A GEOINFORMATICS-BASED MODELING AND MAPPING TECHNIQUES FOR AN INTEGRATED SURFACE WATER QUALITY MONITORING AND ASSESSMENT

Michelle V. Japitana (1), Alexander T. Demetillo (1), Evelyn B. Taboada (2), Chul-soo Ye (3), Marlowe Edgar C. Burce (2)

[1] Univ. of San Carlos, Talamban, Cebu City, 6000, Philippines
[2] Caraga State Univ., Ampayon, Butuan City, 8600, Philippines
[3] Far East Univ., 76-32 Daehakgil, Gamgok-myeon, Eumseong-gun, Chungbuk, Korea
Email: mvjapitana@carsu.edu.ph; atdemetillo@gmail.com; ebtaboada@usc.edu.ph; csye@kdu.ac.kr; mcburce@usc.edu.ph

KEY WORDS: water monitoring framework; water quality modeling, GIS, Remote Sensing

ABSTRACT: Sustainable management of surface water systems requires systematic and comprehensive monitoring of water quality, however, the attempts to obtain this in developing countries are challenged due to the lack of an integrated framework and limited resources. Most of the developing countries' water quality monitoring and assessment (WQMA) program lacks facilities, equipment, manpower and expertise that results in an insufficient number of sampling data that lack temporal and spatial trends. The government-sponsored WQMA programs usually employ traditional procedures like field measurements and collection of water samples for subsequent laboratory analysis. While such conventional approach to WQMA data is accurate at a specific location and time, in most cases, it cannot provide enough information on the overall quality of water. Fortunately, the emerging technologies of Geoinformatics and Wireless Sensing, provide useful tools for a comprehensive WQMA program. Application of these advanced technologies engages communities and local leaders to implement best management practices in water quality monitoring. Hence, the main goal of this study is the implementation of a systematic and comprehensive WQ monitoring and assessment which combines the paradigm of Geoinformatics and Wireless Sensing. An integrated WQMA framework utilizing both wireless sensor-based and *in-situ* water quality data is conceptualized and pilot-tested in Tubay, Agusan del Norte's water catchment as proof of concept. In this study, methods and modeling techniques were presented to show that the proposed framework is effective and operational in performing WQ measurement, catchment characterization, water body mapping, and WQ data modeling and mapping. Results of this study prove that methods and models can be derived in the context of performing a comprehensive but cost-efficient WQMA using free Remote Sensing (RS) tools. By implementing the integrated WQMA framework and validating its results and performances, this study is able to present an operational WQMA system that enhances the traditional method by providing an improved spatial and temporal scale of water quality data collection allowing trend analysis, enhanced WQMA processes, and methods for a convenient and a low-cost monitoring and assessment processes.

1. INTRODUCTION

Safe and secure water supply is vital for the survival of humanity. In the Philippines, it is endowed with rich water resources which include 421 principal rivers with a total length of 3,172 kilometers, and long coastlines reach of 36,289 kilometers (Environmental Management Bureau, 2014). However, the country is still facing challenges and still putting more efforts to improve its water monitoring and assessment programs. Though there was a dramatic shift in water quality management in the Philippines upon the enactment of the Philippine Clean Water Act in 2004, there is a limit to what the government can do to protect and conserve water (Deutsch, Orprecio, & Bago-Labis, 2001; JICA/DENR-EMB, 2010). Most of the water quality monitoring and assessment (WQMA) program of developing countries like the Philippines lacks facilities, equipment, manpower and expertise that results in an insufficient number of sampling data that lack temporal and spatial trends. The government-sponsored WQMA programs usually employ traditional procedures like field measurements and collection of water samples for subsequent laboratory analysis. From the year 2006 to 2013, the EMB of the Department of Environment and Natural Resources (DENR) reported that only 199 out of 688 water bodies (approximately 29%) are regularly monitored [1]. Overall, it can be observed that the monitoring efforts in the country are still in its infancy stage and the application of various emerging technologies are limited.

At present, there is a need for an inventory, assessment, monitoring, and standardization of monitoring systems across all government agencies that must be complemented by an integrated water resources information system accessible to various stakeholders (Rola, Hall, & Pulhin, 2018). The key in understanding and improving water quantity and quality is to have the reliable, consistent and appropriate information. Water quality monitoring data must be responsive to the purpose of science and research and for management and policy-making (Robarts, Barker, & Evans, 2008). Hence, meteorological, landform, hydrological, geologic, socio-economic, and political databases must also be aggregated together with WQM data in a water resource information system to inform research and as basis for devising complementary water resource plans (Barba, 2004; Rola et al., 2018).

This may be a long way to go for the water management authorities in the country. But, implementing a WQMA with wireless sensing and Geoinformatics technologies to improve WQ data acquisition, processing, and interpretation operations is a crucial approach in preparing the Philippines in attaining a national water resource information system. Technology breakthroughs in Geoinformatics and wireless sensing technologies have already opened up various research opportunities in water quality monitoring and assessment that promises a more convenient and cost-effective WQMA method (Capella, Bonastre, Ors, & Peris, 2014; Chung & Yoo, 2015; Dåbakk, Nilsson, Geladi, Wold, & Renberg, 2000; Hartnett & Nash, 2015).

The main goal of this research is to implement a systematic and comprehensive WQ monitoring and assessment that can be applied for the improvement of the traditional WQMA methods in the Philippines. Geoinformatics technologies is aimed to be employed in this study to develop modeling and mapping methods for an improved WQ monitoring and assessment framework particularly for water quality data measurement, catchment characterization, water body mapping and updating, and water quality modeling and mapping. The methods developed in this study was pilot-tested in Tubay, Agusan del Norte catchment area as a proof of concept. The Geoinformatics-integrated WQMA framework proposed in this study aims to derive models, maps, and methods that are enabling and ready to use for establishing a water resource information system that can improve the current WQ data management and dissemination situation in the country.

2. MATERIALS AND METHODS

2.1 The Study Area

The study area (Figure 1) is a catchment with a 22,000 hectare of land area with a diverse land uses that include mining, irrigation and other agricultural uses, fisheries, livestock production (Environmental Management Bureau - Caraga Region, 2015), and mining. Within the catchment lies Tubay River which is one of the classified as Class “A” water body in Agusan del Norte, Philippines. There are two major tributaries of the river, the Aciga River is at its upstream portion and the Kinahiluan River at the mid-downstream part. According to the Environmental Management Bureau (EMB), Tubay River is a receptor of domestic solid and liquid wastes and other non-point sources of pollution (Environmental Management Bureau - Caraga Region, 2015).

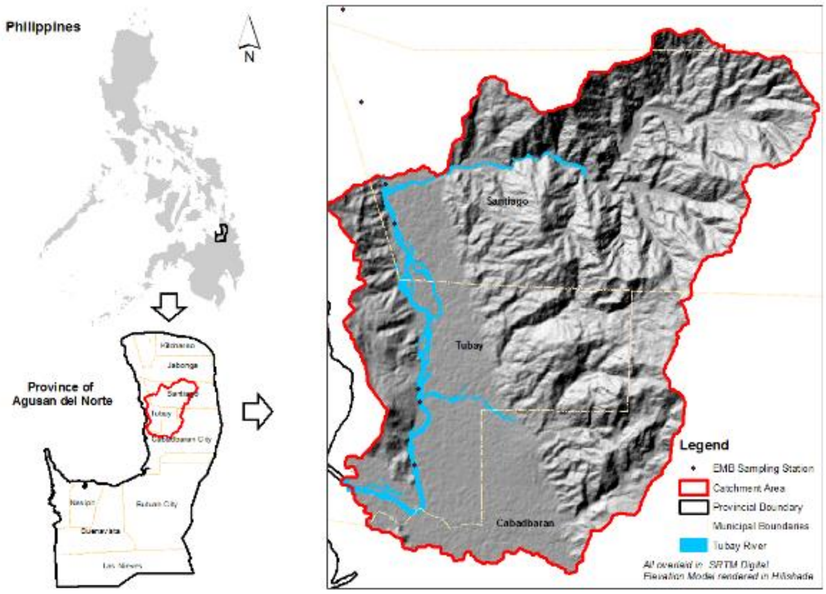

Figure 1. Location of the study area.

2.2 Datasets Used in the Study

For the implementation of a Geoinformatics-integrated WQMA System, various remotely-sensed data like Digital Elevation Model (DEM), satellite images, and on-site spectral datasets are used in this study. For the Catchment characterization, a Shuttle Radar Topography Mission (SRTM) DEM is used for extracting physical profiles while the Landsat 8 OLI image is used to extract land cover information. While the spectral measurements at designated sampling points in the study area are utilized to evaluate its correlation to existing pH and dissolved oxygen (DO) levels. In the water body extraction method proposed in this study, selected bands of the Landsat 8 image are utilized to derive water indices. Also, multi-temporal Landsat 8 images were employed in this study for water quality model development and validation. Shown in Table 1 is the list of satellite images used in the different component of this study.

Table 1. Landsat 8 OLI images utilized in this study.

Datasets	Acquisition Date	Purpose
Landsat 8 (bands 1-7)	March 29, 2017	Land Cover Mapping for Catchment Characterization
Landsat 8 (bands 2,3, 5-7)	March 29, 2017	Waterbody detection
Landsat 8 (bands 1-7)	April 19, 2015	Water Quality model development
Landsat 8 (bands 1-7)	July 26, 2016 August 27, 2016	Water Quality model validation
Landsat 8 (bands 1-7)	April 19, 2015 October 12, 2015 July 26, 2016 August 27, 2016	Water Quality estimation/mapping

2.3 Method

This study proposes a Geoinformatics-based modeling and mapping techniques to implement water body mapping, catchment characterization, and RS and GIS-based modeling and mapping to complement WQMA activities like preliminary surveys, WQ monitoring, and WQ data treatment and interpretation. The general methodological flow of the study is shown in Figure 1.

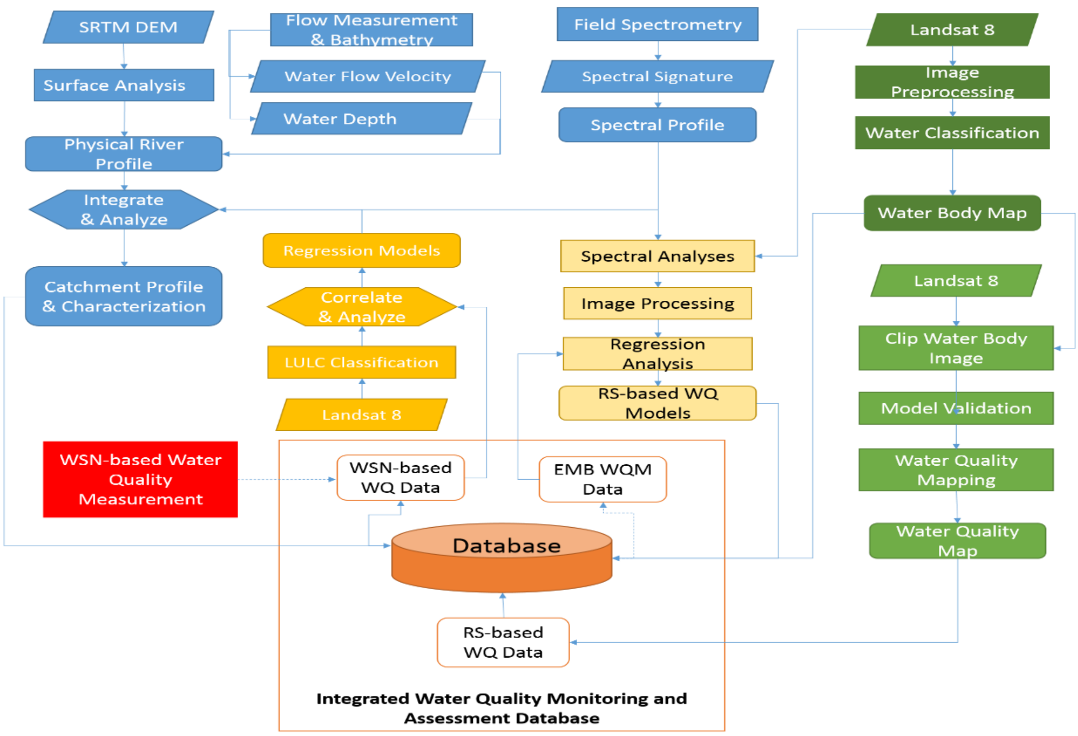

Figure 1.

2.4 Catchment Characterization

This part of the study uses on-site measurements like wireless sensing-based water quality data and spectral signatures, combined with free remote sensing data such as Landsat satellite images and digital elevation models, in characterizing a catchment.

2.5 Waterbody Mapping

A novel method for automatic detection of rivers is proposed in this study by combining water indices as data inputs and employ Minimum Distance as the classification algorithm for delineating accurately water features that resemble shadows and highly turbid color from a satellite image as water bodies.

2.6 RS-based Water Quality Modeling and Validation

This part of the study presents an operational method to extract spectral information from satellite images to develop WQ empirical models. The Landsat 8 surface reflectance bands and derivative images like water indices, band ratio, and Principal Component Analysis (PCA) are utilized as input data in this study. Feature vectors were then collected from the input bands and subsequently regressed together with the WQ data to be able to derive RS-based WQ models. Validation of the models is implemented using multi-temporal Landsat 8 images.

2.7 RS-based Water Quality Assessment

The validated WQ models were applied to the whole input bands of Landsat using Band Math of ENVI 5.1 software to derive the WQ images. Then, the WQ images were loaded in QGIS 2.16 software to generate WQ maps. Using QGIS, the non-water areas in the WQ image was masked out using the waterbody map as the mask image. And finally, gradient colors and histogram stretching were applied for better representation of the spatial and temporal distribution of pH and BOD in the study area.

3. RESULTS AND DISCUSSION

The proposed method for delineating catchment profiles primarily demonstrates the use of free RS datasets like digital elevation model (DEM), satellite images, and on-site spectral measurements for supplementing geospatial data for a comprehensive catchment characterization that is fundamental in water resource management and sustainability studies (Japitana, Demetillo, Burce, & Taboada, 2019). In Japitana, Demetillo, et al., (2019), the established correlation between *in-situ* water quality data and *in-situ* spectral measurements proves its potential in developing empirical models for water quality estimation. In completing this part of the study, the following are some of its important findings and outputs: a) GIS techniques employed in extracting physical profiles of a catchment like the delineation of the extent of the river, the catchment boundary, the width and length of the water body situated within the catchment demonstrated the practical use of RS datasets as an alternative to ground measurements and surveys; b) the use of Landsat 8 image and image processing techniques in characterizing land cover composition of a catchment shows how remote sensing can aid in understanding the influence of human activities on the quality of water, by using the land cover (LC) information; and c) the regression analysis results show that LC classes have significant influence to the existing pH and dissolved oxygen levels in the sampling areas.

A novel method for accurately extracting water bodies is proposed using Landsat 8 image in this study. The essential findings in developing this automated river detection method are detailed in Japitana, Ye, Burce, Japitana, & Burce (2019) and can be summarized as: a) the algorithm was developed by employing Minimum Distance classification on the MNDWI and AWEI water indices as input images which yielded high accuracies in detecting water bodies in three test sites; and b) the automated river detection method accurately delineates water features that resemble shadow pixels and rivers with highly turbid characteristics from satellite images.

Further, RS-based regression models for estimating WQ parameters by analyzing satellite spectral values and ground-based WQ measurements is presented in Japitana & Burce (2019) to improve the spatial and temporal scale of WQ monitoring data. In this part of the work, Landsat 8 image and water quality data from the EMB were utilized to determine empirical models for selected water quality parameters. The summary of findings is as follows: a) RS-based regression models with high R-square values were derived for estimating Turbidity, TDS, DO, BOD, and pH; b) models for pH, BOD, TSS, TDS, and Conductivity can be estimated using Landsat 8 employed with image processing techniques while DO and Turbidity can be estimated using a combination of spectral and water quality parameters; and c) regression results showed the importance of employing atmospheric correction using Dark Object Subtraction method for deriving empirical models for pH, BOD, TSS, DO, and Conductivity.

Validation of the RS-based models was done by implementing spatiotemporal water quality mapping as the targeted feature of a systematic and comprehensive WQ monitoring and assessment. This part of the study is discussed in detail in Japitana & Burce (2019b), the water body map derived from Japitana, Ye, et al. (2019) was used to masked-out non-water areas in the Landsat 8 image. Then the RS-based models were employed using the raster calculator of ArcGIS. After deriving the water quality maps, these are validated using the EMB water quality data, and statistical analysis was employed to determine the strength of the model. The important results obtained in this study are as follows: a) validation results showed that the estimated pH and BOD values derived using RS-based models derived have no significant difference when compared with the actual WQ values obtained from EMB WQ data; b) the WQ maps generated using these models provided a better visual representation of WQ distribution throughout the river extent which further allows analysis on the spatial trends of WQ conditions in the area; c) this RS and GIS-based WQ mapping method also demonstrated the great advantage in discriminating temporal changes of WQ concentrations at different temporal scales; and d) results show that water managers can simulate up to semi-monthly WQ mapping analysis by taking advantage of the 15-day return period of the Landsat missions to augment the existing WQ monitoring data acquired using the traditional methods.

4. CONCLUSIONS

This study demonstrates the advantages of employing Geoinformatics technologies in implementing an integrated and comprehensive water quality monitoring and assessment framework. In employing RS and GIS techniques for developing a catchment characterization method using the customized sensor-based WQ data, *in-situ* spectral signatures, and remotely-sensed datasets, a science-based preliminary WQ monitoring and assessment operation is obtained. Results in developing an automated water body detection method using satellite images provide an accurate and updated river network maps. The water detection algorithm developed in this study can aid in producing an updated, accurate, and complete river network maps. While the use of satellite images in developing WQ models for an RS-based monitoring and assessment proved useful and has high potential for implementation to complement the traditional method of WQ monitoring and assessment method.

5. REFERENCES

Barba, P. F. (2004). The Challenges in Water Resources Management in the Philippines. In *2nd International Conference on Hydrology and Water Resources in Asia Pacific Region*. Singapore. Retrieved from http://rwes.dpri.kyoto-u.ac.jp/~tanaka/APHW/APHW2004/proceedings/JSE/56-JSE-A519/56-JSE-A519.pdf

Capella, J. V, Bonastre, A., Ors, R., & Peris, M. (2014). Sensors and Actuators B : Chemical A step forward in the in-line river monitoring of nitrate by means of a wireless sensor network. *Sensors & Actuators: B. Chemical*, *195*, 396–403. https://doi.org/10.1016/j.snb.2014.01.039

Chung, W., & Yoo, J. (2015). Sensors and Actuators B : Chemical Remote water quality monitoring in wide area. *Sensors & Actuators: B. Chemical, 217*, 51–57. https://doi.org/10.1016/j.snb.2015.01.072

Dåbakk, E., Nilsson, M., Geladi, P., Wold, S., & Renberg, I. (2000). Inferring lake water chemistry from filtered seston using NIR spectrometry. *Water Research*, *34*(5), 1666–1672. https://doi.org/10.1016/S0043-1354(99)00314-0

Deutsch, W. D., Orprecio, J. L., & Bago-Labis, J. P. (2001). Community-based water quality monitoring: the Tigbantay Wahig experience. In I. Coxhead & G. Buenavista (Eds.), *Seeking sustainability: Challenges of agricultural development and environmental* *management in a Philippine watershed* (pp. 184–196). Los Banos, Philippines: Philippine Council for Agriculture, Forestry and Natural Resources Research and Development.

Environmental Management Bureau. (2014). *National Water Quality Status Report 2006 - 2013*. Quezon City, Philippines.

Environmental Management Bureau - Caraga Region. (2015). *Tubay River Water Quality Assessment*. Butuan City.

Hartnett, M., & Nash, S. (2015). An integrated measurement and modeling methodology for estuarine water quality management. *Water Science and Engineering*, *8*(1), 9–19. https://doi.org/10.1016/j.wse.2014.10.001

Japitana, M. V., & Burce, M. E. C. (2019a). Remote Sensing-based Surface Water Quality Estimation using Landsat 8 OLI. *Engineering, Technology & Applied Science Research*, *9*(2), In Press.

Japitana, M. V, & Burce, M. E. C. (2019b). A Satellite-based Remote Sensing Technique for Surface Water Quality Estimation. *Engineering, Technology & Applied Science Research*, *9*(2), 3965–3970.

Japitana, M. V, Demetillo, A. T., Burce, M. E. C., & Taboada, E. B. (2019). Catchment characterization to support water monitoring and management decisions using remote sensing. *Sustainable Environment Research*, *5*, 1–10. https://doi.org/https://doi.org/10.1186/s42834-019-0008-5

Japitana, M. V, Ye, C., Burce, M. E. C., Japitana, M. V, & Burce, M. E. C. (2019). 수계 지수 결합을 이용한 Landsat 8 영상의 수계 검출 Combining Water Indices to Detect Water Bodies using Landsat 8 OLI. *Journal of Institute of Control, Robotics and Systems*, *25*(5), 470–475.

JICA/DENR-EMB. (2010). *Capacity Development Project on Water Quality Management*.

Robarts, R. D., Barker, S. J., & Evans, S. (2008). Water Quality Monitoring and Assessment : Current Status and Future Needs. In *Proceedings of Taal 2007: 12th World Lake Conference* (pp. 167–175).

Rola, A. C., Hall, R. A., & Pulhin, J. M. (2018). Towards a More Responsive Water Policy and Practice: Challenges and Prospects. In A. C. Rola, J. M. Pulhin, & R. Arcala Hall (Eds.), *Global Issues in Water Policy* (Vol. 8, pp. 261–276). Springer, Cham. https://doi.org/10.1007/978-3-319-70969-7_12