A FIELD-MODELING VIRTUAL LABORATORY FOR ENHANCING HYDROLOGIC ENGINEERING EDUCATION

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Abstract

The hydrologic education and research and communities have recognized the need to rejuvenate the observational and modeling components in hydrology and water resources courses especially at the undergraduate levels. The present study takes advantage of recent advances in the areas of in-situ and remote sensing data collection, numerical modeling and scientific visualization to address such recognized needs. A virtual laboratory of a real hydrologic watershed is developed based on integration of field data with numerical simulations of spatiotemporal hydrologic fields. The application provides a virtual-reality experience where students have the ability to walk through or fly over the watershed and visit different areas and monitoring sites. Users have visual tools that will provide them with information about where they are in the watershed, the interesting characteristics of the area of interest, available instruments to perform measurements at that site, and feedback about the measurements taken. An open source scalable interactive visualization environment representing the entire watershed is developed. At its most affordable level, the virtual laboratory will run on a laptop or a graphics workstation with a game-level graphics accelerator and, at its most advanced level, will run in immersive visualization environment. Several virtual learning modules are developed and integrated into the virtual system such as: field and data investigations, effect of soil types and properties on runoff generation, and testing various land-change scenarios.

1. Introduction

Future engineers are likely to face hydro-environmental problems that deal with large-scale and multi-disciplinary issues such as impact of societal activities on quality of streams and water bodies, effects of land-use and climate changes, prediction of extreme events and protection against flooding threats to human life and infrastructure, among others. Therefore, more emphasis needs to be dedicated in the hydrologic and water resources engineering education towards better understanding of basic hydrologic processes, learning from field data and new observation systems, and using simulation models to improve understanding and ability to analyze hydrologic systems and predict their response to natural and human-induced effects. These issues have been highlighted in numerous national and international reports [1-2], which emphasized a pressing need for improving existing undergraduate hydrology and water resources curriculum. Improvements have been recommended in two areas in particular: observations and modeling.

The lack of field and data experience has profound consequences on the hydrology education process, especially at the undergraduate level. Deficiencies in field components will likely lead to adverse effects on the skills of graduating students. For example, students will lack appreciation of spatial and temporal variability of hydrologic processes and will lack the ability to develop self-learning skills and intuitive understanding. An important supplement to the educational power of real field data is the use of computer simulation models [3]. The use of such models have multiple of benefits from a hydrologic educational point of view. Computer simulation models provide a user-friendly, interactive environment for hypothesis. For example, students and instructors can use simulation models to test scenarios of land-change effects, flooding impacts with different storm cases. The use of these models also compensate for inherent limitations of field data which are related to sensors limited spatial sampling density and coverage. However, it is well recognized that all hydrologic models, regardless of their degree of complexity, are subject to certain limitations caused by model assumptions and simplifications and lack of parameter identification, among others. Given the complementary benefits of both field data and modeling techniques, it is natural that educators should focus on combining these resources for improving hydrology and water resources education.

Hydrology is usually taught in a single course in most engineering programs where instructors do not have enough time to teach modeling software or expose students to field instruments. Therefore, innovative educational approaches need to be developed to address these challenges. Interactive visualization and virtual reality methods that are based on the principles of active engagement and discovery [4] can enhance learning by exploiting the visual senses of students and thus engaging their interests [5]. For example, techniques based on Virtual Reality Modeling Language (VRML) [6-7] were used to develop an environmental virtual field soil-topography laboratory tools and introduce concepts of numerical ground-water modeling into undergraduate hydrogeology. Despite the increasing usages of visualization and virtual reality in geosciences education [8], the authors are not aware of particular applications that focus on hydrologic rainfall-runoff processes and their data and modeling aspects. The objective of the current paper is to describe the conceptual design and development of an innovative highly-visual virtual reality educational laboratory that integrates hydrologic field observations and numerical in a real watershed. The laboratory can run on a laptop or a desktop computer with a game-level graphics accelerator and, but can also run in a fully immersive visualization environment. The paper is organized as follows. In the next section, an overview of the overall conceptual design of the virtual system is provided. The following sections provide a detailed description of the field data and hydrologic simulations integrated into the system. The visualization and software techniques used to build the virtual laboratory are then described. A set of classroom applications and learning modules are introduced along with students' activities and assignments. The paper closes with a summary and conclusions section.

2. Overall Design of the Virtual Educational Laboratory

As a framework for integrating the software development and research efforts, the development of the virtual hydrologic laboratory is based on the design-based research paradigm which emphasizes the design of innovative learning environments based on theory and empirical educational research through an iterative process of design, implementation, analysis, and redesign. The purpose of this iterative process is not only to enhance the particular intervention being investigated but to also develop theories to account for the impact of the intervention and to inform the design of other innovations. This emerging methodology has been used to inform the design and investigate the impact of innovative educational programs [9]. Figure (1) shows a schematic representation of the virtual hydrologic system and its different components.

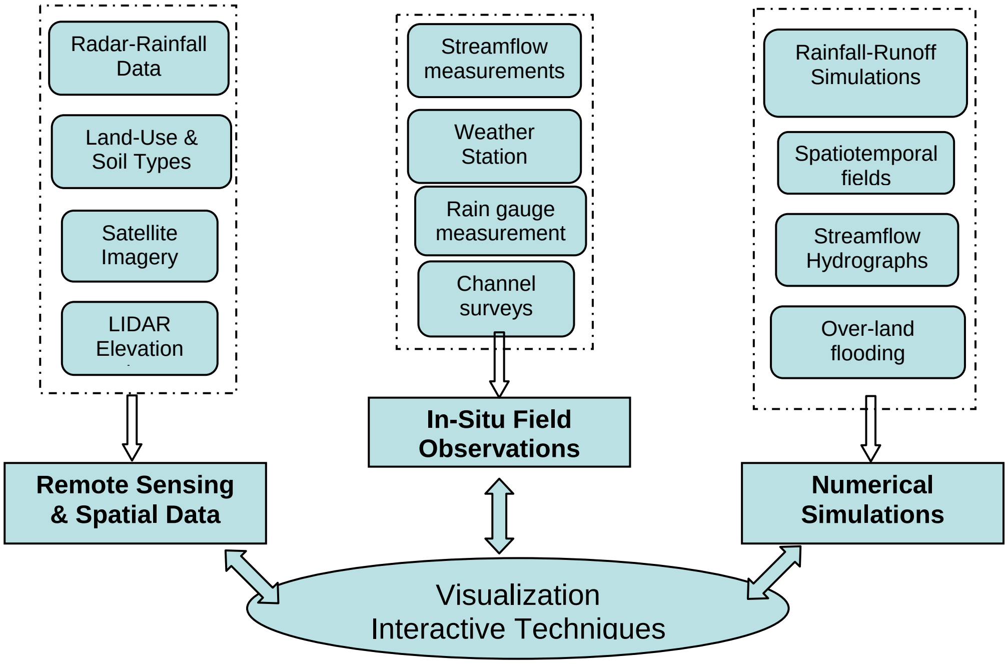

Figure 1: Overall Design and Components of the Hydrologic Virtual Laboratory

3. Experimental Site and In-Situ and Remote-Sensing Data

The virtual-reality hydrologic system is developed using data and simulations that are based on the 35-km^2 Isaac Verot (IV) experimental watershed (Figure 2). The watershed is located in the vicinity of campus of the University of Louisiana at Lafayette. The watershed is a sub-drainage area of the Vermilion river basin which drains into the Gulf of Mexico [10]. The watershed is frequently subject to frontal systems, air-mass thunderstorms, as well as tropical cyclones with annual rainfall of about 140 to 155 cm and monthly accumulations as high as 17 cm. The main soil type in the watershed is silt loam with low to medium drainage capacity. Land-use in the watershed is composed of urban areas, cropland, pasture and some forested areas.

The Department of Civil Engineering at the University of Louisiana at Lafayette has deployed a dense experimental network of rainfall and runoff monitoring sites over the watershed (Figure 1). A total of 13 tipping-bucket rain gauge sites are distributed over the watershed and every site has a dual-gauge setup for improved data continuity and quality. The gauges have an orifice size of 30.5 cm (12 inches) and are equipped with a digital data logger that records the time of occurrence of successive 0.254 mm (0.01 inches) tips, which can be used to construct time series of rainfall intensities at any desired time scale (e.g., few minutes or hourly). Streamflow measurements are collected at the outlet of the watershed, as well as at four interior locations using bi-directional acoustic velocity meters, from which discharge estimates can be obtained. Rainfall drop size distribution data (DSD) are collected at one of the experimental sites located close to the boundary of the IV watershed using a Joss-Waldvogel (JW) disdrometer.

In addition to in-situ data, the virtual system also includes rainfall remote-sensing data from weather radars. The radar data used in this study are the Level II reflectivity data collected at the Lake Charles National Weather Service (NWS) WSR-88D operational radar site (KLCH site). Radar data are available in polar coordinates at a resolution of 1º x 1 km and with a time sampling interval of 5 to 6 minutes. Other remote sensing data that are integrated into the hydrologic virtual system include: high-resolution LIDAR topographic data, satellite-based imagery of land use and land cover, and soil type information assembled over the watershed site.

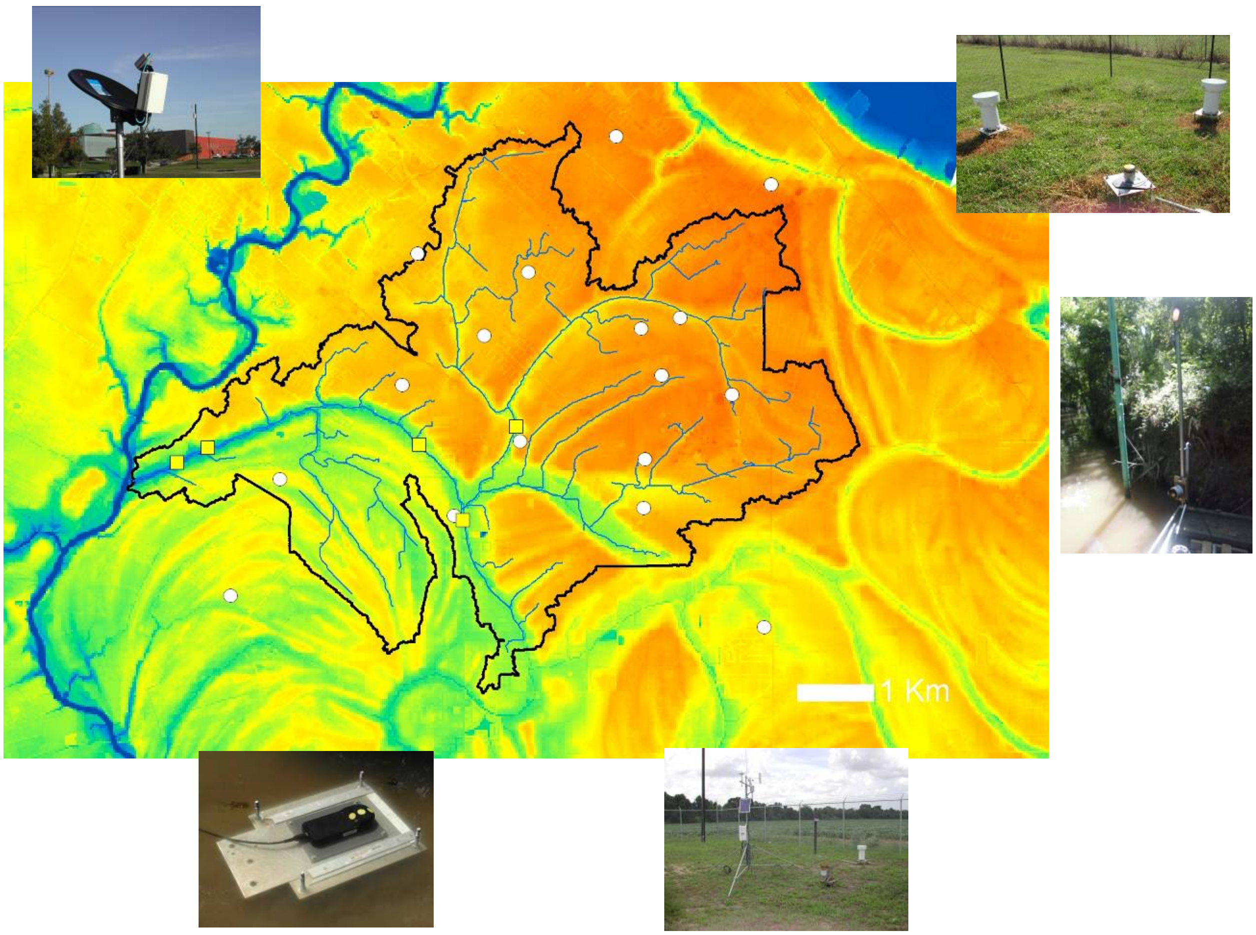

Figure 2: Map of the experimental watershed showing the locations of in-situ hydrologic instruments (circle and square symbols)

4. Hydrologic Model Simulations

The computer hydrologic simulation used by the virtual system in this study is based on the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) system. The GSSHA model is used to develop a rainfall-runoff model for the IV watershed. GSSHA is a fully distributed-parameter, process-based hydrologic model [11]. It uses finite difference and finite volume methods to simulate different hydrologic processes such as rainfall distribution and interception, overland water retention, infiltration, evapotranspiration, two-dimensional overland flow, one dimensional channel routing, and different methods (e.g., Green and Ampt method, and Richards' equation) for modeling the soil moisture profile in the unsaturated zone. The watershed topographic and hydrologic properties are represented using a 25x25 m^2 Cartesian grid. Overland hydraulic properties (e.g., roughness parameters), soil hydraulic parameters (e.g., saturated hydraulic conductivity, soil suction head, effective porosity), and evapotranspiration parameters (e.g., vegetation transmission coefficients and root depths) were initially assigned based on spatial variations in the combined classifications of soil type and land use maps. The parameters were further adjusted through model calibration. Figure (3) shows an example of the model simulated fields superimposed over the computational grid and the land-use imagery of the watershed.

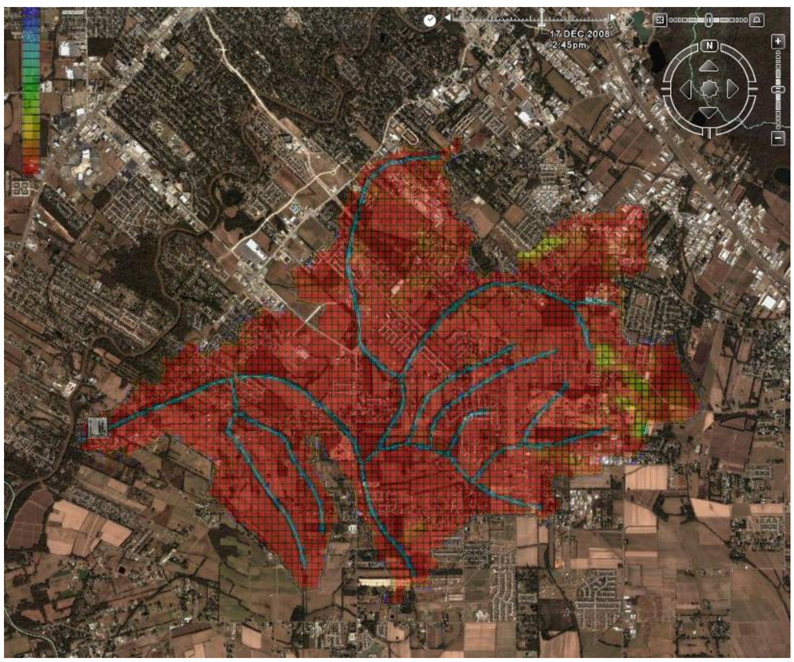

Figure 3: Example results of the model simulations (overland water depth) superimposed over the land-use background of the observatory area

5. Visualization Techniques

The visualization software for the virtual hydrology system is derived from several components including: overland flow depth, spatially distributed rainfall rate, elevation, different land use categories, simulated hydrograph of runoff at the outlet, and surface moisture content mapped over the watershed area. In order to provide the students with accurately generated geospatial information, LIDAR topographic data are used to create the surface geometry of the area. The Visualization Toolkit (VTK) by Kitware, Inc. is used to process all the data and to generate the graphical objects of the application. Once all the visualization components are generated, they are integrated with the simulation data using VRFlowVis and VR Juggler software toolkit. VRFlowVis provides the integration framework for the hydrologic simulation data, graphical objects and user interaction, while VR Juggler is used primarily to provide the virtual hydrology application with fully immersive and real time 3D interaction experience.

The fully immersive and interactive Virtual Hydrology Observatory is implemented in the Total Immersive Space (TIS) system of Louisiana Immersive Technologies Enterprise (LITE). TIS is a 6-sided CAVETM-like rear projected display device on all sides of the cube-like structure. As part of the project to augment the classroom teaching of the hydrology class, a less immersive system with fixed viewport is used. This setup is using a single front projection system with passive stereo viewing. A gamepad with 2 joysticks is used to facilitate navigation in the virtual environment. Although the lack of three dimensional positional and orientation tracking resulted in a limited in three dimensional interaction, this system still provides the user with significant advantage over a desktop viewing of the Virtual Hydrology Observatory application. Careful navigation and interaction with the gamepad and the large screen passive stereo viewing will achieve some degree of user immersion with the application.

Figure (4) illustrates an example of the virtual visualization system during one of the time steps where the water level visualization component is being displayed over the topology and lad-use imageries of the watershed. The opacity of the water level visualization component is set to the level that will enable the user to see both the water level and the topology visualization components. The manipulation of the opacity value provides the user with geospatial orientation of the water level simulation data to better understand the simulation data and creates the effect of flooding over the topology data.

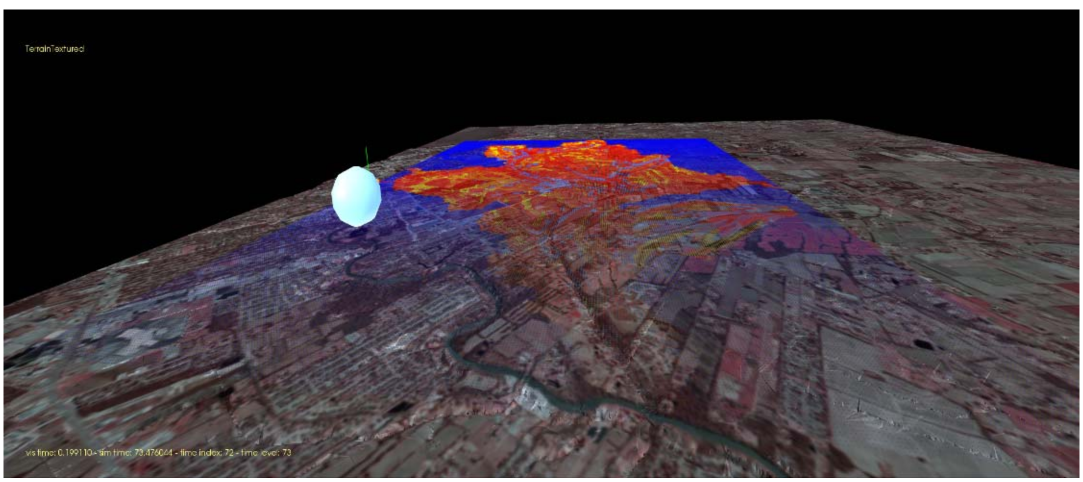

Figure 4: Water level visualization component displayed over the watershed topography.

6. Classroom Applications

The following are some examples of course instructional modules that are built around the hydrologic virtual laboratory and can be used and tested in the classroom.

6.1 Activity 1: Field investigations and data analysis

Objective:

- Perform basic field activities and data analyses.

Students' activities/assignments:

- Navigate the watershed and get familiar with its features
- Identify how many soil types in the watersheds and summarize their properties
- Identify main land use types in the watershed
- Identify sensors, what they measure and their resolution
- Download rainfall, streamflow, soil moisture measurements and produce time series plots

6.2 Activity 2: Effect of soil types and properties on runoff generation

Objective:

- Develop qualitative and quantitative understanding of the effect of soil types/properties on infiltration rates/depths and runoff generation

Students' activities/assignments:

- Be prompted to change the soil types/properties
- Examine the output maps visually (cumulative infiltration & overland water depths)
- Extract and compare hydrographs from different runs
- Identify which aspects of the hydrograph depend on soil characteristics
- Use water budget results to perform simple water balance analysis
- Perform and analyze rainfall/runoff/infiltration partitioning

6.3 Module 3: Effect of land-use change on runoff generation and flooding

Objective:

- Develop qualitative and quantitative understanding of the understanding of effect of land-use land-cover change on runoff generation and flooding

Students' activities/assignments:

- Be prompted to change the land use within the watershed
- Examine the output maps visually (e.g., overland water depths)
- Extract and compare hydrographs from different runs
- Identify Which aspects of the hydrograph have changed (peak, volume, rising/recession)
- Use water budget results to perform simple water balance analysis
- Perform and analyze rainfall/runoff/infiltration partitioning

6.4 Module 5: Watershed nesting/ hierarchy

Objective:

- Understand the concept of watershed nesting/hierarchy and relationship between watershed area and runoff volumes

Students' activities/assignments:

- Identify the sub-watershed nesting in the observatory and their surface areas
- Be prompted to extract hydrographs at several interior locations
- Examine the relationship between sub-watershed area and runoff volume
- Calculate volumes and plot Q and volume versus sub-watershed area
- Develop a relationship between runoff and area

7. Conclusions

This study reported on the design and development of a virtual-reality hydrologic education laboratory that integrates field data and numerical simulations into a highly visual and interactive system. This work addresses the pressing need recognized by the hydrologic community to improve the education of hydrology in engineering programs and increase the number of undergraduate students interested in pursuing further graduate studies and professional careers in hydrology and other related sciences. The design-based research adopted in this study provides a framework that supports the following areas of education practice: the integration of data and simulations in teaching hydrology; the ability to deploy advanced visualization techniques for hydrologic teaching applications; and more generally, the use of instructional approaches situated in virtual-reality environments. Plans are underway to implement the virtual laboratory developed in this study and test it in hydrology and water resources courses in engineering and earth sciences departments at the University of Louisiana at Lafayette. Potential users from other interested institutions are highly sought to provide wider test locations of the system. It is expected that the use of scalable and adaptable software applied to the educational activities will bring field-type experiences to students everywhere through the developed virtual environment. Observational and simulation visual capabilities of the observatory are likely to promote inquiry-based learning in engineering hydrology courses and help students develop investigative skills and ability for continual and lifelong learning.

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References

[1] NRC (1991): Opportunities in the Hydrologic Sciences, National Academy Press, Washington, D.C., 348 p.

[2] Nash, J. E., Eagleson, P. S., Phillip, J. R., and van der Molen, W. H. (1990): The education of hydrologists (Report of the IAHS-UNESCO Panel), Hydrological Sciences Journal, 35(6):597-607.

[3] Beven, K. J. (2001): Rainfall-runoff modelling: the primer. Wiley, Chichester.

[4] Winn, W. (1993): A Conceptual Basis for Educational Applications of Virtual Reality. Technical Report TR-93-9, Human Interface Technology Laboratory, University of Washington.

[5] McGrath, M. B., and Brown, J. R. (2005): Visual Learning for Science and Engineering, IEEE Computer Graphics and Applications, 25(5), 56 – 63.

[6] Ramasundaram, V., Grunwald, S., Mangeot, A., Comerford, N. B., and Bliss, C. M. (2005): Development of an environmental virtual field laboratory. Journal of Computers & Education, 45: 21-34.

[7] Becker, M. W., and Schuetz, J. W. (2003): An introduction to ground-water modeling using virtual reality modeling language (VRML). Journal of Geoscience Education, 51(5), 506-511.

[8] Libarkin, J. C., and Brick, C. (2002): Research methodologies in science education: visualization and the geosciences, Journal of Geoscience Education, 50, 449-455.

[9] Hickey, D. T., Kindfield, A. C. H., Horwitz, P., and Christie, M. A. (2003): Integrating curriculum, instruction, assessment, and evaluation in a technology-supported genetics environment. American Educational Research Journal, 40(2), 495-538.

[10] Habib, E., and Meselhe, E. A. (2006): Stage-discharge relations for low-gradient tidal streams using data-driven models. Journal of Hydraulic Engineering, 132(5), 482-492.

[11] Downer, C. W., and Ogden, F. L. (2004): GSSHA: Model to Simulate Diverse Stream Flow Producing Processes. J. Hydrolog. Eng., 9(3), 161-174.