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ENVIRONMENTAL PROTECTION THROUGH MATHEMATICAL MODELING: DYNAMIC SIMULATION OF DISSOLVED OXYGEN IN WATER RESERVOIRS

Abstract

Population points and industries create pollution pressure over water bodies that affect their quality: BOD depletes dissolved oxygen, which negatively impacts water and surface fauna.

As per its formation in the fields of thermodynamics, chemical kinetics and fluid mechanics, the chemical engineer has the advantage of being capable to address environmental protection problems as systems of functionally interconnected variables. The result of this approach are mathematical models, which serve as objective tools in devising environmental policies and remediation strategies.

This paper presents an application of remote sensing, and CFD modeling techniques to obtain a dynamic mathematical model of the dissolved oxygen concentration. The object of research is the Cerrón Grande. The resulting mathematical model was delivered to the Ministry of the Environment to be used as tool for further development of remediation strategies.

Introduction

Cerrón Grande reservoir

The Cerrón Grande is an artificial reservoir for hydroelectric exploitation that constitutes the largest fresh water body in El Salvador. It’s located between the limits of the states of Chalatenango, San Salvador, Cuscatlán and Cabañas, with an extension of 60,698 hectares [1].

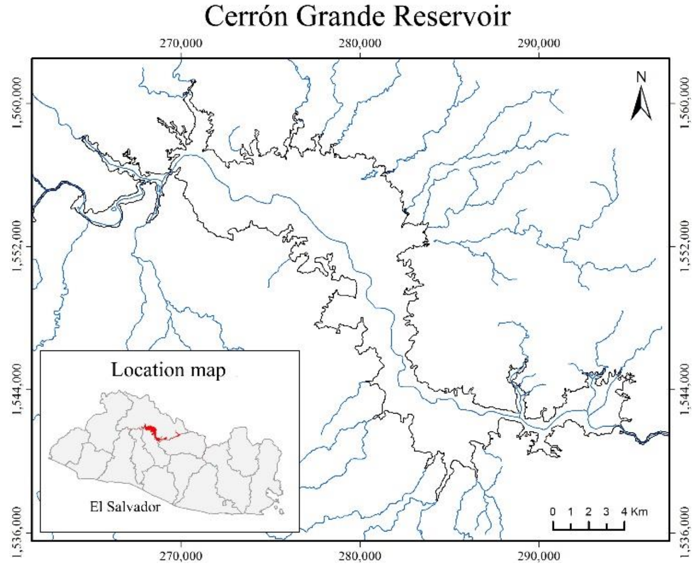

Figure 1. Cerrón Grande reservoir location map.

The reservoir is the core of the Cerrón Grande wetland, which is one of the six national wetlands declared as Ramsar sites [1].

Current environmental monitoring systems consists in periodic point sampling and measurement of physical-chemical and biological parameters, these systems are highly expensive and un-capable to describe the water quality of reservoirs of large extension and complex ecologic dynamics [2], as Cerrón Grande. Therefore, is necessary to

implement a new monitoring system that provides, in a cost-effective way, the spatial and temporal distributions of water quality parameters throughout the reservoir.

Simulation of dissolved oxygen and remote sensing

Dissolved oxygen is a key parameter for water quality monitoring. Its production and decay is governed by phenomena of photosynthesis, atmospheric exchange and oxidation reactions or inorganic and organic matter [3].

Water temperature and currents are key in the development of these interactions, since they determine reaction kinetics and spatial distributions of the agents respectively. In this sense, the approach for a new monitoring system in this study is based in the joint application of dynamic modeling and remote sensing as follows: Modeling of hydraulic, thermal and material transfer dynamics: A mathematical model of the reservoir is formulated through basic transient state equations of momentum, heat and mass transfer, kinetic models for dissolved oxygen production/decay phenomena and a heat budget model.

Reservoir characterization: The equations are solved using site- specific physical-chemical and biological data required by the kinetic models, and geographic limits used as modeling domain frontiers. This information can be acquired by field sampling and satellite observations, which gives place to the remote sensing techniques.

By satellite imagery, the borders of the reservoir can be defined, and its optical properties, as reflectance, can be mathematically related to water quality parameters such as algae concentration and Secchi depth, these relationships are known as remote sensing models. In this way, water quality information can be acquired as reflectances in multi-spectral satellite images of the reservoir [4].

Materials and methods

The methodology implemented in the development of the proposed monitoring system consist of a characterization of the Cerrón Grande reservoir followed by the development, run and calibration of the mathematical model of the reservoir.

A. Characterization

The following tasks were carried out in the dry season of 2013 (from February to May).

1) Physical-chemical and biological variables determination:

Data of dissolved oxygen, temperature (64 records), algae concentration, Secchi depth, BOD and ammonia nitrogen (6 records) was collected throughout the reservoir. 2) Tributary characterization: Water quality and velocity of significant tributaries during dry season was measured (8 records).

The data collected in 1) and 2) is to be used as boundary and initial conditions for the mathematical model and model calibration tasks. All data was collected at daytime in 1-day sampling times in a different date for each record set. 3) Remote sensing: The source for remote sensing operations is a reflectance-calibrated multi-spectral Landsat 7 image with acquisition date of March 24, 2013.

Reflectances are extracted for each data collection geographic point and remote sensing models are developed by stepwise method [5] with Microsoft Excel® multi-linear regression tool taking $R2 > 0.7$, critical F values < 0.05 and p values of < 0.05.

Remote sensing models are then applied to the satellite image to obtain concentration maps for the physical-chemical and biological variables over the extension of the reservoir.

B. Mathematical model

The mathematical model of the Cerrón Grande reservoir is developed and solved by the finite element method using Tdyn® computational fluid dynamics and multi-physics software environment. Basic transient state momentum, heat and mass transfer equations (see [6]), dissolved oxygen kinetic model (see [3]) and heat budget (see [7], [8], [9] and [10]) are specified along with boundary and initial conditions.

Model calibration is done by evaluation of RSR, PBIAS and R2 statistical parameters for the modeled and measured datasets comparison. As a result, the mathematical model gives the reservoir temperature and dissolved oxygen maps.

Results

Characterization

The maps for algae, BOD and ammonia nitrogen concentration and Secchi depth generated with the remote sensing models are presented in Fig. 2. Minimum R2 value was of 0.789 for the algae model.

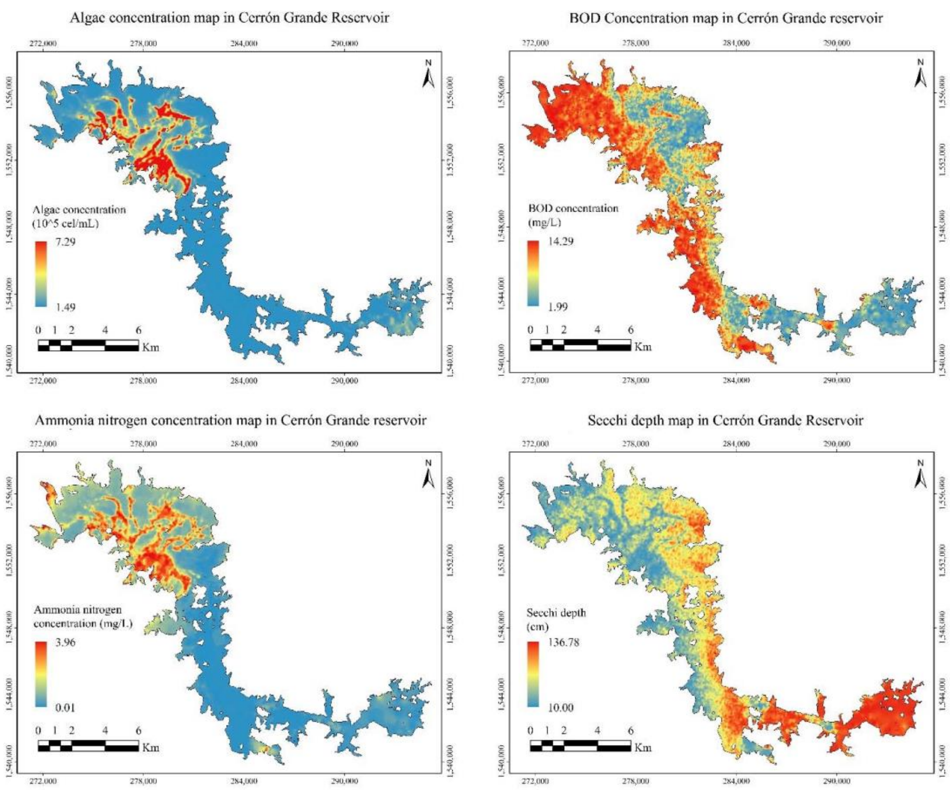

Figure 2. Concentration maps generated with remote sensing models.

Mathematical model

Temperature and dissolved oxygen distribution maps generated by the calibrated model are shown in Fig. 3, along with simulated – measured data comparison graphs. It can be seen that, despite the low number of data records and for the 1-day sampling time datasets, the model is capable to describe the diurnal variations of temperature and dissolved oxygen, since the modeled data approaches the central tendency of the measured data.

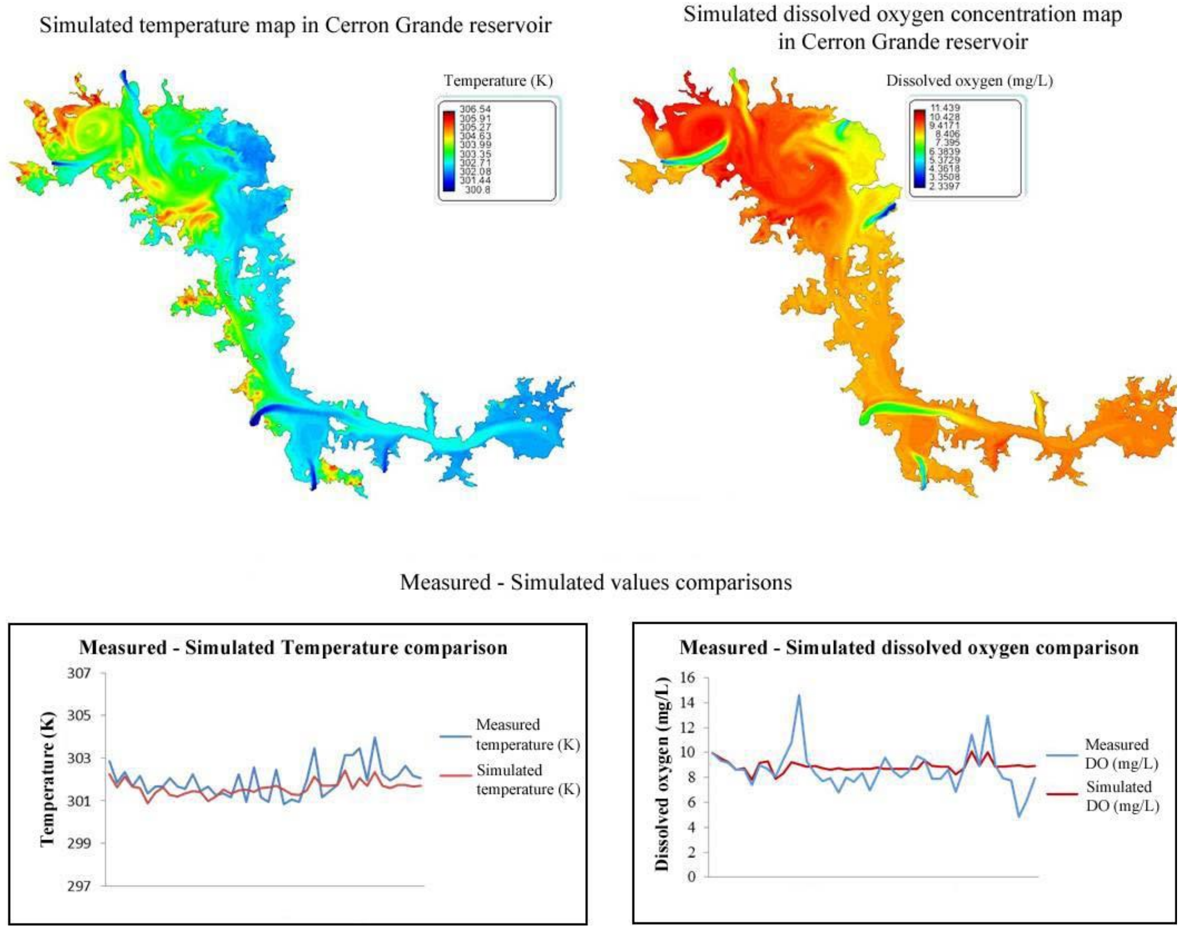

Figure 3. Mathematical model results and simulated – measured data comparisons

Conclusions

The applied characterization methods give sufficient information in order to completely develop the mathematical model; remote sensing has proven to be an integral and cost-effective method for the spatial, physical-chemical and biological monitoring of the reservoir, though wider data collection for improved further development is needed.

Calibrated model results confirm the possibility of a monitoring system based on a mathematical model. The development presented in this study must be extended with exhaustive field data information to take into account dissolved oxygen production/decay phenomena not considered in the present study and perform proper validation.

Results show that the mathematical model can describe the general state of reservoir water quality at the present study state, however, more BOD, algae concentration, ammonia nitrogen and Secchi depth data are needed for an operative state development.

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REVIEW ON THE HISTORY OF THE RESEARCH REACTOR

Introduction

A Nuclear Research Reactor is a device that generates neutrons. These tiny particles are used to check the composition of materials and to produce