An Integrated Methodology for the Environmental Assessment and Management of Lake Izabal (Guatemala)

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Abstract: Lake Izabal is the largest in-land water body of Guatemala with great importance due to the social and economic interest in the country. It has many environmental problems due to the pressure of agriculture, fisheries and mining in its catchment and basin area. In addition, the lack of available data makes quite difficult any kind of study. Authors make use of the few existing data sets and, together with numerical modelling, build a methodology for its study, developing environmental diagnostic tools.

Key-Words: - Lake Izabal, altimetry, remote sensing, hydrology, numerical models

1 Introduction

Fresh inland and coastal waters support the terrestrial ecosystems in which most of human activities are based. Among these, fresh waters can be globally found as ice caps, snow, underground (as soil moisture and underground reservoirs) and surface waters (as rivers, lakes, and wetlands). Among the continental waters, natural lakes are essential study subjects because of their complex relationships between the atmosphere, surface and underground waters. Additionally, lakes are affected by upstream land/water uses for agriculture, industry and/or human consumption [6]. The knowledge of the physical processes on lakes is of utmost importance because these processes determine their chemical, physical and biological spatial distribution [9]. Besides, it is necessary the information about the water mass budget of lakes, in order to improve its water management [5].

Traditionally, the lake's physical processes study requires field campaigns for the acquisition of in-situ measurements, which demand high financial investments. Moreover, it is necessary the establishment of monitoring programs in order to obtain continuous time series. Nevertheless, numerical models and remote sensing techniques have been widely used in those environments. Numerical modelling has been used in different works about physical processes in fresh waters, such as lakes hydrodynamics [12] [9] [17], rivers water discharge and sediment load [22] [10], sediment transport processes in lakes [11] [23], among others. On the other hand, some hydrologic studies have been done by using remote sensing products and techniques: lake levels retrieval from altimetry [3] [6] [18] [19] [20], coastline detection and inundated area estimation from Synthetic Aperture Radar (SAR) images [8] [5] [18] [19] [20], the Shuttle Radar Topography Mission (SRTM) applied to geomorphologic studies in hydrologic basins [4] [13], and optical/radar imagery for land use applications [24].

This work focuses on Lake Izabal (Guatemala), the largest of the country. This has great importance from scientific, ecological and social points of view. A number of studies have been carried out on the physical, chemical and biological parameters of the lake's water quality in the past [2] [7] [21]. However, the physical features of Lake Izabal were still poorly known, until now [25]. Conceptually, this research work was focused on the assessment of the following lake's physical processes: the water mass balance and the sediment transport. Thus a better knowledge of these processes improves the understanding of other lake's features like the water quality, nutrients distribution, biological production and residence time, among others. The water mass balance considered the inputs (rainfall, runoff and groundwater), outputs (evaporation, surface outlet, and seepage), and their relationships with the water volume stored in the lake. Likewise, the sediment transport analysis included the particles detachment, transport and deposition within the basin, the total sediment load entering the lake, and the particles transport processes within the lake, such as diffusion-advection and wind-forced water movement.

The main objective of this work is the development of an integrated methodology able to estimate the above mentioned processes, combining numerical models simulations, remote sensing products and in-situ data. The study period was extended to four years (2003-2006) because of data availability. The research project was designed based on the Lake Izabal biophysical and social characteristics and the state of the art about the ecosystem. In addition, new techniques and scientific approaches applied to other fresh water systems were used. This work is the result of different research activities carried out in the group on Remote Sensing and Oceanography of the University of Cadiz (Spain). Besides, some of the analysis included in this work were developed in the Dipartimento di Scienza della Terra, of the University of Ferrara (Italy).

Organization is as follows. Section 2 is devoted to the description of the area and the available data sets. Section 3 presents the used numerical models. The integrated methodology and its results are presented in Section 5. Finally, the conclusions and drawn in Section 6.

2 Area and data sets

2.1. Area

Lake Izabal is the largest inland water body of Guatemala. It has an elongated irregular shape with an area of 673km2 and a mean depth of 12m (Fig. 1). Its main inputs are due to the Polochic-Cahabon rivers and an amount of minor contributors. The only way out is toward the Caribbean Sea through the so-called Rio Dulce [14] [15] [16].

One of the problems is the lack of information about the inputs and outputs flow rate. Residence time is also poorly known. Authors will give some estimation about them.

2.2. In-situ datasets

Some time series are available in the area. There are five meteorological stations with data from 1987 to 2006. The most useful data for this study were the temperature and rainfall. Short time wind records were available close to the Caribbean.

The data sets about the soil were taken from the last atlas of MAGA [14] [15] [16] updated in the 2001. The susceptibility to erosion was taken from [2] [7] [1].

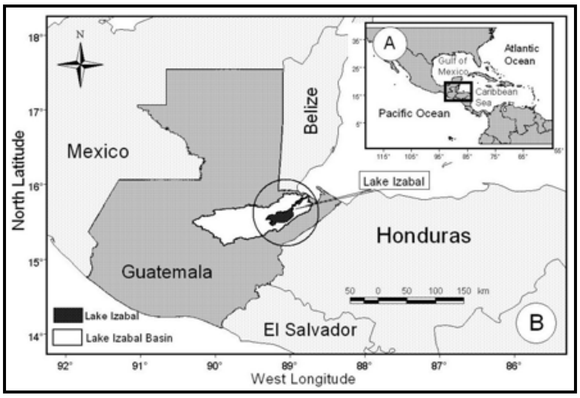

Figure 1: Area under study is the Lake Izabal.

The geomorphologic information was taken from the atlas of [14] [15] [16], isolating the basin of each river (major and minor tributaries) to be treated separately. The topography was taken from the SRTM data base from the files of the USGS (United States Geological Survey) (Fig. 2).

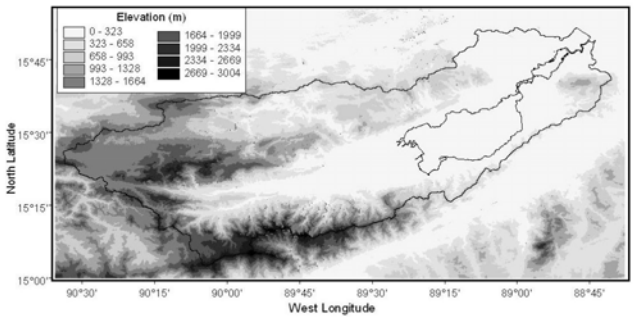

Figure 2: Topography of the catchment area of Lake Izabal.

Social data, useful for the evaluation of the antropogenic pressure, was gently provided by the AMARSULI. This institution gave a seven years long (1987-1994) time series of in situ lake level and Polochic discharges onto the Lake Izabal.

Finally, some remote sensing products were used. These comprise ENVISAT altimetry data of the Lake Izabal, RADAR-SAT and MERIS imagery.

Because of the lack of information some numerical models have been used to build up synthetic series. Models have been tested with the available data and the series compared to the available ones.

3. Numerical models and partial results

3.1. Hydrology

The water discharge of the tributary rivers was simulated with the climate-driven water discharge model, HYDROTREND v. 3.0 [10] [22]. Firstly, the suitability of the model was assessed on the Polochic River basin. The 7 years (1987-1994) dataset of daily in-situ gauges was used to assess the soundness of the model estimations. The mean discharge was 85.7/81.7 m3/s with standard deviations of 61/52 m3/s for in-situ and modelled discharges. Both time series shown a similar variation pattern forced by the rainy and dry seasons. Then, the model was applied for all the tributary rivers in the study period (2003-2006) (Fig. 3).

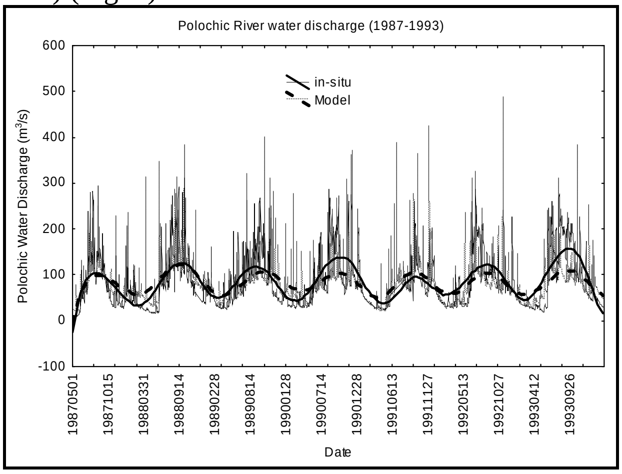

Figure 3: Water discharges from Polochic river from in-situ data and from HYDROTREND model.

3.2. RUSLE

The simulation of spatial variations of soil erosion and time variation of sediment load was accomplished by the combination of Revised Universal Soil Loss Equation (RUSLE) and HYDROTREND models [10] [22]. The final product is the erosion map of the basin (Fig. 4). The relationship between soil erosion and sediment load was calculated by the Sediment Delivery Ratio (SDR), which was computed from its relationship with the catchment area. The first simulations were run for the Polochic River. The erosion map of the Polochic basin showed a very high erosion risk in average (109 × 105 kg/km2/y of modelled soil loss). However, almost 25% of the Polochic basin area has low erosion risk, mainly in the lowlands, evidencing particles deposition regions. HYDROTREND simulates the sediment load by its relationship with the water discharge. This model produces daily sediment loads of the river. Unfortunately, there is only two in-situ measurements of total annual sediment load of the Polochic Basin: 1.53 × 109 kg/y taken in 1999, and 4.78 × 109 kg/y in 2003. Thus the reliability of the estimations was limited to verify that the magnitude orders were in the same range of the only gauge. The annual sediment loads modelled were 2.45 and 2.85 × 109 kg/y for HYDROTREND and RUSLE respectively. For the in-situ measurements years (1999 and 2003) the modelled values were 2.54 and 2.94 × 109 kg/y, respectively.

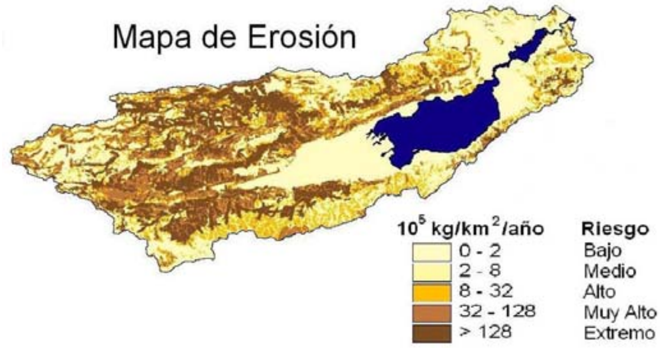

Figure 4: Estimation of potential erosion from RUSLE and HYDROTREND

3.3. Turbulent diffusion

The particles diffusion-advection model was developed based on the classical diffusion expression [11]. It was modified by including water velocity components and a decay coefficient for non-conservative particles. The border conditions depended on the lake coastline and the drainage class of the soil in the shore. The initial condition was a cold start. The sources of sediment were considered as a constant input and the value used was based on sediment concentrations from in-situ measurements taken in previous works (in different periods from 1993 to 2004). The resulting sediment concentration maps, after a simulation of one month, indicate greater pollution in the south-western side of the lake, caused by the Polochic river sediment load, the predominant north-eastern winds, and the lake shape (Fig. 5). In the southwest of the lake, the concentrations were around 20 mg/l without currents, increasing up to 27 mg/l for a constant speed of 3 m/s of north-eastern winds. The sediment concentrations were below 1 mg/l in the rest of the lake body.

3.4. Wind driven circulation

The wind-forced lake water movement model was based on the Navier-Stokes equations solution, and the Lake Izabal bathymetry [11]. The model was initially run with constant 3 m/s north-eastern winds until achieving the steady state of circulation (approximately after a 2 months simulation time period). The steady state was attained when the difference of kinetic energy between time steps falls almost invariable. Once the steady state was reached, the winds input were hourly changed according to the meteorological station measurements (for a simulation of one year). The lake's water velocity fields presented magnitudes between 0.002 and 0.075 m/s being the highest in the lake center (Fig. 6). The flow direction was oriented slightly to the right of the wind direction, due to the combination of lake's morphometry and Coriolis Effect.

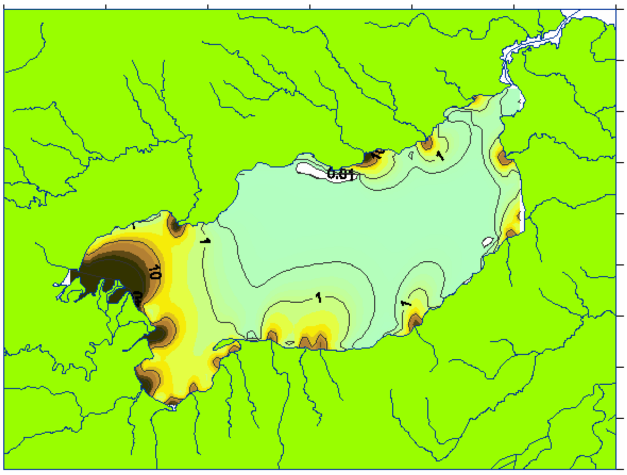

Figure 5: Snapshot of the turbulent diffusion model

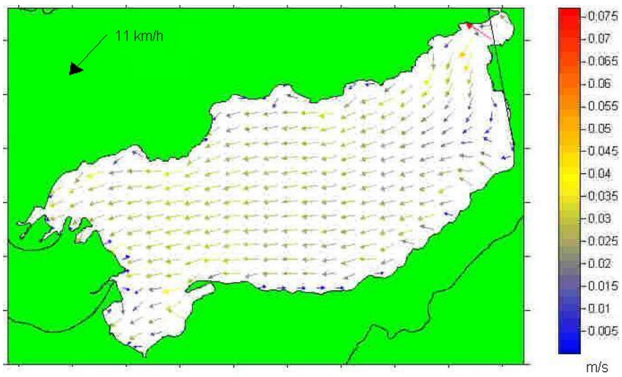

Figure 6: Snapshot of the wind driven circulation model.

3.5. Volumen fluctuations

The water volume fluctuations of the Lake Izabal were determined from the joint estimation of the lake surface height and inundated area variations [3] [6]. The lake level derived from RA-2 yielded a strong correlation with in-situ gauges (r2=0.83). Likewise, the inundated area variations from ASAR imagery (Fig. 7) presented a high correlation coefficient with simultaneously acquired water level in-situ gauges (r2=0.9). The development of rating curves enabled the estimation of inundated area and stored water volume time series. The average inundated area and stored volume estimations were 674.21 × 106 m2 and 8506.5 × 106 m3 respectively. The issued features varied from 672.4 × 106 m2 and 677.2 × 106 m2 for inundated areas and 8271.2 × 106 m3 and 9018.1 × 106 m3 for water volume storages. These extreme events occurred in a level variations range of 1.5 m from lowest to highest surface heights (Fig. 8). The minimum occurred on December 2005 and the maximum in July 2006. The time series of lake level, inundated area and water volume show seasonal variations forced by the rainy and dry seasons. The monthly water balance is presented in Table 1 and the end of the work.

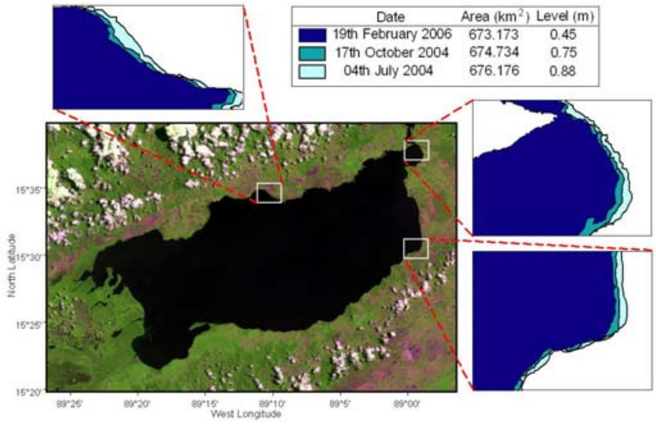

Figure 7: Area variation of the lake Izabal from ASAR imagery.

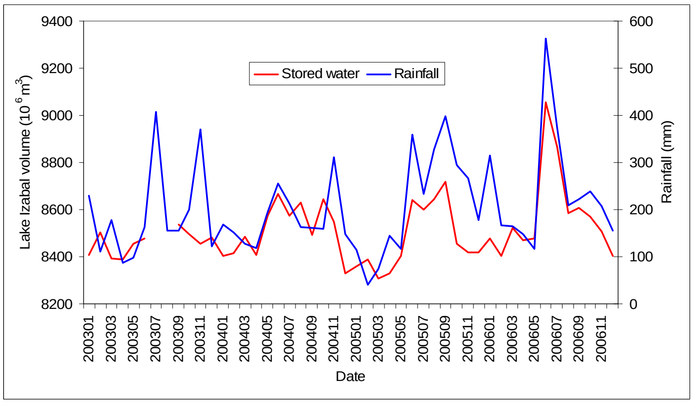

Figure 8: Comparison of the stored and rainfall inputs.

4 Discussion

Regarding the catchment features, the climate conditions obtained from in-situ measurements evidence that the annual rainfall varies from 1825 to 2904 mm within the basin (during the study period), with two defined seasons: rainy (May to October) and dry (November to April). According to the Guatemalan geo-information database, the basin showed a great variability of soil types, with different drainage and erosion susceptibility classes. Based on the SRTM data, the catchment relief varies from 0 to 3004 m Above Mean Sea Level (AMSL) with an average elevation of 734 m AMSL. The combination of remote sensing images (Landsat and SAR) and high resolution aerial photos made possible the land cover classification of the catchment. The results found that 36% of the area is covered by dense forest, 29% by intensive agriculture and the other 35% of the area is divided in 12 different land cover classes (in average from 2003 to 2006). Finally, the morphometry of Lake Izabal is described as an elongated irregular shape, with high surface extension (673 km2) and low depths (mean 12.33 m).

The water mass balance of Lake Izabal was computed by combining meteorological in-situ data, water discharge simulations, and stored water volume variations from remote sensing data (see Fig. 9 along the present discussion). The study was extended to four years (2003-2006). The groundwater inputs and outputs were considered to be balanced between them and negligible in comparison with the surface waters and direct rainfall, following other author's results in similar waterbodies. The average of total surface water feeding the lake amounts 418m3/s, where approximately 78% of that water is contributed by the complex Polochic-Cahabón. The mean monthly volume of water from direct rainfall over the surface is around 178 × 106 m3. The direct rainfall inputs over the lake are one order of magnitude lesser than the surface water inputs (an average of 1100 × 106 m3 per month), giving a monthly total water input of 1278 × 106 m3 in average. The water volume stored in the lake is almost 7 times greater than the total water input. Therefore, the lake works like a buffer regulating the surface water outlet (Rio Dulce). The water mass conservation of the system was equalized in order to determine the surface outlet flow rate. The Rio Dulce mean water discharge was estimated to be 452.7 m3/s. The monthly volume of surface water outlet and direct evaporation losses were 1228 × 106 m3 and 50 × 106 m3, respectively. The difference between them (96.1 and 3.9%) was greater than the difference between the inputs (86.1 and 13.9% for surface waters and rainfall respectively). In addition, the dates of the extreme events observed coincide with dates of extreme events of regional climate change indexes such as El Niño Southern Oscillation and the Tropical North-Atlantic index, evidencing that some links could exist between the water balance and climate changes.

The sediment transport processes of the Lake Izabal system were studied through the assembling of the developed models (soil loss, sediment load, diffusion-advection and wind-forced water movement). The combination of thematic maps within a GIS environment produced the catchment erosion risk map. The simulation estimated a mean soil loss of 83 × 105 kg/km2/y, representing very high erosion risk in the Lake Izabal catchment territory. However, after the particles detachment, most of the sediment particles are deposited in the lowlands (low erosion risk) instead of being transported by the rivers as sediment load. The total tributary rivers sediment load sums 129.2 kg/s. About the 58% of that sediment load entering the lake is contributed by the complex Polochic-Cahabón. The sediment load time series were closely related with water discharge, yielding a correlation coefficient of 0.92 in a relationship of exponential nature. Each tributary river sediment load time series was connected with the diffusion-advection and wind-forced circulation models. The sediment concentration fields simulated for several conditions represent the allochthonous contributions while the autochthonous production remains beyond the scope of this Thesis. During April 2005, when the longest water deficit was found (high evaporation, low rainfall, low water discharge, etc.), the sediment concentration distribution of the lake was mainly forced by the Polochic river sediment load. This was caused by the low sediment loads of the tributary rivers, and the water currents which inhibit the particles to be transported to the lake center. During the other extreme, in June 2006, abrupt erosion forces were found (rainfall and surface runoff) and consequently, sediment loads. The spatial distribution of sediment concentrations, in this period, demonstrated more influence of all the tributary rivers. All the sediment plumes grow to the lake's center with concentrations above 1 kg/m3. In both extreme periods, the south-western side of the lake presented the highest sediment concentration fields (low and high sediment loads). Thus, the Polochic river mouth works as a buffer for the Polochic river sediment load and the Lake Izabal has the same role preventing the transport of sediments through the Río Dulce River to the Caribbean coast. The sediment plumes of the rivers do not reach the lake center (even during rainy seasons), evidencing that the sediment concentrations of the lake center are mainly caused by autochthonous production.

5 Conclusions

The combination of remote sensing techniques with in situ data sets and numerical models has allowed us the study of the spatial and temporal variability of many factors. The rainfall can vary from 1805 to 2904mm/year, with two seasons (rain season: May to October; dry season: November to April). There are many types of soils in the area with very different drainage and erosion susceptibility. By the SRTM data, the heights in the catchment area came from 0 to more than 3000m. The use of the land presents great variety, from forest to intensive agriculture.

It has been found that the HYDROTREND model can be effectively used to study and simulate the river discharges. The discharge of the Polochic river was estimated in 85.7 and 81.7 m3/s (for rain and dry season respectively).

The soil losses were studied and modelled combining the HYDROTREND and RUSLE models. The final erosion map gave a high risk of erosion with an estimation of 109·105 kg/km2/year.

The combination of the wind driven circulation and turbulent diffusion models gave the pattern of how the sediment evolutes in the lake Izabal, following some preliminary studies.

The water volume fluctuations were studied by the combination of ASAR imagery and altimetry with the results of an area of 674.21·106 m2 and 8506.5·106 m3.

The computation of the water mass balance was possible from the integration of all models. Ground water were not taken into account because the lack of these data. The input flow to Izabal was estimated in 418m3/s, from rain is 178·106m3/month in average. The estimated outflow through Rio Dulce was estimated in 452.7m3/s.

Finally, authors are working on an automated model to the environmental management of Lake Izabal. It is expected that it can help to the sustainable development of the area.

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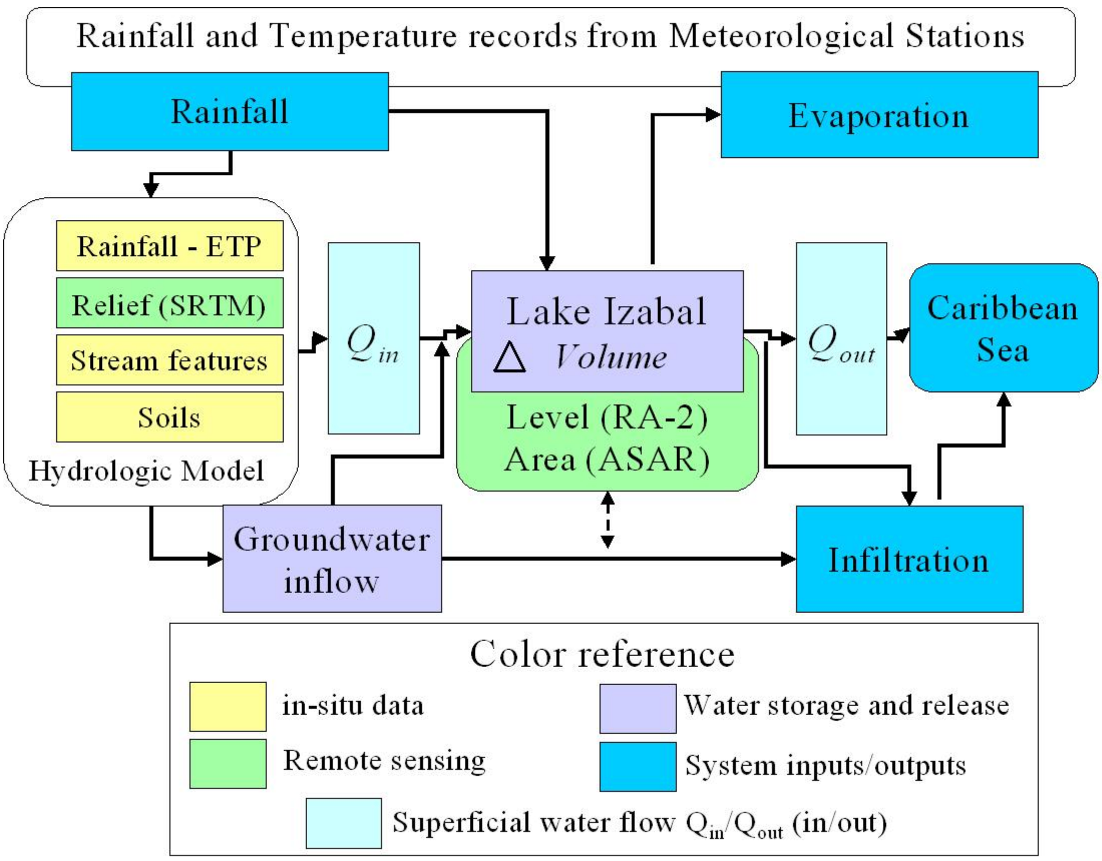

Figure 9: Integrating the different models.

Water Balance	**Rainfall (*P*)**	**Evaporation (*Ev*)**	**Inflow (*R*)**	**Outlet (*D*)**	**Lake volume (*V*)**
Month	**10^6 m^3**				
January	179.030	74.116	990.956	1092.319	8412.738
February	97.404	69.353	741.153	753.703	8428.238
March	90.301	81.757	740.126	749.605	8427.304
April	77.821	85.507	756.603	776.493	8399.728
May	85.200	92.072	898.197	812.518	8478.534
June	224.142	89.026	1346.506	1249.844	8710.313
July	224.001	90.691	1677.096	1885.437	8635.282
August	124.676	87.716	1374.884	1453.743	8593.383
September	148.897	83.345	1121.196	1191.158	8588.972
October	139.439	82.220	1327.597	1432.835	8540.953
November	220.811	73.594	1359.440	1565.368	8482.242
December	112.852	73.656	868.067	980.617	8408.888
Average	143.714	81.921	1100.152	1161.970	98.776*
%	11.6	6.6	88.4	93.4	8**
Imbalance	0.025				
*average of the monthly variations (Standard Deviation) ** percentage of the volume variations related to the total water flux					

Table 1: Lake Izabal monthly water balance (2003-2006)