Satellite Images as a Tool for Hydrodynamic Modelling

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Abstract – The development and construction of a hydrodynamic distributed model designed to simulate discharge and water levels as a function of space and time depends strongly on the knowledge of the vegetational, edafological and topobathymetric aspects of the physical system under study.

In the specific case of the Esteros del Ibera, a large freshwater wetland located in the Province of Corrientes, NE region of Argentina, more than ten million hectares of flooded lands, which are difficult to access, prevent any in situ collection of the required information. The complex geological evolution of the Iberiana depression, that includes successive displacements of riverbeds, the effects of exogenous processes of erosion, and the succession of vegetation, strongly conditions the general flow of the system.

Based on the study carried on by INCyTH-ICA in 1980, we propose in the one hand an updating of information through the use of satellite images that allows the inference of the submersed bathymetry in a digital elevation model (DEM). On the other hand, the processed satellite information using habitat classification techniques, allows the fitting of Manning's roughness parameters that condition the surface flow. Both techniques converge in the formulation of the physical foundation of the hydrodynamic model for the Esteros del Ibera.

I. INTRODUCTION

The freshwater wetland ecosystem under study is that of the Esteros del Ibera, in the Province of Corrientes, in NE Argentina. The region is located between latitudes 27°30' and 29° S, and longitudes 56° 25' and 58° W. The system's area has been estimated in 13,780 Km². It has a triangular shape some 250 Km long and between 20 and 140 Km wide. A difference of only 20 m in the water levels between the headwater and the outlet is observed along 250 Km, with a smooth general slope of 1/10,000 from the NE to the SW. Roads and human settlements are to be found only on the surrounding areas, not within the wetlands. Nowadays, 90% of its area is covered by permanent or temporary floods, depending on the balance of atmospheric input and output, the surface runoff, the underground water balance, as well as on the previous storage level. Indeed, the behavior of the system is strongly conditioned by vegetation. The weedlands (malezal) and marshlands (esteros) cover some 67% of the total area. The deeper

wetlands are for the most part covered by aquatic vegetation forming characteristic "embalsados" (Neiff, 1981) or dammedlands-floating vegetation islands which cover some 21 % of the permanent flooding area. The dammedlands are formed by accumulation of interweaving aquatic plants that create floating platforms strong enough as to allow the growth of other plants and trees over them. These floating islands are generally 1 to 3 m. thick and can go up or down with the fluctuations of water level. The lagoons and the permanent channels are the only free water areas and conform only a 2 % of the system. Their boundaries have not changed substantially with time, even though the variations in water levels have been important. The reason for them remaining unchanged may be given by the fact that the borders are dammedlands (*embalsados*) rather than firm soil. The remaining 10% of the system is firm soil which basically surrounds the wetlands. In general terms, as a consequence of the strong relationship between morphological, hydrological, climatic, and edafological factors, the macrosystem may have a regulatory mechanism that corresponds to an ultrastabilized system that has a long response time and a tendency to reach a dynamic equilibrium with the environment (INCyTH-ICA, 1981 a). Hence, the Ibera wetlands are composed by a mosaic of open water, permanent shallow water covered totally or partially by fixed and floating aquatic vegetation, temporary inundated lands with alternative and successional patterns of vegetation and permanent emergent land, mainly the central sandy hills and its borders. For this reason, the knowledge of the water level at each point of the system is essential to develop any other model of species population because of the strong relationship between animal and vegetal species with water. Temporal and spatial variations in the storage of water cause changes in vegetation patterns and, consequently, movements and changes in the population structure of animals living inside the wetland. For this reason, the construction of a hydrological distributed model at landscape scale is necessary, but the large and variable area that conforms the Ibera ecosystem and the lack of knowledge of the hydrogeological characteristics create several important difficulties.

In wetland systems, there is a strong and variable relationship between surface, subsurface and groundwater storages, but no study was carried on in Ibera in order to quantify the variables involved that link them. The full geology and hydrology of the system is unknown and, additionally, there is no measure of ground inflows and outflows. However, we have seen that, under normal conditions, the ultra-stable Ibera ecosystem responds tightly to atmospheric processes. For this reason, a closed and coincident superficial and subterranean theoretical watershed was considered and a first approach to a surface flow model was built searching to adjust it to stage data available in open water sites inside the system.

Being unable to use classic hydrologic methods developed for small scales in controlled systems, the challenge here is to construct a simple model with an appropriate spatial and temporal resolution that reflect the state of each portion of the system for each time step.

II. METHODOLOGY AND RESULTS

The spatially distributed water balance model applies the Mass Conservation Law to describe the mass balance within each spatial unit, and couples a momentum equation which defines the water movement between cells.

When large temporal and spatial scales are used, discrete approximations of the essentially continuous hydrologic processes become a source of potential problems. In place of continuous movements of water and constituents over the area, we need to deal with essentially discrete motions, when large volumes of material are moved over large distances on relatively rare occasions (Voinov et al., 1998).

The simplified approaches to surface water fluxing more commonly used in 2-dimensional overland flow are based on the kinematics wave approximation of the Saint Venant's equations (Beven and Wood, 1993).

The complete Saint Venant equations of the mass conservation equation (1) and the momentum equation (2) are:

$$\frac{\partial A}{\partial t} = -\frac{\partial F}{\partial x} + q \quad (1)$$
$$\frac{1}{A}\frac{\partial F}{\partial t} + \frac{1}{A}\frac{\partial (\beta F^2/A)}{\partial x} + g\left(\frac{\partial h}{\partial x} + S_f\right) = 0 \quad (2)$$

where F is the flux of water between cells, A is the cross-sectional area of water flux, q is the lateral inflow or outflow, h is the surface water elevation above sea level, and S_f is the friction slope.

In this case, the horizontal flow between cells is simulated using slope-area method, which evaluates the friction slope using a uniform, steady-flow empirical resistance equation such as Manning equation (3).

$$F = AR^{2/3}G^{1/2}/M \quad (3)$$

were R is the hydraulic radius, G is the slope of the energy gradient and M is the coefficient of Manning of surface roughness.

The equations of conservation (1) and equation of approximation of moment (3) in their discrete forms are

$$D_{i}(t + \Delta t) = D_{i}(t) + (F_{i-1}(t) - F_{i}(t)) \Delta t / S \quad (4)$$

$$F = sgn(H_{i} - H_{i+1}) \sqrt{|H_{i} - H_{i+1}|} D^{5/3} \sqrt[4]{S} / M \quad (5)$$

where S is the area of a square cell, H is the hydraulic heads (m) of the cell, E is the cell elevation above sea level, and the subscript describe the link between neighbor cells as can be see in the next figure (Fig.I) (Voinov et al, 1998).



Fig.I. Geometry of flux between two adjacent cells.

Two computational schemes can be used to model 2dimensional overland flow: implicit or explicit. A computational simple explicit method was used. Courant's

necessary but not sufficient condition
$$\frac{\Delta x}{\Delta t} \ge \frac{F}{S}$$
 is

proposed to be verified due to the instability of the explicit scheme. Due to this, a short time step must be considered, which becomes a problem at the moment of evaluating the computational effort.

The model assumes homogeneity in physical and hydrologic characteristics and simulates hydrological processes within each grid cell. The hydrological processes within the cells are rainfall, evapotranspiration and seepage.

Data input: Spatial data

A <u>Topographic map</u> was created using information from the Military Geographic Institute (IGM, Instituto Geográfico Militar). Nineteen maps in the scale 1:100000 were required to cover the study area. The main information retrieved from the maps were the Level Curves (LC). The LC were used for the definition of the limits of the watershed by using a Geographic Information System (GIS). The GIS utilized was ERDAS 8.4. This was performed by first digitalizing the LC and then using the GIS functions to define the watershed.

In some places information such as bathymetric data was missing, while in others the LC presented some discontinuities. In order to solve the lack of information, the maps were completed with data retrieved from other documents. The additional data were recovered from phytogeographic maps, from soil maps developed by INTA (Instituto Nacional de Tecnología Agropecuaria), from geomorphological studies and flux analysis maps (Estudio del Macrosistema Iberá–ICA-1981). These were added to remote sensing data and the information provided by the bathymetric studies made by Laboratorio di Idrobiologia di Roma for the INCO DC project. The results allowed to infer the topography in the areas where the IGM topographic maps are incomplete. All the information was drawn by hand into a unique topographic map. Finally, the map was digitalized.

The <u>Digital Elevation Model</u> (DEM) was defined by bidimensional interpolation of the previously digitalized topographic map. The DEM thus created was resampled in order to obtain a DEM with a spatial resolution of 180 meters. This is required for a later overlapping with SAC-C satellite images. In order to run the watershed definition process, is was necessary to smooth the DEM using a mean filter in order to remove some of the angularities of the linear interpolation.



Fig.II. Smoothed DEM of the Iberá system.

After the watershed definition process was finished, the GIS internal functions created a vector file that delimits the watershed image obtained.

In order to develop an index for landscape classification. Modified Tasseled а Cap (MTC) transformation was applied to SAC-C images and Brigthness, Greenness and Wetness bands were obtained. The MTC transformation used was suggested by S.Loiselle & L.Bracchini, University of Siena (unpublished pers. com., see work presented by Ruiz-Moreno et al.). When the MTC transformations were combined, a so called Synthetic Map was obtained and used as a base for an unsupervised classification. With the aims of developing an index to evaluate the Vegetation Roughness parameters that conditions the surface flow in the Hydrological Model and working from the images in the inner watershed, a Wetness Index (from MTC) was taken into account from a threshold value that represent areas with permanent water. The inner watershed map was classified with ISODATA clustering technique obtaining 8 classes of terrain with different roughness.



Fig.III. Spatial distribution of the Roughness Coefficients.

Land elevation data is required to describe the physical features of the modeling domain. The domain is formed by 0.0324 Km^2 grid cells which cover the 14,000 Km² of the surface system, in concordance with the pixels (180 x 180 m) of the satellital images utilized. The total number of cells in the minimal rectangle that contains the basin are 1245 x 1025. The watershed image (a matrix of zeros and ones) is utilized to cut this rectangle and to obtain the modeling domain where the processes are simulated.

Over the basin thus defined, initial parameters are assigned to each cell using the image of roughness parameters obtained with the Modified Tasseled Cap Transform method applied to the Wetness Index image.

Temporal data

A fixed one-day time step is used in the model, due to the periodicity of the available hydrological data. All the hydrologic processes are modeled within one time step.

The available historical records of daily precipitation, discharge, stage, and monthly evapotranspiraton data by station are summarized in Figure IV and one period of six months is selected in order to obtain the optimal density and length of time series.



Fig.IV. Temporal and spatial distribution of available data.

Initial and boundary conditions

Boundary conditions refer to the time series of flows at the peripheral cells of the model domain. The external borders of all peripheral cells, except the cells of the Corriente River, were identified and no-flow boundary condition was imposed on them. The boundary condition at the Corriente River was defined in terms of mean historical discharge during the first stage ("filling" of the watershed) and with mean daily discharge data series corresponding to the above mentioned period once the "filling" is completed.

From an initial condition of stage (water level), homogeneously distributed over the system surface, a constant input is added to each pixel. With the aims of reaching the water levels observed at the initial time in four sites located inside the borders of the system, a subroutine for the optimization of the coefficient matrix is used. When the error between observed and calculated stages reaches a minimum, it indicates a first adjustment of the coefficient matrix for the initial time considered, that is January 1st., 1977. At the same time the initial conditions for the second step are obtained.

Starting in January 1st., 1977, the atmospheric balance is calculated in each pixel, pondering with Thiessen polygons precipitation and evapotranspiration recorded in each of the stations. Observed daily discharge are used to set boundary conditions at Paso Lucero, in the Corriente river. The optimization is now done taking into account the stages observed at nine days in between January 1st. and August 1st., 1977. These nine days are chosen among those when data has been recorded in all stations, taking at least one such day for each month. An optimal coefficient value and an adjusted stage is calculated for each pixel and is later used as the initial condition for running the simulation.

Calibration

The physical parameter used to calibrate the distributed model is the Overland Flow Roughness Coefficient in each cell. Initial values are taken from the literature and the purpose of this first approach, in spite of the limitations and strong simplifications, is to improve the adjustment of the calibration of parameters by incorporating as much available data as possible and to obtain a close agreement between the model output and the historical stage data at Ibera Lagoon. Model calibration aims at the fact that a well calibrated model enhances its predictive capability.

As a first approach, a static definition of OFRC has been used. In future developments a sequence of images will be used in order to introduce seasonal landscape variations.

III. CONCLUSIONS

This methodological approach has been attempted in order to produce a distributed hydrological model when the available in situ data is scarce and discontinuous. The final objective is to have a tool that may help answer a variety of questions related to the impact of human actions (i.e. construction of megadams) and activities (i.e. extraction of water for agriculture) developed in the periphery of the system. Given that the hydrogeology of the Iberá system is unknown, such a tool could help simulate scenarios in order to understand the effect of past disturbances in particular locations as well as possible future disturbances.

Presently, the first stage, the "filling" of the watershed, is being tested and a preliminary adjustment of the parameters is obtained. Average constant values taken from the atmospheric water balance are being considered as inputs, and average constant discharge is considered as boundary condition. Numerical oscillations occur due to the selected spatial and temporal scales, and are being analyzed.

In a second stage, with new and more realistic initial conditions and coefficients obtained from the "filling" process, the model is being run with the purpose of adjusting the parameters until the initial water levels in the cells at day one are obtained. Thus the stabilized model is obtained.

Finally, the simulation initialized at day one with real input and boundary conditions, to which arbitrary disturbances in space and time can be added, can be run and the output can be compared with stage data in the lagoons.

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