Physically-Based Hydrologic Modeling of Clear Creek Watershed

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Abstract

The Clear Creek Watershed covers about 270 km² with three headwater streams converging in Iowa Township. The watershed comprises 60% of agriculture, 23% pasture and other grasslands, 10% forest, and 7% urban areas. The hydrologic dynamic response of the Clear Creek Watershed was numerically simulated with the Generic Hydrologic Overland-Subsurface Toolkit (GHOST). GHOST includes specific models to properly predict water budgets for multi-year simulations in large basins. The numerical model takes into account interception, throughfall, infiltration, recharge, evapotranspiration, and infiltration, enabling discharge through the surface or subsurface into downstream water bodies or aquifers. The model considers the spatial distribution of land use and soil type. The model was calibrated and validated using 15 years of hourly climatological data with 4-km spatial resolution. Model results indicate that the model capture the watershed’s hydrology and can be used to evaluate potential flood mitigation strategies.

Introduction

Devastating flooding caused by heavy rains brought economic, social, and environmental impacts in many watersheds across Iowa, USA. From 2011–2013, Iowa suffered eight Presidential Disaster Declarations, encompassing more than 70% of the state.

In Iowa’s flood history, the events of 1993 and 2008 are on an entirely different scale than the others. These two events stand out from the rest when looking at the extent of the area impacted, recovery costs, precipitation amounts, and stream flows recorded (Bradley 2010; Smith et al., 2013). Figure 1 shows the extent of the flooding during the flood events of 1993 and 2008. In both years, flooding impacted the Clear Creek watersheds.

A hydrological model for the Clear Creek watershed was developed to better understand the hydrological response of the watershed and evaluate the potential impact of alternative flood mitigation strategies in the watershed. This paper presents model details of the hydrological model GHOST as well as calibration and validation against monitoring data from 2002 to 2017. A new watershed model SRH-W is under development, SRH-W will use several modules of
GHOST but the runoff engine is to be an implicit unstructured polygonal mesh. Efforts to model Clear Creek with SRH-W and preliminary results comparing both codes will be presented and discussed in the conference.

![Map of the region](image)

**Figure 1.** The extent of the flooding during the 1993 and 2008 floods (Bradley, 2010)

## Hydrologic Model

The Generic Hydrologic Overland-Subsurface Toolkit (GHOST) is an integrated model able to represent the hydrologic response at watershed scale over time periods on the order of decades. GHOST is a physically-based model, based on physical laws and empirical correlations, that can be used for a wide range of applications and beyond the range of calibration. The model was developed to simulate watersheds ranging in area from 500 to 1,500 square miles, explicitly resolving Iowa’s varied topography, soils, and land use.

GHOST is based on the open source hydrologic code MM-PIHM (Qu and Duffy 2007, Yu et al. 2013), which was developed to simulate fully coupled surface and subsurface water systems to predict streamflow and groundwater recharge for normal and extreme rainfall and snowmelt events. The watershed is conceptualized in three distinct zones: a surface region and two regions beneath the surface representing the unsaturated soil and groundwater (Kumar et al. 2009). The surface model consists of 2D overland flow and a 1D stream network. Overland flow is modeled using the diffusive wave approximation of 2D St. Venant equations. Channel flow is modeled using a 1D approach to properly capture the channel geometry and effect of flood mitigation structures without local grid refinement along the network. Water movement in the unsaturated zone is assumed to be vertical and the saturated groundwater region is modeled using the 2D Dupuit approximation.
Additional models were developed and incorporated into MM-PIHM to properly predict water budgets for long-term simulations in large-scale watersheds. Model development focused on improving efficiency while guaranteeing mass conservation. Figure 2 shows hydrological processes modeled in GHOST. The model uses meteorological data and vegetation characteristics to compute evaporation and plant transpiration. The form of precipitation, rain or snow, is determined by temperature. At above freezing temperature, accumulated snow melts contributing to net precipitation. The canopy can intercept rain, which then evaporates from the canopy or can reach the ground surface by canopy drip. Water from net precipitation at the ground surface can infiltrate to the unsaturated region or contribute to surface runoff. Infiltrated water can evaporate from the soil surface, be transpired by plants, or drain to the groundwater. Water stored in the groundwater can evaporate or discharge to a stream.

Figure 2. Schematic representation of GHOST
A finite-volume formulation is used to discretize the system of coupled equations. The ground surface of the watershed is discretized using a Delaunay triangulation and the subsurface is represented by vertical projection of each triangular element. Figure 3 shows variables and fluxes in the control volume $i$.

![Figure 3. Numerical discretization](image)

The resulting ordinary differential equation system is solved with using the library CVODE of SUNDIALS (SUite of Nonlinear and DIfferential/ALgebraic Equation Solvers) developed by Lawrence Livermore National Laboratory (Hindmarsh & Serban, 2016). The Backward Differentiation Formulas (BDFs) with Newton iterations recommended for stiffs problems are used in GHOST. A scaled preconditioned GMRES (Generalized Minimal Residual method) solver is used for the solution of the linear system within the Newton corrections.

The new watershed scale model SRH-W is an event based physically-based and distributed model for runoff and soil erosion simulation. Application targets include flood prediction and sediment delivery to streams and reservoirs caused by a large precipitation event. The code uses a finite-volume discretization method, explicit and implicit schemes, and diffusive wave routing equation.

**Evapotranspiration**

Interception and evapotranspiration are modeled following Panday and Huyakorn (2004). Available energy is first used to evaporate water intercepted by plant canopy and then surface water. If not depleted, available energy is used for soil evaporation and plant evapotranspiration.
Coupling between Regions

The driving force required for net mass flux from a 2D surface element $i$ to the subsurface is modeled as:

$$\Delta h_i = [y_i^{\text{surf}} - \max(y_i^t - D_i^{\text{soil}}, 0)] - \psi_i$$

(1)

Where $y_i^{\text{surf}}$ is the water depth at the ground surface, $y_i^t$ the total head in the soil, $D_i^{\text{soil}}$ is the soil depth and $\psi_i$ represents capillary head, which can be modeled following van Genuchten (1980).

Mass flux from the surface to the unsaturated region is modeled as:

$$q_i^{\text{surf-uns}} = \begin{cases} 
\frac{\zeta_i^{\text{surf}} \Gamma_i}{y_i^t - y_i^{\text{uns}}} & \text{if } \Delta h_i > 0 \text{ (infiltration)} \\
\frac{y_i^{\text{uns}}}{y_i^t} \Gamma_i & \text{if } |y_i^{\text{uns}}| < |\Gamma_i| \\
\Gamma_i & \text{if } |y_i^{\text{uns}}| > |\Gamma_i| 
\end{cases}$$

(2)

where $\Gamma_i = \frac{k_i^v}{l_i^{\text{exch}}} \Delta h_i (1 + \delta_{ik} f_{ik})$ is the maximum mass flux, with $k_i^v$ the vertical hydraulic conductivity and $l_i^{\text{exch}}$ the coupling length. $f_{ik}$ takes into account the area occupied by the channel and $\delta_{ik} = \begin{cases} 1 & \text{if stream } k \text{ contiguos to element } i \\
0 & \text{otherwise} \end{cases}$

$\zeta_i^{\text{surf}}$ is a sigmoid function to reduce infiltration when ponded water is comparable to the depression storage. The model assumes preferential exfiltration from the unsaturated soil if water is available at that region. If the rate of water depletion in the unsaturated region is smaller than the maximum flux, exfiltration from the groundwater occurs and the flux from the unsaturated zone is proportional to the ratio of head in that region to total head in the soil.

Exfiltration or flux from the groundwater to the surface is:

$$q_i^{\text{GW-surf}} = -\min(\Gamma_i - q_i^{\text{surf-uns}}, 0)$$

(3)

Recharge or mass flux from the unsaturated region to groundwater is modeled as:

$$q_i^{\text{uns-GW}} = \max\left(\frac{s_{mi}^n}{s_{mi}^n + s_{ni}^m} q_i^{\text{surf-uns}}, 0\right)$$

(4)

Following Panday and Huyakorn (2004), the flux from the overland element $i$ to the stream segment $k$ is modeled using the equation for a broad crested weir:
\[
q_{ik}^{surf-chan} = \begin{cases}
2 |q| L_{ik} \left( Y_{ups} - Y_{down} \right)^{3/2} \\
\frac{C_i}{3} \sqrt{2|q| L_{ik}} \left( Y_{ups} - Y_{down} \right)^{3/2} \\
\frac{C_i}{3} \left( Y_{ups} e_x + z_{ele} e_z \right) - \left( Y_{chan} e_x + z_{chan} e_z \right) \\
\frac{C_i}{3} \left( Y_{chan} e_x + z_{chan} e_z \right) - \left( Y_{ups} e_x + z_{ele} e_z \right) \\
\frac{C_i}{3} \sqrt{2|q| L_{ik}} \left( Y_{ups} - Y_{down} \right)^{1/2} \\
\frac{C_i}{3} \left( Y_{ups} e_x + z_{ele} e_z \right) - \left( Y_{chan} e_x + z_{chan} e_z \right) \\
\frac{C_i}{3} \left( Y_{chan} e_x + z_{chan} e_z \right) - \left( Y_{ups} e_x + z_{ele} e_z \right) \\
\frac{C_i}{3} \sqrt{2|q| L_{ik}} \left( Y_{ups} - Y_{down} \right)^{1/2} \\
\frac{C_i}{3} \left( Y_{ups} e_x + z_{ele} e_z \right) - \left( Y_{chan} e_x + z_{chan} e_z \right) \\
\frac{C_i}{3} \left( Y_{chan} e_x + z_{chan} e_z \right) - \left( Y_{ups} e_x + z_{ele} e_z \right) \\
\end{cases}
\]

where upstream and downstream heads are:

\[
\begin{align*}
Y_{ups} &= y_{surf} + z_{elem}, \quad Y_{down} = y_{chan} + z_{chan} \\
Y_{ups} &= y_{chan} + z_{chan}, \quad Y_{down} = y_{surf} + z_{elem}
\end{align*}
\]

It is assumed that \( q_{ik}^{surf-chan} = 0 \) if \( Y_{ups} < Y_{weir} \). Figure 4 shows variable definition. \( Y_{weir} = Z_{i,weir} + z_{i,elem} \) is the weir head with weir coefficient and weir elevation, \( C_i \) and \( Z_{i,weir} \), model parameters.

**Figure 4.** Schematic representation of coupling between 2D surface elements and channel. (a) and (c) free-flow conditions and (b) and (d) submerged-flow conditions.
Clear Creek Watershed

Hydrology

The Clear Creek Watershed (Figure 5), as defined by the boundary of ten-digit Hydrologic Unit Code (HUC10) 0708020904, is located in East-Central Iowa and encompasses approximately 104 square miles (mi²). Clear Creek flows west to east into the Iowa River at Coralville, Iowa. The Clear Creek Watershed boundary falls within two counties; Iowa and Johnson counties. For the region of East-Central Iowa, the annual precipitation ranges from roughly 21 to 55 inches. About 70% of the annual precipitation falls as rain during the months of April - September. During this period, thunderstorms capable of producing torrential rains are possible with the peak frequency of such storms occurring in June. The region has experienced increased variability in annual precipitation since 1975, along with a general increase in the amount of spring rainfall. Analyses of streamflow records at the USGS stations near Oxford and Coralville show that on an annual basis approximately 30% of the precipitation is transformed into streamflow and 60% of the streamflow is derived from groundwater.

Figure 5. The Clear Creek Watershed

Topography

Figure 6 shows the topography of the Clear Creek Watershed. Elevations range from approximately 900 feet above sea level in the upstream and western part of the watershed to 500 feet above sea level in the downstream portion of the watershed in Coralville.
Forcing Data

Stage IV radar rainfall estimates were used as the precipitation input for the simulations. The Stage IV data set is produced by the National Center for Environmental Prediction by taking radar rainfall estimates produced by the 12 National Weather Service (NWS) River Forecast Centers across the Continental United States and combining them into a nationwide 4 km x 4 km (Figure 7) gridded hourly precipitation estimate data set. These data are available from January 1, 2002 – Current. Use of radar rainfall estimates provides increased accuracy of the spatial and time distribution of precipitation over the watershed and Stage IV estimates provide a level of manual quality control performed by the NWS that incorporates available rain gage measurements into the rainfall estimates. 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 forcing data used was hourly.
**Geology and Soils**

The Clear Creek Watershed is located almost entirely within the Southern Iowa Drift Plain landform region. There is a very small area in the northeastern portion of the watershed that is part of the Iowan Surface landform region. The characteristics of each landform region have an influence on the rainfall-runoff potential and hydrologic properties of the watershed.

Soils are classified into four Hydrologic Soil Groups (HSG) by the Natural Resources Conservation Service (NRCS) based on the soil’s runoff potential. The four HSG’s are A, B, C, and D, where A-type soils have the lowest runoff potential and D-type have the highest. In addition, there are dual code soil classes A/D, B/D, and C/D that are assigned to certain wet soils. The soil distribution of the Clear Creek Watershed per digital soils data (SSURGO) available from the USDA-NRCS Web Soil Survey (WWS) is shown in Figure 8. Viewing the soil distribution at this map scale is difficult, but the map does illustrate the relative consistency of the HSG on this portion of the Southern Iowa Drift Plain landform region. The Clear Creek Watershed consists primarily of HSG B type soils (76.3%), which have a moderate runoff potential when saturated. Relatively small components of type B/D (16.3%) soils are present, occurring in the adjacent valleys. The remaining classes each comprise less than 4% of the total.

![Figure 8. Distribution of Hydrologic Soil Groups in the Clear Creek Watershed](image)

**Land Use**

Land use in the Clear Creek Watershed is predominantly agricultural, dominated by cultivated crops (corn/soybeans) at approximately 55% of the acreage, followed by grass/pasture at approximately 20% (Figure 9). The remaining acreage in the watershed is about 14% developed land, concentrated in the downstream part of the watershed, 7% forest, 3% crops other than corn/soy and 1% open water and/or wetlands, per the 2017 USDA/NASS Cropland Data Layer. For each land use, time series of crop coefficient, vegetation height and root depth are provided to compute actual plant evapotranspiration. Please refer to Krasowski (2019) for references on these model parameters.
Instrumentation and Field Data

The Clear Creek Watershed has instrumentation installed to collect and record stream stage, discharge, and precipitation. There are two United States Geological Survey (USGS) streamflow gages and nine IFC stream stage sensors located within the watershed. There are also seven Rain Gage/Soil Moisture Sensors owned by IFC (Figure 10).
Model Calibration and Validation

Model calibration was carried out for an eight-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 streamgage stations: near Coralville: USGS 05454300, and near Oxford: USGS 05454220.

Figures 11 and 12 show the daily flow time series for both the calibration and validation periods. Overall, model predictions match well the measurements. These figures display both periods where the simulated values follow closely measured values, and others when it does not. Table 1 presents common metrics used in hydrologic model performance evaluation. 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 ($R^2$) values are close to 1. Clear Creek model results for both the calibration and validation periods display metrics that meet those criteria.

<table>
<thead>
<tr>
<th></th>
<th>NSE</th>
<th>PBIAS</th>
<th>$R^2$</th>
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<td></td>
<td>Cal</td>
<td>Val</td>
<td>Cal</td>
</tr>
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<td>0.67</td>
<td>3.30</td>
</tr>
<tr>
<td>Oxford</td>
<td>0.63</td>
<td>0.71</td>
<td>3.08</td>
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</tbody>
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Table 1. Hydrologic model evaluation metrics for both the calibration and validation periods.

Figure 11. Observed and simulated daily flow time series. Calibration period. Top: Coralville, Bottom: Oxford
Figure 12. Observed and simulated daily flow time series. Validation period. Top: Coralville, Bottom: Oxford

Figure 13. Observed and simulated average monthly runoff depth (in inches) for Clear Creek watershed. Results are shown for both the calibration and validation periods
To assess the model ability to predict flood characteristics in Clear Creek, simulated and observed annual peak flows were compared at Oxford and Coralville (see Figure 14). For values below 2,500 cfs the model shows no bias and annual peaks are both slightly under-predicted and over-predicted (data on both sides of the one-to-one line). For values above that threshold the model displays a slight tendency to underpredict extreme values with that behavior being more apparent at Oxford than at Coralville.

The flow duration curve shows the percent of the time that a given flow exceeded. For the entire record daily flows were ranked from smallest to largest and then plotted against the probability that a given flow will be equaled or exceeded (Figure 15). The observed and simulated flow duration curves show good agreement for flow values with exceedance probabilities lower than 10% (e.g. flood events).

![Figure 14. Simulated versus observed annual maximum peak daily discharges (cfs) for Clear Creek at Coralville (top) and Oxford (bottom)](image)

**Conclusions**

A physically-based integrated model, based on the open source hydrologic code MM-pihm, was developed to simulate the hydrologic response at watersheds ranging in area from 100 to 2,500 square miles over time periods on the order of decades. Specific models were developed and incorporated into the code to properly predict water budgets for long-term simulations in large-scale watersheds. The model fully couples surface and subsurface domains to predict streamflow as well as groundwater movement for normal and extreme rainfall and snowmelt events. Model calibration and validation were performed using observed flows at two USGS stream-gage stations for an eight-year and two-year periods, respectively.

Clear Creek model results meet the criteria of Nash-Sutcliffe efficiency (NSE) > 0.50, Percent bias (PBIAS) ± 25% for streamflow, and the coefficient of determination (R2) values are close to 1. Annual peak flows were accurately predicted by the model. The model captures the statistic behavior of the historic record and therefore can be a useful tool to make flood impact reductions assessments. Future work involves the evaluation of best management practices
including increasing infiltration with native vegetation and with Cover Crops/Soil Health/No-Till, and distributed storage.

![Graph](image)

**Figure 15.** Daily flow duration curves for Clear Creek at Coralville (top) and Oxford (bottom)

### References


Krasowski, M. 2019. “Continuous Watershed-scale hydrologic modeling of conservation practices for peak flow reduction”. Master’s Thesis. The University of Iowa, Iowa City, IS, USA.


