Development of an Environmental Observational Database to Minimize the Gap between Science and Practice

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ABSTRACT

The burgeoning human growth, climate change and its variability are putting stress on our finite water resources. To ensure an adequate supply and quality of water for present and future needs under these critical conditions, it is necessary to understand the effects and consequences of the anthropogenic activities and natural variability on these resources. Beacon Institute for Rivers and Estuaries (BIRE) in collaboration with Clarkson University and IBM Corporation are in the stage of implementing River and Estuary Observation Network (REON) that will collect wide varieties of physical, chemical and biological parameters via an integrated network of sensors, robotics and computational technology distributed throughout the Hudson River in New York. Data collected from this large network will help to understand the important processes controlling water quality of the river. These large and diverse datasets are managed through the developed database schema in this study for easy discovery, access and dissemination to the broader user communities. Our developed database is capable to handle both point and gridded observations such as surface current maps captured by the high frequency (HF) radar system. The observational datasets are also stored with the metadata such as location and unit of measurements, calibration coefficients, data qualifying comments, etc. which facilitate easy interpretation of the stored datasets. This database will be interfaced with the point observation data model (ODM) developed by the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI), Inc. and thereby, will facilitate interoperability of our data model and will provide greater access to the broader user communities. In addition, the developed data visualization software in this study queries the data into the database and publishes simple color-coded contour plots of measured data for a specified time (e.g., the last 24 hrs, last 7 days, or last 30 days of measurement) on the static Web pages of BIRE's Web portal. This simple illustration of measured data in near real time will make general public aware of the environmental conditions and thereby, promote their participations in implementing policies in conserving our natural water resources.

INTRODUCTION

Natural aquatic systems are the most dynamic ecosystems where physical, chemical and biological properties of water column are undergone through frequent temporal and spatial changes. The understanding of these changes is crucial in comprehending and predicting effects and consequences of anthropogenic activities and natural variability especially the change in global climate and land-use on our finite water resources. The Hudson River watershed in NY has already shown possible indications of global climate change impact (NY State Department of Environmental Conservation information at http://www.dec.ny.gov/lands/39786.html). In addition, municipal wastewater and combined sewer overflows, urban/stormwater runoff has resulted in recreational uses such as swimming being prohibited at several reaches of the river after storm events. Moreover, agricultural and other nonpoint sources of nutrients and pollutants lead to deterioration of overall water quality. In order to understand the impacts from these natural and anthropogenic events, it is necessary to measure various environmental parameters at high resolution which can shed light on the important processes controlling aquatic ecosystem health. Moreover, real-time availability of these datasets will provide many added benefits: real-time water level and current information can be used for safe navigation, search and rescue operations, water treatment and cooling plant's regular operation, oil spill trajectory predictions and clean up activities for contaminated sites such as the Hudson River PCB site which has been listed as a National Priority List (NPL) site. Real-time information on the sediment transport dynamics through continuous monitoring can also help in efficient dredging and proper maintenance of the shipping lanes and thereby, can assist in continuous operation of New York Harbor which is one of the largest harbors in the world.

The advances in sensor technologies and communication infrastructure provide opportunities to measure environmental parameters at high temporal and spatial resolution and make them available to users in real time. Beacon Institute for Rivers and Estuaries is in the state of implementing River and Estuary Observation Network (REON) through using these smart technologies that will capture real-time condition of the Hudson River in New York. REON will collect, sort, analyze and graphically portray information from continuous streams of physical, chemical and biological sensors deployed along these waterbodies. The wide varieties of these datasets need to be organized and stored with sufficient ancillary information of the measurements for easy access, unambiguous interpretation and dissemination to broader user communities. Various government agencies within the USA developed several different data storage and publication methods. Among them the USGS's National Water Information System (NWIS) (http://waterdata.usgs.gov/nwis), the USEPA's STORET/WQX (http://www.epa.gov/storet), the NOAA's National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov/oa/ ncdc.html) and the USDA's SNOpack TELemetry (SNOTEL) system (http://www.wcc. nrcs.usda.gov/snow/) are mentionable. Also, various investigators and local organizations make measured data at different watersheds available through their developed systems (Slaughter et al., 2001; Bosch et al., 2007; Moran et al, 2008). However, it will be challenging for the users to discover and synthesize useful information for their investigations as they have to navigate through pages, menus and files of the systems from the disparate sources. In addition, syntactic (e.g., file type, file format) and semantic (e.g., variable names, units) heterogeneities will further acerbates the situation to discover necessary data. The development of standardized data storage and publication system will help to better manage those data. In addition, software applications can then be easily developed depending on the standardized system for data analysis, visualization and many other purposes.

The management of observational data in relational database management systems (RDBMS) can assist in data mining, sensor anomaly detection, quick query in addition of other associated benefits of relational database system such as reliability, scalability, available tools and performance (Connolly and Begg, 2005). Considering the extensive benefits of RDBMS for data management, the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) has developed standard database schema namely observation data model (ODM) for the storage of point observations data (Horsburgh et al., 2008). This schema provides a framework through which data of different types and from different sources can be stored and organized in a consistent way so that users can easily discover and interpret the necessary data without going through the different vocabulary and data formats used by various sources. Using the input from community review, ODM was modified so that it will be simple, easily implementable in different application systems (e.g., relational database, GIS, Microsoft ® Excel) and can accommodate data from a wide range of disciplines (e.g., hydrology, environmental engineering, meteorology,) (Tarboton, D.G., 2005). The semantic differences of different data sources are reconciled through the use of controlled vocabularies which are developed for different attributes in ODM tables based on the community survey. Data managers, therefore, need to select the appropriate terms from the vocabulary instead of using their own, potentially inconsistent terms. Moreover, loading data into the ODM automatically removes the syntactic differences as data will be in the consistent relational database format and provides greater interoperability among disparate data sources. As of June, 2009, data collected by fifty different sources including USGS and EPA over 1.75 million sites has been uploaded into the ODM (Whtieaker, 2009).

Although ODM is able to successfully manage point observational datasets, this model does not inherently support data that was collected over a spatial domain. For example, Acoustic Doppler Current Profiler (ADCP) system which measures vertical profiles of water current cannot be represented well in the ODM. Also, this data model is not able to accommodate raster datasets such as surface current maps captured by high frequency (HF) radar system (Islam et al. 2010). In addition, measured datasets from sensors installed on mobile monitoring platforms such as glider, remotely operated vehicle (ROV), autonomous underwater vehicle (AUV) are not managed well in the ODM. As an intermediate solution, data collected from this type of monitoring platforms can be represented into ODM considering the metadata of a measured parameter (i.e., measurement locations (e.g., latitude, longitude)) as a data value. But this type of representation does not keep measured data with the observed location and so are suffered from lack of data integrity. Moreover, this data model does not contain detail information of the sensors (e.g., sensor type, sensor serial number, sensor related calibrated coefficients) used in measuring data value. The presence of observational datasets with the resources used to measure them will help in better interpretation and post-processing of the measured raw data. Therefore, in this study, we have developed a database schema which allows storing both point and spatial observational datasets and keeps record of sensor related detail specific information. In addition, development of interface between our database and ODM will facilitate interoperability and share of datasets with large user communities. Moreover, data visualization software was developed to make general public aware about the environmental condition of the Hudson River through providing simple illustration of real-time change in environmental parameters.

DESCRIPTION OF OBSERVATION NETWORK

REON comprise four different types of sensor platforms with multiple nodes within the network. The four platform types are: 1) fixed robotic vertical profiler (FRVP); 2) mobile robotic undulating platform (MRUP); 3) fixed ADCP (FADCP); 4) remote high frequency radar (RHFR). On the first type of platform, an automated profiler system vertically moves a suite of water quality measuring sensors within the water column for continuous measurements. Along with water quality sensors, in-situ sensors are installed on the platform to measured meterological and vertical profile of water currents. This platform is self-powered through Solar PV panels. The MRUP (Instrumented undulating tow-body which is deployed behind the research vessel) measures the same spectrum of environmental parameters 'synchronically' over a highly-resolved spatial regime. The third platform is the FADCP where Acoustic Doppler Current Profiler is installed to measure water current profile. On the fourth type of platform, HF-radar system is installed to measure surface current maps. Sensors installed on these platforms measure wide variety of environmental parameters such as chlorophyll "a", fluorescein, colored dissolved organic matter, dissolved oxygen, conductivity, temperature, depth, particle size distribution/optical back scatter, wave/currents/shear/turbulence, bio-genic particles ID/count, wind, barometric press. and air temperature.

Figure 1 shows the location of current REON monitoring platforms in the Hudson River watershed which encompasses about 13,300 square miles in eastern New York and parts of Vermont, New Jersey, Massachusetts, and Connecticut (Wall et al., 1998). The black solid circles represent the location of FADCP: two of them are placed in Albany (Latitude 42°38'31"N, Longitude 73°44'56"W) and Poughkeepsie (Latitude 41°39'06"N, Longitude 73°56'38"W) in upward-looking position to measure vertical profile of water currents along with wave measurements whereas the third one is installed at horizontal-looking position in West Point (Latitude 41°23'10" N, Longitude 73°57'20"W) to measure cross-sectional variation of water current. In addition, one FRVP is installed at Denning's Point in Beacon, NY (Latitude: 41° 29' 39.60" N, Longitude: 73° 59' 23.88" W) which is shown as solid red circles in the figure. In addition, we conduct periodic research surveys along the lower Hudson River with MRUP to capture the spatial variation of various environmental parameters. These datasets also provide site-specific design data for the network nodes to be added in future. We will extend our current REON sensor network through installing FADCP at four sites, FVRP at three sites and FHFR at three sites along the Hudson River in next few years. These extensive REON datasets needs to be managed efficiently for easy discovery, access, archive, interpretation and dissemination to the broader user communities.

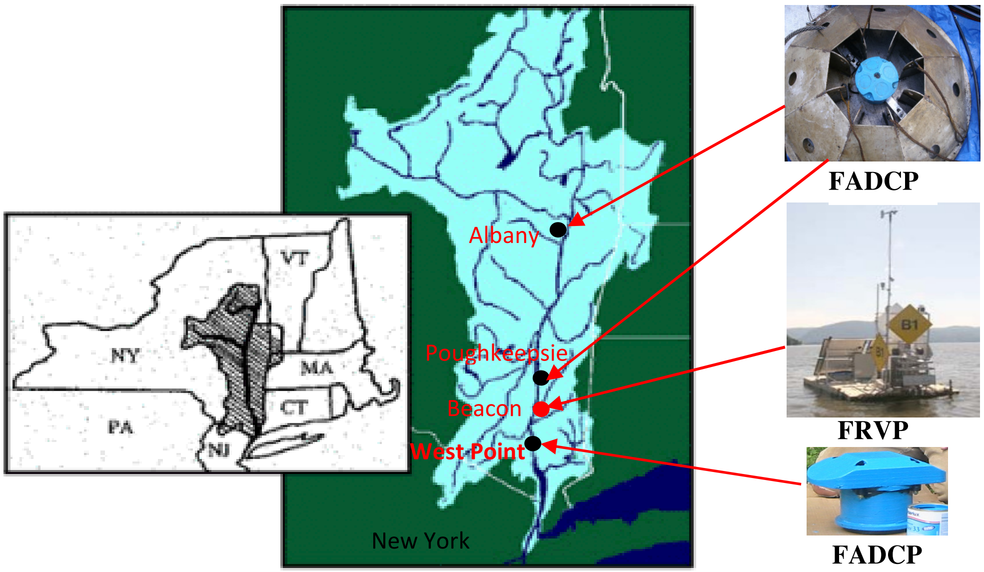

Fig. 1 Location of current REON monitoring platforms in the Hudson River watershed

DESCRIPTION OF THE DEVELOPED ENVIRONMENTAL DATABASE

The developed database in this study helps to manage wide varieties of data captured by various sensors installed at different platforms in REON. Figure 2 shows the schematic diagram of our developed database schema. The numeric relationship between entities in each of the tables is shown at either end of each of the linking line between the tables. For example, the linking line between "Platforms" and "Deployments" tables has 1..1 at the "Platforms" end and 0..* at the "Deployments" end representing that there is one and only platform associated with 0 or many Deployments. The central table of this database is "Deployments" table which contains detail information regarding deployment of sensors on monitoring platforms such as deployed sensor name, name of the persons who deploy the sensors on the platform, pre and post deployment related parameters and sensor recovery date. The primary key of this table is the 'deployment _id' which takes unique value for each sensor deployment in a monitoring platform. The table also keeps 'sensor_id' which is linked to the primary key of "sensor" table that describes different attributes of the deployed sensor. 'Platform_id' in the "Deployments" table relates to "platform" table which stores site specific information of the deployed sensor. Moreover, "Deployments" table contains other metadata such as sensor calibration coefficient, pre and post deployment related notes, recovery date and recovery note that may include any noticeable changes about the sensor condition during its recovery. This information is useful in interpretation of the measured sensor data afterwards. The information regarding pre- and post- deployment of sensor can help to calculate sensor drift that is used in correcting measured data. Other important columns of this table are 'profiler', 'serialport', 'status'. The 'profiler' column takes the logical value of "1" or "0" depending on the sensor being deployed on the profiler system or stationary position. 'serialport' column stores the communication port number of the data collection machine with which sensor is connected. This information is useful for sensor operators

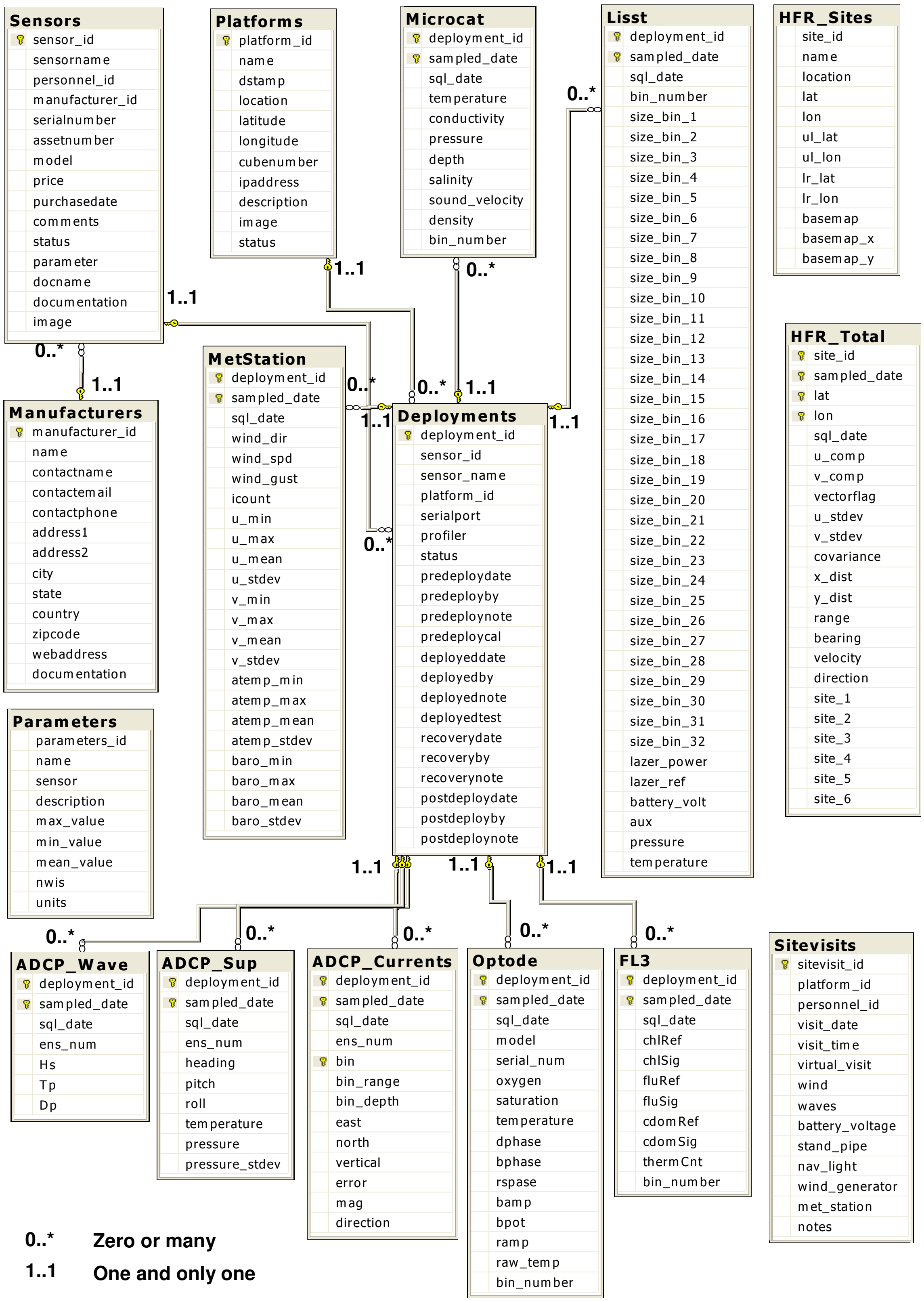

Fig. 2 REON database schema displaying the primary key of each table with the "key" symbol and denoting the relationship between tables through the connecting line with the cardinality indicated by numbers.

in remote access and sensor control. The ‘status’ column takes the value of “1” if the sensor is presently running on a platform. Otherwise, it takes the zero (“0”) value. Whenever a sensor is recovered from the platform, its status is changed from previously assigned value “1” to “0” in the “Deployments” table and “1” is then reserved for next deployed sensor in the platform. This will help in better sensor/resource management as it is possible to quickly find list of currently deployed sensors in different platforms.

The site specific information of the monitoring platform is inserted into the “Platforms” table. It keeps record of platform name, its geographical co-ordinates, file name of the platform photograph, description of the location and access information for the deployed data acquisition control box in the platform. The metadata stored in this table thereby assists in linking observed data with the location of measurements and also provides remote access information regarding the monitoring site. On the other hand, information regarding deployed sensors on these platforms is recorded in “Sensors” table. This table contains information such as sensor name, its model, serial and asset number, manufacturer’s supplied sensor specific parameters, sensor prices, manual. “Sensors” table is linked with “Manufacturers” table where contact information of sensor vendors is recorded.

Meteorological, hydrodynamic and water quality parameters measured by different sensors on our observational network are uploaded into the developed database. Data from in-situ sensors that measure point variation of parameters are inserted into sensor specific tables. For example, data collected from in-situ water quality sensors such as Optode, FL3, Microcat and Lisst are stored into “Optode”, “FL3”, “Microcat” and “Lisst” tables, respectively. The output of the deployed meteorological sensor (i.e., Metstation by RM Young. Inc.) is stored into the “MetStation” table. ‘Deployment_id’ and sampling time are used as the composite primary key of these tables. Each data record in these tables has distinct values for coupled of these two variables (i.e., deployment_id and sampling time). Each sensor table is also filled up with various parameters measured by that specific sensor and the information regarding the level of measurements (denoted by bin_number in the table). The information regarding the level of measurements on the sensor table helps to correlate measured data with the measurement depths which are captured by the Microcat sensor. “Optode” table stores information measured by Optode sensor such as dissolved oxygen (DO) concentration (i.e., ‘oxygen’ in the table), % DO saturation (i.e., ‘saturation’ in the table), water temperature (i.e., ‘temperature’ in table). “Microcat” table contains information such as water temperature, conductivity, pressures, measurement depth, salinity, water density, etc. which are measured by this specific sensor. FL3 table stores information of reference and measured chlorophyll-a, colored dissolved organic matter. “Lisst” table contains information for particle size distribution (i.e., particle concentrations at thirty two different size categories), water temperature, pressure and other auxiliary parameters measured by the LISST sensor. “MetStation” table keeps record of meteorological data such as wind speed and direction, atmospheric pressure, air temperature. On the other hand, output of ADCP sensor which includes spatial (e.g., vertical/cross-sectional profile of water currents) and point measurements (e.g., water temperature, pressure, wave height) are recorded into three separate tables namely “ADCP_Currents”, “ADCP_Sup” and “ADCP_wave”. The “ADCP_Currents” table contains information regarding profiles of water currents such as measurement bin depth (i.e., bin_depth in the table), measurement bin number, components of water current (i.e., north, east, vertical) and measurement error. The composite primary key of this table is deployment_id, sampling time and measurement bin number. "ADCP_sup" contains supplemental information such as pitch, roll, heading, water temperature and pressure which are point measurements at the level of the installed sensor. In addition, significant wave height (Hs), significant wave period (Tp) and direction (Dp) captured by upward looking ADCP sensors are stored into the "ADCP_Wave" table. Sampling time and 'deployment_id' are the composite keys for both "ADCP_Sup" and "ADCP_Wave" tables.

Data collected from HF-radar systems are stored into the "HFR_Sites" and "HFR_Total" tables. "HFR_sites" keep site specific information of the coverage of the HF-radar system. It is necessary to collect radial data from at least two remote monitoring sites to resolve the surface current map. Latitude-longitude of the upper left corner and lower right corner of the base coverage map are stored into this table. In addition, it keeps the filename that contains base map image and description of the coverage area. This table assigns a unique site id for the array of HF-radar monitoring platforms that resolve the surface current map of the coverage area of the base map. The 'site_id' is the primary key of the "HFR_Sites" table. On the other hand, "HFR_Total" stores measured data from HF-Radar system. It keep records of the east, north component of the surface current along with the latitude-longitude of the points where HF-radar system resolves water current. It also stores other parameters measured by this system.

"Sitevisits" table are used to log the status of various infrastructure that supports the platform operation and other notes which can help in proper maintenance of the platform. For example, condition of physical infrastructure of the platform (i.e., pylon pipe), status of battery voltage, navigation light and other site notes are recorded in this table. Data from our mobile monitoring platform (MRUP) needs to be uploaded into the developed database which will be straight forward as the same suite of sensors are deployed on this platform. One additional sensor installed on the MRUP is GPS which provides location (i.e., latitude and longitude) and time of measurement. This information assists in correlating the data measured by different sensors on the platform. One additional sensor specific table needs to be added for the inclusion of GPS data into our database. This will not change our overall database schema which allows for easy inclusion of table that will contain parameters measured by the added sensor.

DATA VISUALIZATION AND DISSEMINATION

Data measured at our observational network should be made available to scientists, policy makers, educators, students and the general public in near real time. This will facilitate to conduct collaborative research among various investigators located at different geographical locations. As our database contains processed data along with metadata in a relational table, it will be easier for investigators to interpret the measured data and to explore interrelationship among measured parameters to understand the processes controlling the dynamics of the observed waterbodies. We have also developed data visualization software to display data on the Web in real-time. This software makes a query into our database and retrieves the measured data related to parameter of interests. This data are then used to draw simple color-coded contour plots for a specified time (e.g., the last 24 hrs, last 7 days, or last 30 days of measurement) and are populated in static

Web pages of our Web server. This simple illustration of measured data in near real time will make general public aware of the environmental conditions and may encourage them to use this information. For example, people would like to swim at the Hudson River but they are worried about the water quality. The excessive rainfall can overload the sewage system which can induce microbial contamination in the water column. Therefore, people usually wait for two/three days after the rainfall to swim. Real-time availability of measured data from REON will help public in making educated decisions in the determination of the suitable time when water is safe for swimming. Particle concentration measured by the sensor at our observational platforms may indirectly indicate about the potential harmful condition of the water column. As precipitation-driven flooding events can carry sediment from the watershed, high particle concentrations at the monitoring platform suggest that the observational sites may be contaminated from the flooding event. Figure 3 shows the vertical profile of particle concentration variation at our fixed robotic platform in the Hudson River from September 30 to October, 06 2009. In this figure red color means, high particle concentration whereas blue color means low particle concentrations. The sudden increase of particle concentration on October 03 suggests that this time is not good for swimming whereas particle concentration is low at other time. In addition, measured water current data at our platform is useful in the determination of the optimum calm time period for swimming. Figure 4 displays the vertical profile of north component of water current at the same fixed robotic platform from September 30 to October, 06 2009. Positive velocity

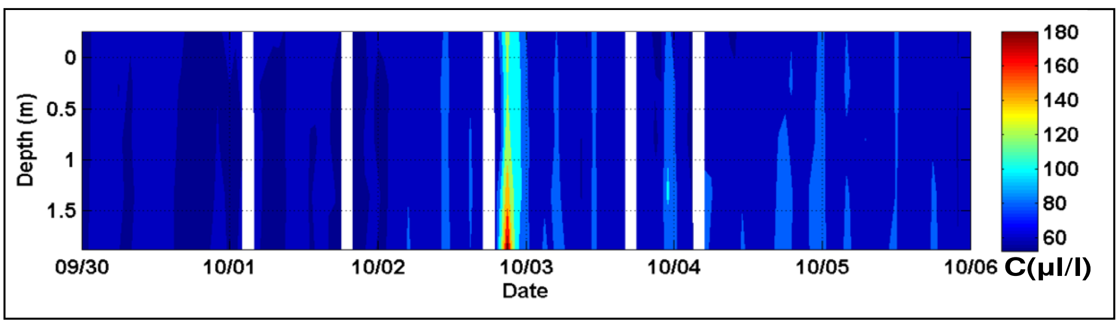

Fig. 3 Vertical profile of total particle concentration at Denning's Point in Beacon, NY form September 30 to October 06, 2009.

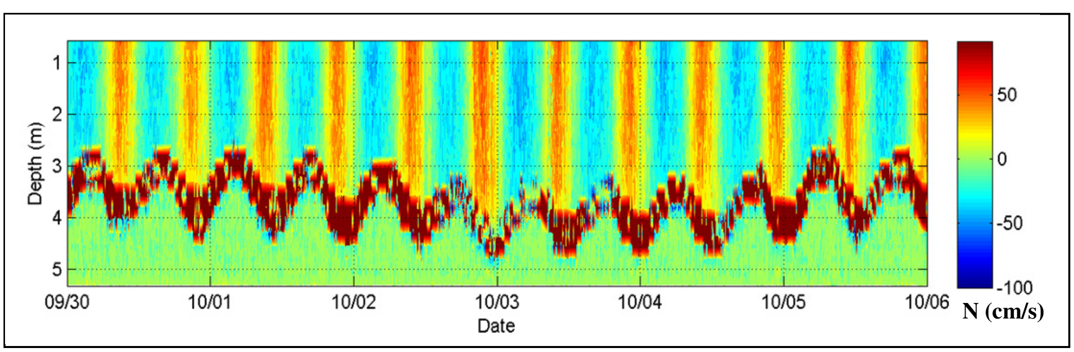

Fig.4 Vertical profile of North component of water current at Denning's Point in Beacon, NY form September 30 to October 06, 2009.

magnitude (yellow to red) indicates that water is moving up the river to the north whereas negative velocity magnitude (turquoise to blue) shows water moving to the south. This river is flowing from north to south where it is connected with the Atlantic Ocean. The observational data suggests that the river is dominated by strong tidal forces and the significant slack period exists during ebb and flood tide. People can select this period for safe swimming. This is an example of the use of real-time data which can be utilized in other daily applications such as implementation of adaptive operational management plan for water treatment, wastewater treatment and power plants.

The developed database can also be interfaced with the ODM using the controlled vocabulary listed by the CUAHSI and thereby, will aid interoperability with other observational networks. We will implement CUAHSI's WaterOneFlow Web services (http://his.cuahsi. org/wofws.html) that will provide opportunity to the broader user communities in downloading the data and performing analysis in real-time. Data collected from our monitoring platforms can also be shared with regional data centers and national data repositories through installing National Oceanic and Atmospheric Administration (NOAA) data integration framework (DIF) Sensor Observation Services (SOS) (http://ioos.gov/dif/) onto our Web server. SOS will help to convert observation and sensor metadata into XML format which will be compatible with Integrated Ocean Observing System (IOOS) data management and communication (DMAC) standards and protocols. We will need to map our observational parameters with that of SOS supplied configuration parameters to avoid semantic differences. As we have processed raw sensor data through our developed software and also stored metadata into our developed database, no significant steps or post processing are required here to map parameters. A simple modification of SOS provided common gateway interface (CGI) script and registration of our observatory with national registries (http://www.obsregistry.org /map2009/index.php) will facilitate to discover and retrieve data from our database. In addition, the gridded datasets (e.g., surface current maps captured by RHFR) stored into our database can be easily converted to standard netCDF (network Common Data Form) (http://www.unidata.ucar.edu/ software/netcdf/) which is widely used by atmospheric and oceanographic communities to store various data especially array-oriented datasets. The data stored in netCDF format can then be shared using OPeNDAP Data Access Protocol (DAP) (for example a THREDDS data server – Thematic Real-time Environmental Distributed Data Services – is one possible approach for implementing DAP services) (http://opendap.org/). This will provide access to the broader user communities in our observational datasets and thereby will assist researchers, scientists, policy makers in analyzing and understanding various environmental phenomena that control the dynamics of the studied waterbodies.

CONCLUSION

The developed database schema is able to organize and store both point and gridded measurements. In addition, storage of observational data with metadata (e.g., location and unit of measurements, calibration coefficients and data qualifying comments) facilitates easy interpretation of the stored datasets to the end users. Moreover, capability of the developed database schema for inclusion of diverse sensor data and easy addition of new type of sensor measurements makes it a suitable candidate for environmental data management as new and diverse sensors are being developed to clarify the complex processes controlling natural ecosystem quality. The high spatial and temporal measurements of various physical, chemical and biological parameters at different monitoring platforms in REON sensor network are being imported into the current database. This data are disseminated to the general public through publishing simple color-coded contour plots of measured data for a specified time (e.g., the last 24 hrs, last 7 days, or last 30 days of measurement) on the static Web pages of BIRE's Web portal. This simple illustration of measured data in near real time will make general public aware of the environmental conditions and thereby, promote their participations in implementing policies in conserving our natural water resources. Moreover, the interfacing of current database with the observation data model (ODM) and storing data into netCDF format will increase interoperability and thereby facilitate greater access of the measured datasets to the broader user communities.

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