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Real-time estimation of TP load in a Mississippi Delta stream using a dynamic data driven application system

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ABSTRACT

Elevated phosphorus (P) in surface waters can cause eutrophication of aquatic ecosystems and can impair water for drinking, industry, agriculture, and recreation. Currently, no effort has been devoted to estimating real-time variation and load of total P (TP) in surface waters due to the lack of suitable and/or cost-effective wireless sensors. However, when considering human health, drinking water supply, and rapidly developing events such as algal blooms, the availability of timely P information is very critical. In this study, we developed a new approach in the form of a dynamic data driven application system (DDDAS) for monitoring the real-time variation and load of TP in surface water. This DDDAS consisted of the following three major components: (1) a User Control that interacts with Schedule Run to implement the DDDAS with starting and ending times; (2) a Schedule Run that activates the Hydstra model; and (3) a Hydstra model that downloads the real-time data from a US Geological Survey (USGS) website that is updated every 15 min with data from USGS monitoring stations, predicts real-time variation and load of TP, graphs the variables in real-time on a computer screen, and sends email alerts when the TP exceeds a certain value. The DDDAS was applied to monitor real-time variation and load of TP for 30 days in Deer Creek, a stream located east of Leland, Mississippi, USA. Results showed that the TP concentrations in the stream ranged from 0.24 to 0.48 mg L^{-1} with an average of 0.30 mg L^{-1} for a 30-day monitoring period, whereas the cumulative load of TP from the stream was about 2.8 kg for the same monitoring period. Our study suggests that the DDDAS developed in this study was useful for estimating the real-time variation and load of TP in surface water ecosystems.

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1. Introduction

Phosphorus (P) is an essential nutrient in aquatic systems as it is required for all forms of life. However, over-enrichment of P can cause eutrophication in lakes and reservoirs and excessive periphyton growth in rivers (Hem, 1985; Mueller and Helsel, 1996). Phosphorus in aquatic systems may be derived from naturally occurring P in soils, but significant amounts may also be contributed to aquatic systems by anthropogenic sources such as fertilized fields, animal waste, wastewater treatment plants, and industries that use P in cleaning processes (Mueller and Helsel, 1996; Djodjic et al., 2004; Bond et al., 2006). Unlike nitrogen, P loss depends on multiple and dynamic factors such as solubility, soil retention capacity, soil erosion, runoff, leaching, source of applied P, and method of P application. Most surface water bodies have low P concentrations because of its low water solubility. Therefore, a small increase in P concentrations would result in eutrophication of surface waters. The concentrations of biologically available P in excess in surface water can lead to diverse problems such as toxic algal blooms and eutrophication resulting in hypoxia, fish kills, and loss of biodiversity. In addition to seriously degrading aquatic ecosystems, P enrichment in surface waters can also impair the use of water for drinking, industry, agriculture, and recreation. With an increased understanding of the importance of drinking water quality to public health and raw water quality to terrestrial life, there is a greater need to assess P dynamics in surface water ecosystems.

Currently, to determine water quality in most streams, it is necessary to manually collect samples and send them to a laboratory for analysis. These analytical methods require at least 24 h or longer. However, when human health, water supply, or other rapidly forming events such as algal blooms are concerned, timely

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water-quality information is required. In response to the need for timely and continuous water-quality information, the US Geological Survey (USGS) has begun using an innovative, continuous, real-time monitoring approach for many of the Nation's streams (http://waterdata.usgs.gov/nwis/rt). These real-time monitoring water quality data normally include conductance, chlorophyll, discharge, dissolved oxygen, pH, temperature, and turbidity; all valuable surface water quality indicators. However, there is currently no activity to monitor the real-time variation of P in surface waters due to the lack of suitable wireless sensors. Knowledge of real-time variation of P is critical to estimate surface water-quality status. Therefore, a need exists to develop a new approach for this purpose. To this end, a dynamic data driven application system (DDDAS) was developed in this study.

DDDAS is a real-time symbiotic field measurement and computer simulation system where measurements provide timely data for simulations. In reverse, simulations can guide the measurements on when and where to collect data. The DDDAS was first conceived by the US National Science Foundation (NSF) in 2000. A basic concept of a DDDAS commonly consists of the following four interactive components (Fig. 1): user control, real-time data acquisition, dynamic computation, and dynamic visualization. Users control and interact with real-time data acquisition, dynamic computation, and visualization. Dynamic computation includes the application models, necessary algorithms, and all of the computer machinery and their connections. Real-time data acquisition involves instantaneous data collections from GIS map sources, remote sensing, wireless sensors, or existing USGS stream monitoring stations via a USGS website. Dynamic visualization includes supporting software and hardware that enables the user to see current conditions, control the system, and making decisions. A similar concept can also be found in NSF (2000), Douglas et al. (2004), Darema (2005) and Ouyang et al. (2007, 2011). A major advantage for DDDAS is the use of real-time input data for better predicting the instantaneous behaviors occurred in the nature. Detailed reviews on the advantages and disadvantages of DDDAS can be found in Darema (2005) and Ouyang et al. (2007).

Despite the DDDAS has been employed to estimate the real-time loads of nitrogen and dissolved organic carbon in the rivers recently

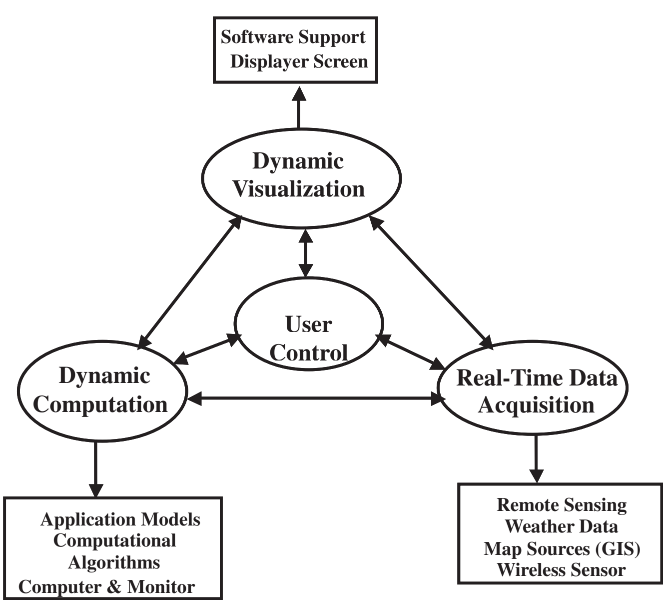

Fig. 1. A schematic diagram showing the basic concept of a dynamic data driven application system redrawn after NSF (2000).

(Ouyang et al., 2007, 2011; Ouyang, 2012), no such effort has been devoted to investigating real-time load of P in streams. The purpose of this study was to develop a DDDAS for indirectly and remotely monitoring the real-time variation and load of total phosphorous (TP) of a stream in the Mississippi River Alluvial Valley, Mississippi, USA. Our hypothesis is that although no effort has been devoted to monitoring real-time variation and load of TP in surface waters due to the lack of suitable wireless sensors, one can indirectly monitor such variation and load if there is a good relationship between TP and other water quality variables that are measured in real time by existing stations such as those employed by the USGS throughout the country. In this study, we used the relationship between TP and turbidity to estimate TP since turbidity is measured in real time by USGS monitoring stations at the location of interest. The approach developed in this study will not only be used for real-time monitoring of TP but also could be adapted for real-time monitoring of other water quality variables in surface waters. In addition, a new model (i.e., the Hydstra model) rather than the STELLA model (used in our previous works for designing DDDAS) has been used in this study to friendly download the real-time USGS data and to calculate the real-time TP loads. The major advantages for using Hydstra model against STELLE model are that the former has the abilities and flexibilities to automatically download data from any USGS monitoring stations, automatically send alerting emails, and automatically display simulation results on the computer screen with little to no efforts on computer coding.

2. Materials and methods

A DDDAS for estimating the real-time variation and load of TP in surface waters described in this study is shown in Fig. 2. This diagram shows the following three major components of the DDDAS: (1) a User Control that interacts with Schedule Run to implement the DDDAS with starting and ending times and time intervals (e.g., 15-, 30-, or 60-min) using Windows Schedule Wizard; (2) a Schedule Run that activates the Hydstra model; and (3) a Hydstra model that downloads the USGS real-time data from a website, predicts real-time variation and load of TP in surface waters using correlation equations, depicts real-time simulations on a monitor, and sends email alerts when the TP concentration exceeds preset level. A detailed description of the DDDAS development is given below.

2.1. Data mining

The first step in developing the DDDAS is to select the study sites (i.e., watersheds) and the USGS real-time monitoring stations of interest from the USGS website (http://waterdata.usgs.gov/nwis/current/?type=quality). In this study, we selected the USGS real-time monitoring station # 0728875070 (Latitude 33°24′04″, Longitude 90°53′31‴46″) located on Deer Creek east of Leland, Mississippi, USA. This station is within the Yazoo River Basin (YRB), which is the largest river basin in the Mississippi Delta. Pollution of the Yazoo River (YR) and its tributaries with sediments and nutrients are of great environmental concern. Sediments, excess nutrients, and pesticides in the YR and its tributaries come from both point and non-point sources such as storm water runoff, discharge from ditches and creeks, groundwater seepage, naturally occurring organic inputs, and atmospheric deposition. During the last century, land cover type in the YRB changed from predominantly forest to mainly agricultural. The concomitant increases in human activities in the YRB over that period have resulted in the accumulation of significant levels of sediments, excess nutrients, and other contaminants (Pennington, 2004; Shields et al., 2009).

The selected real-time monitoring station (# 0728875070) is currently managed by USGS in cooperation with the Yazoo

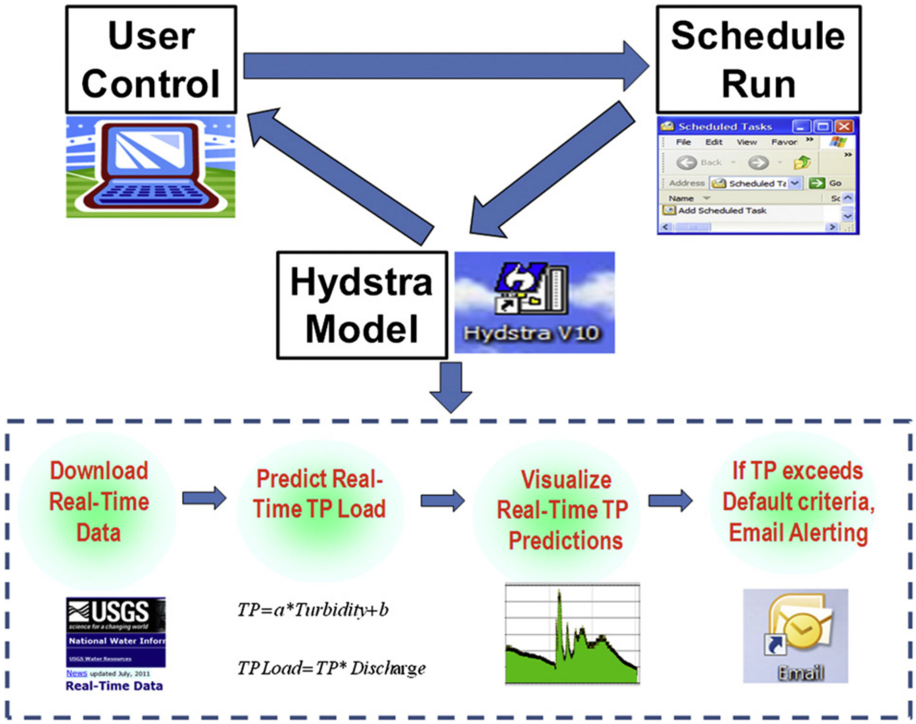

Fig. 2. A dynamic data driven application system for monitoring real-time variation and load of TP in surface waters.

Mississippi Delta Joint Water Management District. This station measures the real-time variations of turbidity and discharge but not TP. To indirectly monitor the real-time variation and load of TP in this stream, a relationship between TP and turbidity is needed. Pennington (2004) examined the relationships between surface water sediment concentration, TP, and total Kjeldahl nitrogen in Mississippi Delta streams. This author found that many good linear relationships exist among those water quality constituents. In this study, we choose the following relationship to estimate TP from turbidity in the stream (Pennington, 2004):

$$\mathrm{TP_{con}} = 0.0007{*}\mathrm{Turb} + 0.2669 \quad \left(R^2 = 0.83\right) \tag{1}$$

where $\mathrm{TP_{con}}$ is the TP concentration (mg $\mathrm{L^{-1}}$), Turb denotes the turbidity (Nephelometric Turbidity Unit or NTU), and R the correlation coefficient. This equation is used to estimate the real-time variation of TP concentrations based on the real-time variation of turbidity from the USGS real-time monitoring station. The real-time load of TP is then calculated using the following equation:

$$\mathrm{TP_{load}} = \mathrm{TP_{con}}{*}\mathrm{Discharge} \tag{2}$$

The data for the real-time discharge (L $\mathrm{s^{-1}}$) in Eq. (2) is from the USGS monitoring station.

2.2. Hydstra model and DDDAS framework

Once the USGS real-time monitoring station was selected and the relationship between the TP and turbidity was obtained, a Hydstra model was employed to download the real-time data from the selected USGS website, estimate real-time variation and load of TP in the surface water using Eqs. (1) and (2), graph real-time estimates on a computer screen, and send email alerts when the estimated TP concentration exceeds a certain level (Fig. 2). The Hydstra Model (Version 10.3.2, Kisters Inc.) is a commercial software package used to analyze hydrologic characteristics, water quality, and other ecological and environmental factors of streams that have time-series data; to perform data acquisition and exporting, data management and analysis, and perform simulation and automated task scheduling. In this study, the Hycreate function from the Hydstra Model was employed to download USGS real-time data (i.e., turbidity and discharge); the Telview function was utilized to calculate TP load and display the real-time estimates; and the Hyaudit and Hymailer functions were used to send email alerts when the TP levels exceeded a preset limit. Detailed descriptions of these functions can be found in Kisters Inc. website (http://www.kisters.net/hydstra.html).

After the Hydstra model was set up for monitoring the real-time variation and load of TP in surface waters, a Schedule Run was created using the Windows Schedule Task wizard. The Schedule Run controlled when to start and end the real-time simulations. Users can always reset the Schedule Run for new simulations. A completed DDDAS for monitoring real-time variation and load of TP in surface waters is shown in Fig. 2.

3. Results and discussion

Prior to applying the DDDAS for estimating real-time loads of TP in the stream, its applicability was validated. The validation is a process of comparing the DDDAS predictions with the field measurements. Since there are no TP data available from the USGS station (#0728875070) selected for this study, an attempt was made to validate the DDDAS predictions using the field data collected from the stream about 4 km away from the station. This stream is within the same watershed. Comparisons of the field measured and DDDAS predicted TP concentrations are shown in Fig. 3. With the linear regression $R^2 = 0.9732$, we concluded that a good agreement between the field measurements and the DDDAS predictions was obtained.

To obtain a better understanding of the real-time variation and load of TP in surface water from the Mississippi Delta area, a forecasting (or simulation) scenario was performed in this study.

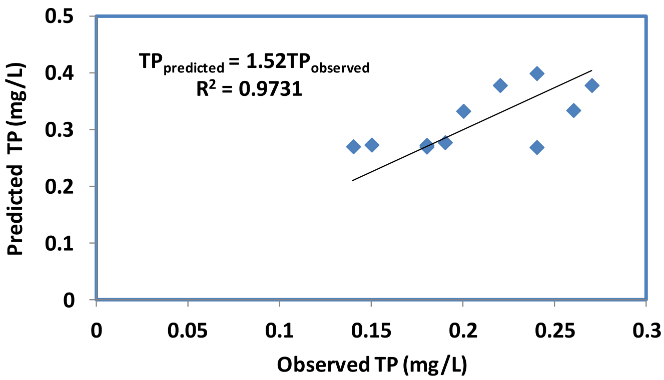

Fig. 3. Comparison of field measurements and DDDAS predictions for TP concentrations.

This scenario investigated the real-time variation, load, and accumulation of TP in Deer Creek east of Leland, MS over a 30-day monitoring period. Input values for real-time stream discharge and turbidity at a 15-min interval were instantly downloaded from the USGS station (#0728875070). The forecasting began on December 11, 2011 and ended on January 10, 2012. It should be pointed out that the USGS only provides the most current 120-day real-time data for this station with an interval of 15 min. A month of real-time data was selected in this scenario for the purpose of data storage efficiency and simplicity although it is very easy to modify the DDDAS for a 120-day simulation.

Real-time variations of discharge, turbidity, TP concentration, and TP load in the Deer Creek surface water are shown in Fig. 4. Of which, the real-time variations of discharge and turbidity were measured by the USGS monitoring station, and the real-time variation and load of TP were predicted using the DDDAS. It should be emphasized that although this figure demonstrated the variation and load of TP for the entire simulation period (i.e., 30 days), in reality, the DDDAS was run every 15 min and the TP concentration and load in surface water at that particular time were displayed immediately on the computer screen. Users can therefore access P estimates in a timely manner.

Turbidity refers to the cloudiness of water caused by suspended solids and is an important water quality variable. Fig. 4 shows that the real-time variations of turbidity in Deer Creek ranged from 40 to 280 NTU for a 30-day monitoring period. A similar real-time variation pattern was observed for TP concentration in the stream. This occurred because the TP concentration was estimated using Eq. (1), which describes a linear relationship between TP and turbidity. In contrast, a somewhat different real-time variation pattern was found for discharge in the same stream as compared to that of turbidity. More specifically, the maximum discharge (8.0 m^3 s^{-1}) occurred on the 30 December 2011, whereas the maximum turbidity (280 NTU) occurred on the 23 December 2011. A possible explanation for the discrepancy would be that the transport of turbidity is not only dependent on stream discharge but also dependent on precipitation characteristics. In this case it appears that the highest turbidity occurred during the steepest portion of the hydrograph possibly caused by a very high rate of precipitation.

Variations of TP concentration in the stream ranged from 0.24 to 0.48 mg L^{-1} with an average of 0.30 mg L^{-1} for a 30-day monitoring period (Fig. 4C). The average TP concentration was within the range (0.24–0.76 mg L^{-1}) measured in the laboratory for the same

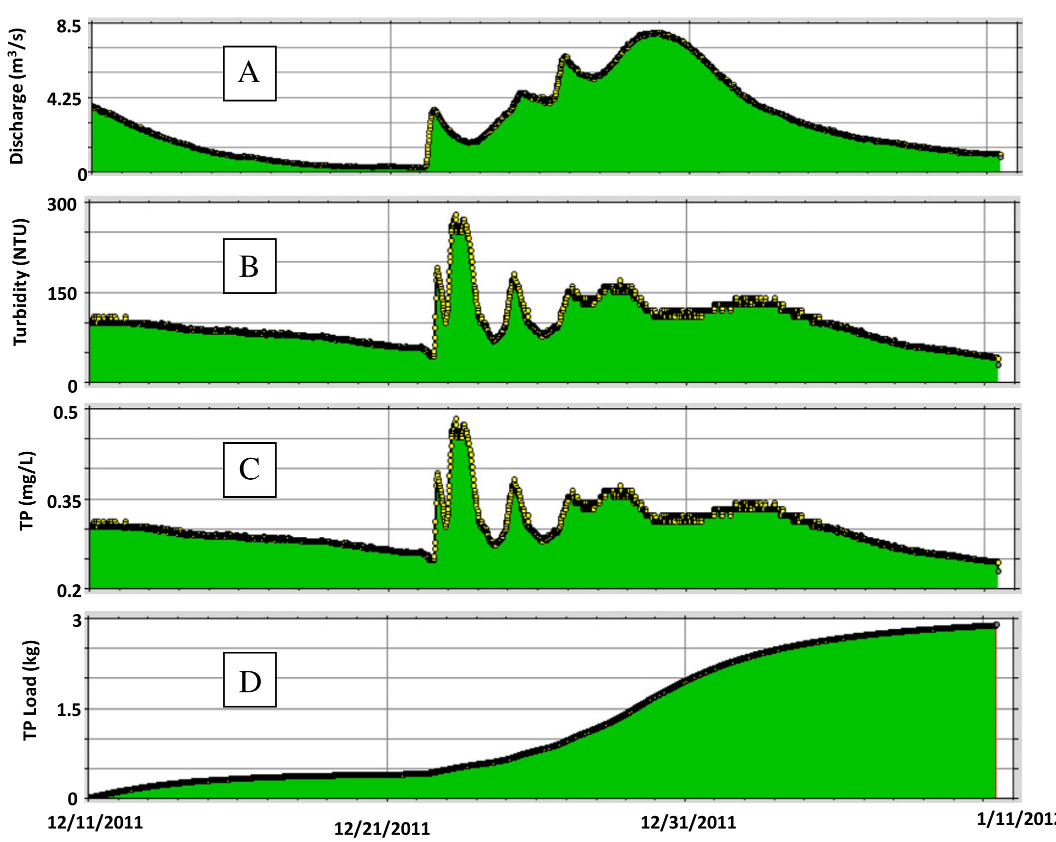

Fig. 4. Real-time variations of discharge (A) and turbidity (B) measured by USGS and real-time variations of TP concentration (C) and load (D) predicted from the DDDAS for a 30-day monitoring period from December 11, 2011 through January 10, 2012.

watershed reported by Pennington (2004), indicating that the real-time TP concentrations estimated by the DDDAS were reasonable. The cumulative load of TP into the stream was about 2.8 kg for a 30-day monitoring period (Fig. 4D). Currently, the State of Mississippi's surface water nutrient criteria are under development. Therefore, no TP standard has been set in the DDDAS for email alerts to water resources managers and decision makers although the DDDAS was designed for such an action. It should be noted that the US EPA's rivers and streams TP criterion is 0.04 mg L^{-1} for Ecoregion XII or Southeastern Coastal Plains (US EPA, 2000) and the Mississippi Delta area is within the Ecoregion XII.

4. Conclusions

A DDDAS was developed to monitor the real-time variation and load of TP in surface waters and was validated prior to its application. This DDDAS has the following features: (1) a User Control that interacts with Schedule Run to implement the DDDAS with starting and ending times and time intervals using Windows Schedule Wizard; (2) a Schedule Run that activates the Hydstra model; and (3) a Hydstra model that downloads the USGS real-time data from a website, predicts real-time variation and load of TP in surface waters using correlation equations, graphs real-time simulations, and can send email alerts when the TP concentration exceeds a preset level.

A forecasting scenario was chosen to monitor the real-time variation and load of TP in Deer Creek east of Leland, Mississippi, USA although the DDDAS developed in this study can be easily modified to monitor TP in other surface water ecosystems. The TP concentrations in the stream ranged from 0.24 to 0.48 mg L^{-1} with an average of 0.30 mg L^{-1} for a 30-day monitoring period, whereas the cumulative load of TP into the stream was about 2.8 kg for the same period.

Comparison of the DDDAS predictions and experimental measurements showed that the TP concentration predicted by DDDAS was within the range from those measured by laboratory experiments (Pennington, 2004). Results indicated that the DDDAS developed in this study can be applied to estimate the real-time variation and load of TP in other surface water ecosystems equipped with monitoring stations linked to a website. Furthermore, the approach developed in this study can be used not only for real-time monitoring of TP but also can be adapted for real-time monitoring of other water quality constituents in surface waters.

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