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Orographic shading effect on water/sediment heat exchange in two dams of Guanajuato river, Mexico

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Abstract

Heat fluxes in dams affect the concentrations of dissolved oxygen and the liberation of potentially toxic elements (Fe, Mn, As and sulfides) from sediments. Sediments/water column heat exchange in dams traditionally is neglected by numerical models because it represents a few percent of heat exchange processes; however these exchanges become important in small reservoirs located at hilly areas. The present work attempts to focus on the importance of orographic shading in small dams (<1 Mm^3). Two dams, Esperanza and Santana, located at Guanajuato river basin, Mexico, between two physiographic provinces with very irregular relief were investigated. Hydrodynamic model for reservoirs, CE-QUAL-W2, was used to detect orographic shading effects in dams studied. A heat diffusive model was developed with finite element method to calculate atmosphere/water surface and sediment/water column heat fluxes. Results show that the percent of sediment/water column heat flux is 85% for Esperanza dam and 96% for Santana dam, while heat fluxes in atmosphere/water surface interface were of 15% and 4% for Esperanza and Santana dams, respectively. With this, the importance of heat fluxes in this interface are revealed, also the increase of these flows in relation to bigger dams in lower relief zones was quantified.

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Keywords: Orographic shading, heat exchange, sediments

1. Introduction

The main heat exchanges in reservoirs or dams are of two types: between air/water surface and the limits between sediment/water column[1]. Heat exchanges between inputs and outputs of water from tributaries, thermal effluents, and water withdrawals also affect the balance, but to a lesser degree.

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The heat exchange processes in dams are given by 82% between the atmosphere and water surface, and 15% between sediments and water column; the remaining 3% is energy exchanged by other processes[1].

For small dams located in hilly areas, where wind and orographic shading effects are important, the heat exchange rate between the atmosphere and water surface is reduced, and heat flows in the interface sediment/water column becomes more important[2]. Moreover, these fluxes control the conditions of dissolved oxygen in water, the distribution of contaminants, habitat fish species, etc., so that, these are an important variable for determining water quality.

A 2D model CE-QUAL-W2, referred to as W2, was used. W2 is a hydrodynamic and water quality model that describes both longitudinal and vertical variations of flow and water quality characteristics while assuming homogeneity along the lateral direction[3]. The W2 is also provided with a dynamic shading model that considers the effects of shading caused by mountains and vegetation around the dam. Although the W2 has some limitations, one of which is that even if including the heat flux process between sediment and water column, cannot display the magnitude and direction of these, complicating an adequate description and use of this information.

2. Material and methods

2.1. Study Site

Guanajuato river basin is located at the center of Mexico, between 101° 02'W - 101°20'W and 21°05'N - 20°52'N. This basin is mostly in the sub-physiographic province known as "Sierra de Guanajuato", which has an area of 100 km^2 and orientation NW-SE[4].

Sub-basin Esperanza-Soledad-Santana (ESS) (Fig. 1) is located in Río Guanajuato basin and contains three dams, two of them supply water to 40% of the population in Guanajuato City[4]. Table 1 shows the main features of dams Esperanza, Soledad and Santana.

In "Sierra de Guanajuato" the climate is temperate-semiarid, with contrasting extreme temperatures: hot summers and cold winters, low rainfall (between 600-800 mm per year) sparse vegetation and few clouds[4], here is where ESS sub-basin is located.

Table 1. Main features of Esperanza Soledad and Santana dams.

Dam	Area [ha]	Volume [Mm^3]	$Vol_{sediments}$ [Mm^3]	Vol P_{annual} [Mm^3]	Dam age [years]
Esperanza	16.1	1.2	0.61	13.1	102
Soledad	27.5	4.2	2.96	20.2	60
Santana	6.2	0.3	0.25	13.7	210

2.2. Sampling and data sources

In 2016 field campaigns in April 19th at the Santana dam and April 25th in Esperanza dam were carried out (Fig. 2). Temperature of water, sediments and air was measured. DIVERS were installed in dams' incoming rivers to get inflow and water temperature of rivers. Meteorological data (temperature, dew point, wind speed, wind direction, and percentage of cloud cover) were obtained from the Meteorological Observatory of Guanajuato City (http://smn.cna.gob.mx/emas/), 3.26 km from Santana dam and 4.05 km from Esperanza dam.

2.3. Orographic shading effect

Temperature of water simulations were made in Esperanza and Santana dams with the W2 for April 2016. First dynamic shading model included in the W2[3], was set on considering the topography, and then dynamic shading was set off with a flat terrain.

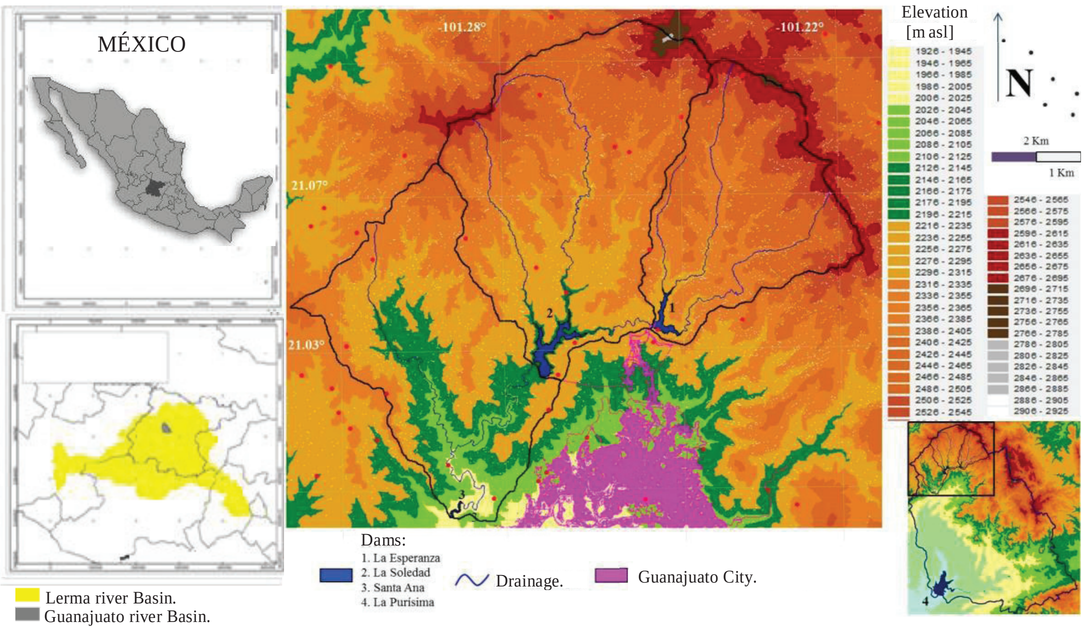

Fig. 1. Location of Río Guanajuato Basin.

2.4. Finite element model

A 2D finite element model to solve the heat equation was developed from Fourier's formula[5] (Eq. 1). Three phases (air, water and sediments) were set and measured data in sampling campaigns were used. Coefficients of thermal conductivity for standard atmosphere, freshwater and chemical sediment[6] (which is predominant in both dams) were used. It was considered that no flow of water between the column and the sediments exists, so that all heat exchange was basically produced by conduction.

$$q = k\frac{d\phi}{dx} \tag{1}$$

Where $\phi = \phi(x)$ is temperature, k is the thermal conductivity and q is the heat flux.

3. Results and discussion

Simulation results with W2 in studied dams, highlight the effects of orographic shading as the surface temperature of water decreases by 3 to 4 ° C in all water mass of Esperanza dam (Fig. 2b), and between 2 to 3 °C in Santana dam. (Fig. 2d).

This can be deduced from increased sediment/water column heat fluxes, as shown in Fig. 3, where atmosphere/water surface heat fluxes are very low, in range of -0.27 W/m^2 (corresponding to 15%) in Esperanza dam. At Santana dam, this flux is of 0.1 W/m^2 (corresponding to 4%), while sediment/water column heat fluxes are of the order of 1.5 W/m^2 (corresponding to 85%) in Esperanza dam and -2.5 W/m^2 (corresponding to 96%) in Santana dam, contrary to values reported for larger water bodies[1].

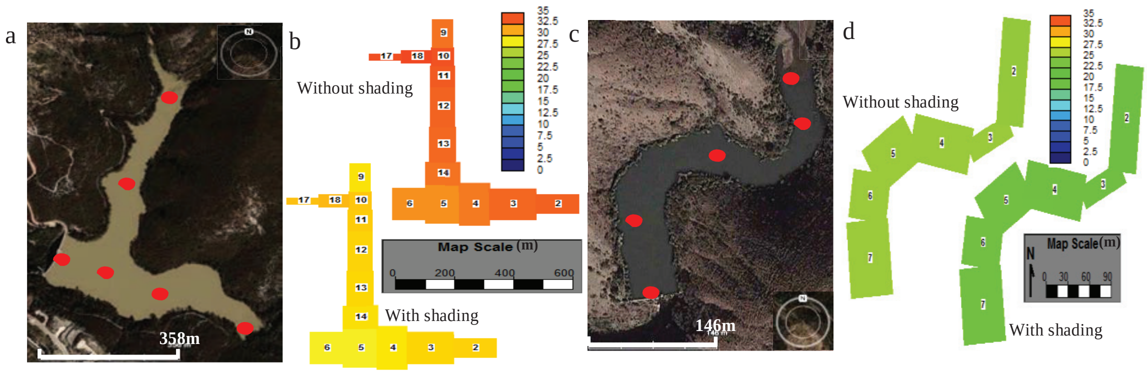

Fig. 2. (a) Esperanza dam; (b) W2 temperature simulation in Esperanza dam (°C); (c) Santana dam; (d) W2 temperature simulation in Santana dam (°C). Sample points are shown in red dots.

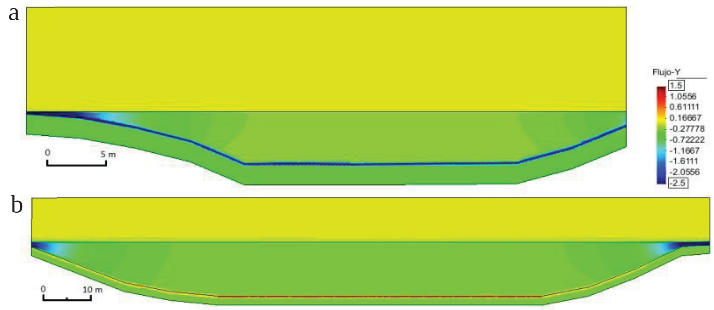

Fig. 3. Heat fluxes (W/m2). (a) in Santana dam; (b) in Esperanza dam.

4. Conclusions

In small dams located in hilly areas sediment/water column heat fluxes take great importance, as they are approximately ten times greater than atmosphere/water surface heat fluxes. That is why hydrodynamic models should consider these processes, and also be able to view them, as this can serve to detect areas with lower water quality by decreasing dissolved oxygen or by increasing pollutants that can be released from the sediments.

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