<td>3</td>
<td>490</td>
<td>549</td>
<td>157</td>
<td>0.32</td>
<td>7</td>
<td>-6</td>
</tr>
<tr>
<td>4</td>
<td>38</td>
<td>6</td>
<td>1</td>
<td>0.04</td>
<td>5</td>
<td>-21</td>
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<td>6</td>
<td>767</td>
<td>651</td>
<td>193</td>
<td>0.25</td>
<td>5</td>
<td>-7</td>
</tr>
</tbody>
</table>
Figure 13. Sample probability distribution of annual maximum peak discharges for the baseline, distributed storage, and distributed storage plus increased precipitation simulations. Results are shown at the six index points displayed in Figure 9. Baseline corresponds with the calibrated model.
Summary and Conclusions

We used physically-based hydrologic modeling to evaluate the flood reduction benefits of three different flood mitigation strategies in an agricultural watershed. Hydrologic modeling results presented in this paper can be used to perform loss-avoidance and cost-benefit analyses to assist watershed stakeholders and policy makers in making decisions to reduce flood damages. Furthermore, our modeling results highlight the flood reduction benefits of maintaining a vegetation cover all year round and more generally the potential of implementing nature-based flood protection systems.

References


