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객체지향성 프로그래밍 방법을 통한 GIS 연계의 수문모델

Object-oriented Prototype Framework For Tightly Coupled GIS-based Hydrologic Modeling

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Abstract

With the availability of multi-scale hydrologic data in public domain depending on DEM size, there is a need for a modeling framework that is capable of using these data to simulate hydrologic processes at multiple scales for different topographic and climate conditions for distributed hydrologic model. To address this need, an object-oriented approach, called Geographic and Hydrologic Information System Modeling Objects (GHISMO), is developed. Main hydrologic approaches in GHISMO are storage-release for direct runoff and SCS curve number method for infiltration part. This paper presents conceptual and structural framework of storage-release concept including its application to two watersheds will be presented.

Keywords : GIS, object-oriented, GHISMO, storage-release

요 지

DEM (Digital Elevation Model) 크기의 변화에 따라 특정 지역에 많은 규격의 수문 데이터가 존재할 수 있기 때문에, 어느 지역, 어느 기상 데이터에도 작동할 수 있는 수문 모형의 개발이 절실히 필요하게 되었다. 이와 같은 필요성을 설명하기 위해서 객체지향(object-oriented)적인 프로그래밍 기술을 적용한 GHISMO (Geographic and Hydrologic Information System Modeling Objects)라는 수문모형(hydrologic model)을 개발하였다. GHISMO의 가장 핵심적인 수문학적 접근방법은 저류-배출(storage-release)과 지표면 유효 강수량을 구하기 위하여 SCS curve number 방법을 사용한 것이다. 이 연구에서 수문모형의 모의실험 결과를 제공할 것이다.

핵심용어 : GIS, 객체지향, GHISMO, 기저-유출

1. INTRODUCTION

An object-oriented approach to hydrologic modeling increases model flexibility and reduces efforts when adapting the model for a new application, area and algorithm. Rather than replacing old code that already works, the model code can be extended using the object-oriented *characteristic of inheritance* (Kiker et

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al., 2006). An object-oriented approach allows building an incremental model that can be adapted to different watershed conditions (Wang et al., 2005). In spite of many advantages, object- oriented approach has found only limited applications in hydrologic modeling (Band et al., 2000; Kralisch et al., 2005; Liu et al., 2003). Band et al. (2000) describes a spatial object-oriented framework for modeling watershed system to include hydrological and ecosystem fluxes. Chen and Beschta (1999) developed 3-dimensional distributed hydrological model OWLS (the Object Watershed Link Simulation model) for dynamic hydrologic simulation and applied it to the Bear Brook watershed in Maine. Garrote and Becchi (1997) employs object oriented programming techniques with distributed hydrologic models for real-time flood forecasting. Boyer et al. (1996) presents an object-oriented method to simulate a rainfall-discharge relationship using a lumped hydrologic model. Band et al. (2000) introduced an object-oriented approach to simulate hydrologic processes, specifically infiltration excess overland flow. The above applications used object-oriented approach and achieved reasonable results for hydrologic simulations. However, object-oriented approach is not comprehensively discussed in the hydrologic literature and no general guideline exists for implementing them in hydrologic models (Wang et al., 2005 and Kiker et al., 2006).

Computer based models have been used as planning tools in water resources management over the last three decades. The researches in computational water resources are well known and organized. Also, many models are applied to resolve a variety of hydrologic components (Ajward, 1996). It is necessary to combine several of these models (e.g., surface water model, groundwater model and reservoir model) to bring a holistic idea in water resources planning and management. Realization of this approach requires a modular structure in water resources research, and it allows different sub- models to be interconnected depending on the hydrologic system. Another important aspect that must be considered in new development of hydrologic models is creating software elements that can be adapted in future projects. If a modular structure provides reusable components, both regarding development time and reliability of the software produced, it will be an extensive water resources platform (Goodchild et al., 1993). This also will reduce development and maintenance cost for the project.

Running a hydrologic model involves several steps including data collection, pre-processing, parameter estimation, calibration and validation. With the advancement in data collection methods and their representation in digital form, the use of GIS is common for data management, pre-processing and post-analysis in any hydrologic modeling study (Maidment, 1993). While GIS provides a user friendly visual environment for handling hydrologic data, it lacks the computational engine to perform hydrologic simulations. Also, many hydrologic models have limitations of GIS capabilities for data handling, pre-processing and visualization. As a result, several efforts have been made to couple GIS with hydrologic models. These efforts include: (i) the development of GIS tools for Hydrologic Engineering Center's (HEC) Hydrologic modeling system (HMS) and River Analysis System (RAS) models [U.S. Army Corps of Engineers (USACE)]; (ii) the integration of GIS and modeling tools in EPA BASINS analysis environment; (iv) the development of a GIS pre-processor for the Soil Water Assessment Tool (SWAT; 2002); and (v) the development of Watershed Modeling System (WMS; Environmental Modeling Research Laboratory, 1997).

Most previous attempts listed above to link GIS and hydrologic models can be categorized as 'loosely coupled' because both systems act independent of each other, and are only linked through input or output data. For example, GIS tools are used to develop the input file, which is then used to run the hydrologic model. Any changes in the model domain or input attributes during the modeling process are not reflected in the data that are used in creating the model input. With the availability of high resolution geospatial and temporal data, and improved capability of GIS to handle continuous, dynamic datasets including time series, it is now possible to expand the role of GIS beyond that of a pre- or post-processing tool for hydrology to a tightly coupled modeling environment where GIS can perform hydrologic simulations.

If a hydrologic model investigates a new hydrologic component within the frame, an object-oriented approach allows for increased model flexibility without changing the main frame. The model codes that already exist in the old module can be extended by using the inheritance characteristic through an object-oriented approach (Kiker et al., 2006). In recent years, object-oriented based hydrologic models are increasingly used in water resources research, and also the modeling paradigm in water resources is changing to the object-oriented approach (Wang et al., 2005). Creating an incremental watershed model can be made by object-oriented design methods and using an object-oriented programming language (Wang et al., 2005), and this model can be applied to various watershed conditions. Even though object-oriented based hydrologic models have attractive advantages, few object-oriented based hydrologic models exist, and there is no detailed discussion for the principle of object-oriented hydrologic approach (e.g. Band et al., 2000; Kralisch et al., 2005; Liu et al., 2003).

2. Object Orientation in Hydrology

According to Bian (2007), object orientation involves three levels of abstractions: object oriented analysis, object oriented design, and object oriented programming. Object oriented analysis involves conceptual representation of the world including the facts and relationships about a situation. In hydrology, this would mean the conceptual representation of a watershed as a set of objects to include streams and corresponding catchments. Object oriented design uses the conceptual representation from object oriented analysis to create a formal model of objects, their properties, events, and relationships. Object oriented programming involves the implementation of objects and their events to accomplish a certain task. Object orientation relies on two basic principles: encapsulation and composition. Encapsulation considers that the world is composed of objects, and that each object has an identity, properties and behavior. The properties of an object are defined by its attributes (e.g., length, area), and the behavior is represented by methods. While the value of an attribute can define the state of an object, a method can change the state of an object, and that change is referred to as an event. For example, a river object will have properties such as length and slope, methods such as RouteFlow and ComputeStorage, and routing a hydrograph through the river (by using RouteFlow method) is an event.

The principle of composition describes how objects are related through relationships including inheritance, aggregation and association. In object orientation, all objects belong to object classes, and all classes are hierarchal. A sub-class is a kind of this own super-class (through inheritance) and inherits all properties and methods from the super class, but also may have its own additional properties and methods. An object can also be a part of another object (through aggregation), and can simultaneously maintain relationships with other objects (through association). For example, an AlluvialRiver class can be a sub-class of River super class (inheritance), a River class can be a part of RiverNetwork class (aggregation) and River class is related with Watershed class through streamflow (relationship). Past studies that used object orientation for hydrologic modeling include Whittaker et al. (1991) who used object-oriented approach to model infiltration excess overland flow. Boyer et al. (1996) used object oriented approach to develop a lumped rainfall-runoff model. Boyer et al. (1996) used object orientation to combine remote sensing and hydrologic data to develop a forecast model. Garrote and Becchi (1997), Band et al. (2000), and Wang et al. (2005) proposed object oriented frameworks for modeling hydrologic processes at watershed scale. Most of these studies used object orientation to model hydrologic processes using the concepts of inheritance and aggregation. Recently, Richardson et al. (2007) proposed a prototype geographically based object framework for linking hydrologic and biochemical processes in the sub-surface. The process objects, however, were loosely coupled with geographic objects, thus leaving an opportunity for a tightly coupled geographically based object oriented modeling.

Relatively recent advances in GIS have enabled adaption of object orientation in storing and handling geospatial and temporal hydrologic data in research and practice. For example, Arc Hydro (Maidment, 1993) uses an object oriented approach to represent hydrologic environment through feature, object and relationship classes within a geodatabase. In Arc Hydro, a Hydro Edge (stream) is sub class of generic Polyline super class (inheritance), and is a part of HydroNetwork (aggregation). HydroEdge is related to Watershed (which itself is a sub-class of Polygon super class) through a common identifier (HydroID). Thus, ArcHydro uses object orientation to develop a physical representation of hydrography by using GIS objects. Thus, by knowing the HydroID of any geographic feature, it is possible to trace the flow of water by using points, lines, and polygons at multiple scales including at continental scale. The National Hydrography Dataset (NHD) available for the entire United States from the United States Geological Survey (USGS) also uses the object oriented (or geodatabase) design to provide data to its users.

The geodatabase approach to hydrology data overcomes several practical issues which are associated with storing and handling heterogeneous multi-scale data by providing a relational data model. Besides overcoming the data issues, the geodatabase approach provides an opportunity to exploit the potential of object oriented approach to overcome the limitations of scale and parameterization in distributed modeling of hydrologic processes. For example, if a polygon representing a watershed in GIS is treated as a hydrologic object that has some properties (e.g. area and slope) and methods (to compute runoff and route flow), then multiple watersheds can be linked and executed in parallel to scale-up the modeling domain from one single watershed to larger (national or continental) scales. Similarly, the availability of increasing GIS layers to represent soil, landuse and topography at multiple scales, can enable parameterization of hydrologic processes (or watershed methods) through GIS tools, which is not possible with most existing models that do not explicitly work within a GIS environment. This research builds on past studies to create a prototype tightly coupled object oriented GIS based hydrologic model to simulate hydrologic processes using geospatial inputs. The prototype modeling approach presented in this research is developed by using Visual Basic and ArcObjects within ArcGIS, and is referred to as GIS and Hydrologic Information System Modeling Objects (GHISMO). The new conceptual hydrologic model is based on storage-release with grid travel time approach. In addition, the study uses an object-oriented programming approach which can provide useful data handling and model flexibility in hydrologic applications. The remainder of the paper is structured as follows: the storage-release of the new grid-based hydrologic dynamic and its conceptual object (class) are first outlined. The data used in the study are then described. Subsequently, the results obtained are discussed, and a set of conclusions are presented.

3. GHISMO framework

3.1 GHISMO Object Classes

An object-oriented hydrologic model framework is implemented in ArcGIS by developing hydrologic modeling objects as shown in Fig. 1. The hydrologic modeling object framework implements both principles of aggregation (represented with diamond) and inheritance (represented with triangle arrow) as shown in Fig. 1. HydroShed is the highest level class that includes the following six classes: (1) HydroGrid (to process gridded hydrologic information such as topography and rainfall), (2) ParameterGrid (to process gridded hydrologic parameters such as Mannings n), (3) HydroArea (to process vector hydrologic data for lakes and rivers), (4) HydroCatchment (to process vector hydrologic data for catchments or sub-watersheds), (5) HydroLine (to process vector hydrologic data for streams), and (6) HydroTable (to process tabular data). As displayed in Fig. 1, those classes dealing with raster, vector and tables are implemented in this research.

ProcessGrid (to implement hydrologic processes) and TopoGrid (to implement terrain processes) are two

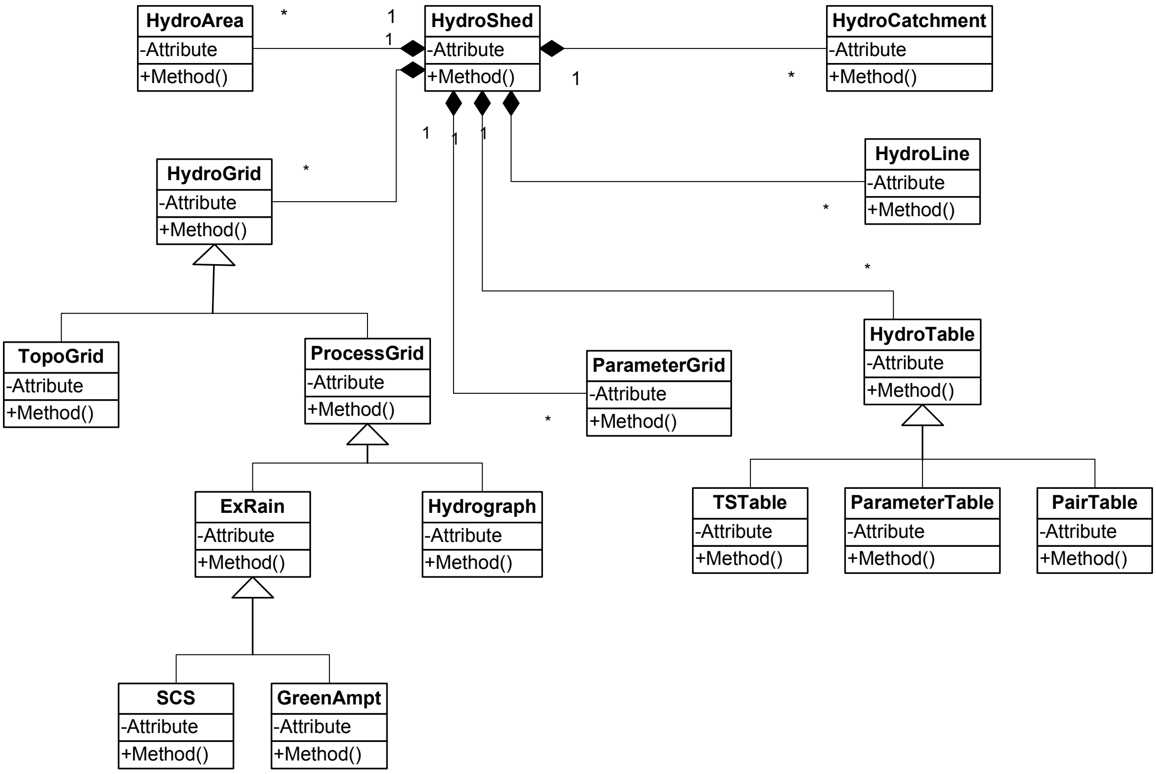


Fig. 1. Object Model Diagram for GIS and Hydrologic Information System Modeling Object (aggregation and inheritance characteristic in object-oriented represents with diamond and arrow, respectively)

sub-classes of the HydroGrid class. ProcessGrid can work on gridded data to implement hydrologic processes to create excess rainfall and runoff hydrograph by implementing specific sub-classes such as ExRain and Hydrograph as shown in Fig. 1. ExRain implements specific techniques such as SCS curve number (through SCS sub-class) and Green-Ampt (through GreenAmpt sub-class) to compute excess rainfall using the rainfall input. Hydrograph class implements specific techniques such as storage release to compute runoff hydrograph from excess rainfall. TopoGrid implements sub-classes to create terrain attributes such as flow direction, flow accumulation, stream network and catchment by using topography data (DEM).

HydroArea can work on flow transformation by implementing specific techniques such as SCS dimensionless unit hydrograph (through SCSUnit sub-class) and Clark unit hydrograph (through ClarkUnit sub-class) for vector data. Also, HydroLine can work on river routing by implementing specific techniques such as Kinematic wave river routing (through Kinematic Wave sub-class) and Muskingum river routing (through Muskingum sub-class).

HydroTable implements three tables: TSTable, ParameterTable and PairTable. TSTable class processes time series table (e.g., rainfall and streamflow time series); ParameterTable processes parameter values linked to geographic features (e.g., Manning's n values for different land cover types); and PairTable processes paired data such as stage-discharge rating curves.

3.2 Updating the GHISMO Framework

An object in the GHISMO allows making a class or a function to handle a variety of hydrologic components. The GHISMO provides flexibility in modular development of the model without changing the basic framework through object-oriented approach, if hydrologic mechanisms need more advanced investigations. For example, this research creates a new object, Radar (to implement different radar rainfall processes), to investigate the effect of different rainfall inputs on hydrologic simula

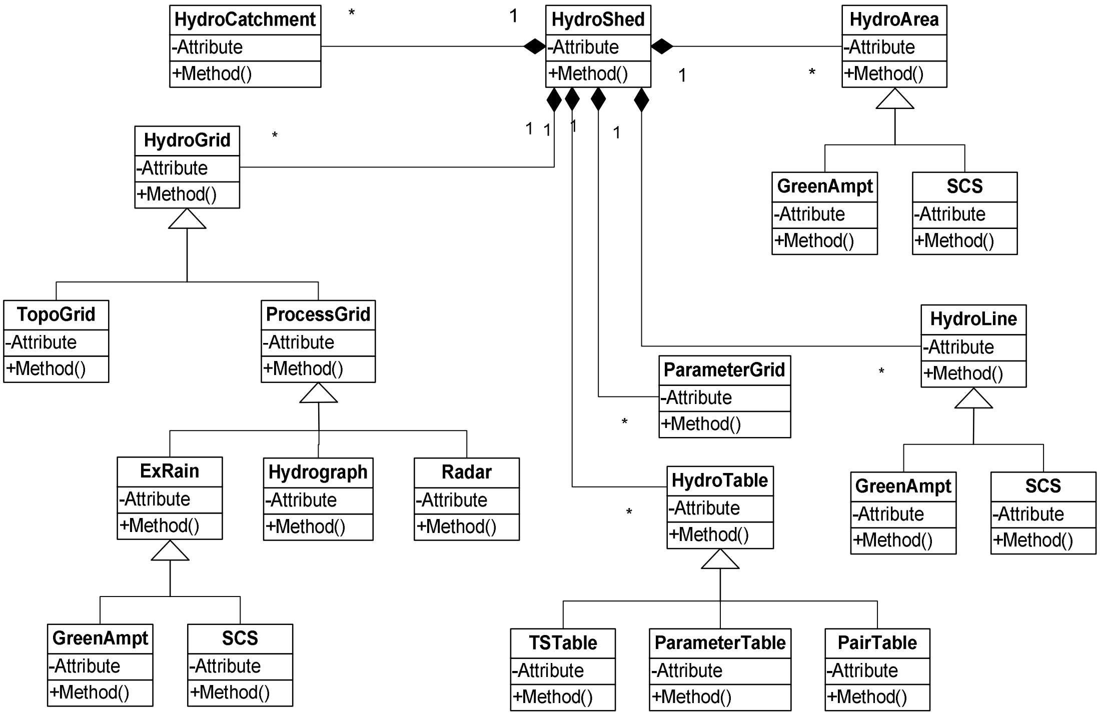


Fig. 2. Update Object Model Diagram for GHISMO: Radar Object

tions as shown in Fig. 2.

The GHISMO allows adding a Radar object that is a part of the new modeling processes without changing its main framework because the GHISMO is designed to open for extension for modification. The greatest benefit in the application of this design approach (open for extension for modification) is reusability and maintainability, and its advantages can overcome a prospective hydrologic modeling issue, such as making a large and complex hydrologic model.

3.3 Travel time in each grid

The storage-release is a distributed conceptual hydrologic model in which grid-based hydrologic processes are assumed kinematic wave approximation as given in Eq. (1).

$$S_f = S_i \tag{1}$$

where s_f is the friction slope and s_i is the slope of the surface each cell at i.

This study proposes travel time in grid can be estimated by combining the kinematic wave approximation with Manning's equation as given in Eqs. (2) and (3).

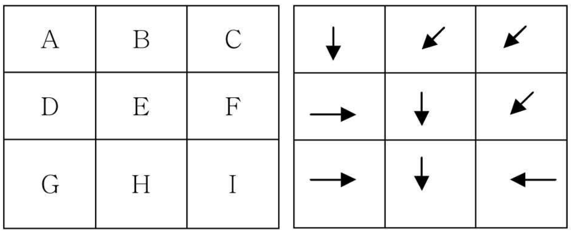
$$Q_{i,t} = \frac{1.49}{n_i} s_i^{0.5} y_{i,t}^{1.67} L_i \tag{2}$$

$$T_{i,t} = \frac{L_i}{V_{i,t}} \tag{3}$$

where $Q_{i,t}$ is the total flow of cell i at given t^{th} time step after considering upstream movements (described in 3.3 section), n_i is the manning coefficient of cell i, $y_{i,t}$ is the flow depth corresponding to $Q_{i,t}$, L_i is the flow length of cell i, $T_{i,t}$ is the travel time of cell i at t, and $V_{i,t}$ $(Q/L_i y_{i,t})$ is the flow velocity of cell i at t^{th} time step.

3.4 Conceptual Storage-Release in Each Grid

Grid-based travel time method in hydrologic modeling can create a direct runoff hydrograph without relying on unit hydrograph during a rainfall event (Du et al., 2009). In grid based travel time method, the travel time from each grid to the watershed outlet is the sum of travel time of grids along a flow path, and the total flow rate is determined by the sum of the volumetric flow rate from all contributing grids at each respective travel time. However, this method cannot account for variations in travel time due to flow from upstream grids



Cell Identifier Flow Direction

Fig. 3. Example Calculation in Existing Grid Based Hydrologic Model

during a rainfall event. Also, this method cannot account for maintaining mass balance because some grids can be counted multiple times for runoff calculation. For example, in Fig. 3, cell A flows to outlet cell H through cells D-E. Similarly, the flow from cell B reaches the outlet through D-E. So if the flow at the outlet from cells A and B is computed as cumulative flow along the flow path, flows from D and E are accounted twice, thus compromising the mass balance. To overcome the above issue, this study proposes a simple conceptual bucket (storage-release) model with grid-based travel time (Kang and Merwade, 2011) as given in Eqs. (4) and (5).

$$Q_{i,t} = q_{i,t} + Q_{i,t-1} - R_{i,t-1} + \sum R_{u,t-1} \tag{4}$$

$$R_{i,t} = \begin{cases} Q_{i,t} & \text{if } T_{i,t} < \Delta t \\ Q_{i,t} \times \dfrac{\Delta t}{T_{i,t}} & \text{if } T_{i,t} > \Delta t \end{cases} \tag{5}$$

where the flow $q_{i,t}$ (m^3/s) is corresponding to excess rainfall intensity of cell i in the tth time step, $R_{i,t}$ (given by Eq. 5) represents the release term from a cell i in the t^{th} time step, and the difference between Q and R represents the storage in the cell. The subscript u in Eq. (4) represents the surrounding upstream cells that are draining to cell I.

4. DATA USED IN THE STUDY

The data collected include topographic information in the form of DEM from United States Geological Survey (USGS). The DEM is projected to Universal Transverse Mercator (UTM) NAD83, Zone 16 for the state of Indiana. Stream paths are delineated for each watershed using DEM and National Hydrography Dataset (NHD). Spatial datasets of landuse type are obtained from the National Land Cover Database (NLCD, 2001). Landuse classifications contained in the NLCD are reclassified to four (Water, Residential, Forest and Agricultural) types. The SSURGO spatial data consisting of county level maps, metadata, and tables, which define the proportionate extent of the component soils and their properties for each map unit, are obtained from NRCS (Natural Resources Conservation Service). Hourly gauge and next generation radar (NEXRAD) *StageIII* rainfall data are obtained from NCDC (National Climatic Data Center) and NWS (National Weather Service), respectively. Description of the study areas is given in Table 1 and its geographical location is shown in Fig. 4.

5. RESULTS AND DISCUSSION

The developed grid-based hydrologic model frame (GHISMO) is evaluated on Pleasant Run Creek and Little Buck Creek watersheds using different meteorological inputs (rain gauge and NEXRAD with isolated two storm events (Table 2). After calibrating model parameters (Manning's n for SCS method, and effective porosity, suction head and initial water content for Green-Ampt method: this study just used SCS method) from gauge simulation, the model is applied to the same event using NEXRAD input. Its simulation results are

Table 1. Description of Pleasant Run and Little Buck Areas

Watershed	Area (km^2)	Land use	Elevation Range (m)	Ave. Slope (%)
Pleasant Run Creek	20	Urban (80%); agricultural (14%); forest (6%)	240-268	0.7
Little Buck Creek	50	Urban (81%); agricultural (12%); forest (7%)	205-274	1.1

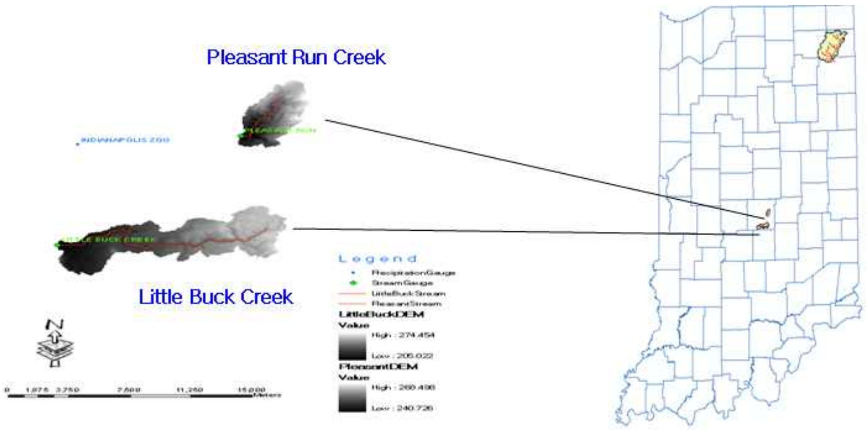


Fig. 4. Geographic Location of Study Area

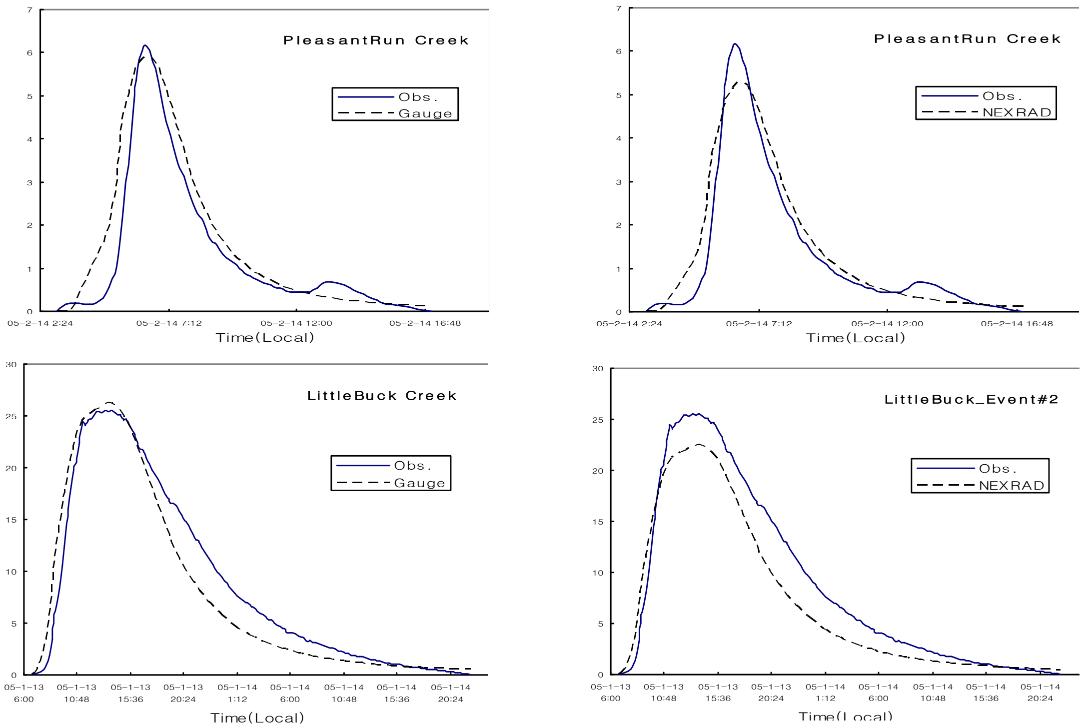


Fig. 5. Model Hydrographs

presented in Fig. 5 which corresponds to quantitative and qualitative analysis in Table 2 and 3. Accuracy of peak flow prediction and time to peak are mainly important elements in event-based hydrologic modeling. Overall accuracy of peak flow and time to peak in this study are within ± 0.5 hours and ± 2.79 m^3/s, respectively (Table 2).

Four performance measures (R^2-square of the pearson product moment correlation coefficient, E_{NS}-Nash Sutcliffe efficiency, RMSE-root mean square error and MAPE-mean absolute percentage error) used in this study and these results are presented in Table 3. Mean error the simulated model in terms of direct runoff at Pleasant Run and Little Buck creek is 0.56 m^3/s *RMSE* and 2.33 m^3/s *RMSE* in simulation with NEXRAD rainfall, respectively. Whereas the error statistics in simulation with gauge rainfall is 0.42 m^3/s *RMSE* at Pleasant Run Creek and 0.91 m^3/s *RMSE* at Little Buck Creek (Table 3). Also, average of R^2 and E_{NS} are obtained 0.89 for Pleasant Run Creek simulation and 0.83 for Little

Table 2. Information of Storm Events and Quantitative Simulation Results

Study Site	Start Date and Time	Time Step (hr)	Difference of Time to Peak (hr) between obs. and model		Difference of Peak Flow (m^3/s) between obs. and model	
			Gauge	NEXRAD	Gauge	NEXRAD
Pleasant Run Creek	05-02-14, 03:00	0.25	+0.25	+0.25	-0.22	-0.85
Little Buck Creek	06-01-13, 06:45	0.25	0.00	-0.50	0.67	-2.79

Table 3. Qualitative Simulation Results

Study Site	Simulation with Gauge rainfall (calibration)				Simulation with NEXRAD rainfall (simulation)			
	R^2	E_{NS}	RMSE (m^3/s)	MAPE (%)	R^2	E_{NS}	RMSE (m^3/s)	MAPE (%)
Pleasant Run Creek	0.92	0.88	0.56	65.48	0.94	0.94	0.42	51.17
Little Buck Creek	0.94	0.92	2.33	49.40	0.89	0.81	3.81	54.83

Buck Creek simulation (Table 3). The simulation results both quantitative and qualitative are promised in hydrologic modeling part inside GHISMO frame.

6. CONCLUSIONS

This research is focused on developing a prototype GIS based tightly coupled object-oriented framework called the GHISMO. This research presents an object-oriented approach using object-oriented design techniques and object-oriented language, Visual Basic, to the description and simulation of a watershed based hydrologic process. The GHISMO allows flexibility and extensibility to investigate future hydrologic issues without changing its main framework because it uses characteristics of inheritance and aggregation through object-oriented hydrologic approach.

Expanding of the GHISMO framework will be essential for robustness of the hydrologic model. For example, linkage between GHISMO and water quality model (e.g., SWAT) can predict effect of storm event on water quality assessment. Similarly, linkage between the GCMs (General Circulation Models), which are the most advanced tools for estimating future climate change, and GHISMO will provide a foundation to assess the impact of climate change on rainfall-runoff prediction. The conceptualization and characterization of this coupling strategy can be extended to a hydrologic management and decision supporting tool such as a real-time flood warning system. If the prototype of the object-oriented hydrologic framework, the GHISMO, is successfully used to develop a coupled open source and platform for seamless hydrologic components, it may lead to change a hydrologic modeling paradigm to object-oriented approach through its flexible modeling schemes.

As the first part of the broader GHISMO framework, this research develops the grid based hydrologic model as modular development for hydrologic modeling. The modeling framework presented in this research is operated within ArcGIS environment such that all the steps from extracting information from geospatial data to running model simulations are executed in an ArcGIS environment. The approach from data to model output within a single environment is attractive from a practical point of view. The hydrologic modeling employs a simple storage-release approach which uses a travel time within each cell to compute how much water is stored or discharged to the watershed outlet at each time step. The travel time within each cell is computed by combining steady state uniform approximation with Manning's equation. Considering that there is whole upstream movement at each time step, the storage-release concept does not need unnecessary calibration approaches. Also, the storage-release concept results show that its approach and application is promising and practical. Even though tested simulations in this study are performed well, additional work is needed to conduct simulation with different size of study areas and grid sizes to be useful for practical applications.

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