The integration of mathematical models of the dams in GIS

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Abstract. Mathematical models (MM) applied to hydraulics are a consequence of the union between alphanumeric information and geographic information in a GIS. They are increasingly necessary to carry out planning, forecasting. Having a reliable model would favor operators in the daily tasks of exploitation of water resources. The present investigation justifies the functionality of these technologies and suggests a wide range of possibilities of exploitation of the models through the SIG-MM integration.

1. Introduction

Geographic Information Systems (GIS) are an important tool in the analysis and management of geographically referenced data. They allow the representation of the real world based on digital data and the simulation of effects that a natural or anthropic process produces on a given scenario at a given time.

The hydrological cycle, a term that describes the circulation and storage of water in the earth [1], is affected by human influence at different scales, from the local to the planetary [2]. The effect of changing vegetation covers and land use associated with the expansion of agriculture and livestock has had a profound influence on hydrological processes in small basins and at the regional level [3]. Watershed management provides the conceptual, spatial and comprehensive framework that allows the ecosystem management of natural resources, which minimizes the effects of changing vegetation covers and land use. Currently, this conceptual framework is the best option for the management and conservation of natural resources [4],[5]. The water cycle regulates the natural variability of the physical processes that impact the ecosystem [6]. However, hydrologists cannot quickly diagnose conditions at the regional level, if hydrological data is insufficient for this level of analysis [7]. The problem is solved by quantifying the hydrological processes in periods of the order of several years or, simulating the hydrological processes [8].

At present there is a clear recognition of the need to develop more widely the technical capabilities in the determination of the area’s most prone to suffer some kind of hydrological phenomenon (floods, droughts, etc.), developing prediction and warning systems, through the compilation and analysis of existing hydro meteorological information. The use of a river basin model to simulate these processes plays a fundamental role in addressing a variety of water resources and environmental and social problems.

The development of remote sensing (RS) techniques and GIS capabilities has encouraged and improved the expanded use of river basin models worldwide. The GIS is a suitable tool for the efficient management of large and complex databases and to provide a digital representation of the
characteristics of the river basins used in hydrological modeling. It has added confidence in the accuracy of modeling by providing a more practical approach to basin conditions, defining basin characteristics, improving the efficiency of the modeling process and, ultimately, increasing the estimation capabilities of hydrological modeling [9].

2. Integration of the mathematical models of hydraulic networks in the GIS
GIS are consolidating in the current landscape as powerful management tools for all information related to the exploitation of drinking water distribution networks. The direct link between the alphanumeric information and the geographic information that a GIS allows, provides the basis for carrying out an endless number of tasks, including not only the management of water resources but also the preparation of hydraulic models of the network supply from the GIS itself. However, it should be borne in mind that the information required to carry out the management tasks is not the same as what is needed to make a model.

In recent years, very important progress has been made in the field of the integration of mathematical models of hydraulic networks in the GIS, thus enriching the information merely inventoried so that it can also be used in the decision-making process. But for the hydraulic models to be truly useful, they must be permanently updated and calibrated, and for this it is necessary to know the way in which the network actually operates, which in turn requires connecting the GIS with systems that allow the demands to be updated, the status of all components, and with the SCADA system (Supervisory Control and Data Acquisition) to access measurement data in the field [10]. The model must be in tune with what is actually happening on the network; thus, part of the SCADA data will be used to set the ‘boundary conditions’ of the simulation, while others will be used to contrast the results of the model with the observed values, and based on that adjust the parameters of the simulation, that is, those initially unknown data that are part of the information stored in the GIS, and that will have to be determined during the calibration process in order to be used with guarantees in the preparation of new models.

These and many other difficulties make the development of a model from a GIS not an immediate task, but there are many advantages that exist when the GIS is conferred the additional ability to abstract network models from all available information in the geographical environment itself or in alternative information sources also available through connections or shortcuts from the same environment. The ultimate goal of the integration of hydraulic models in geographic information systems is the use of such models in decision making that directly affect the companies that manage water supply services. However, building a model is not an easy task and requires considerable effort.

The current problem for the use of the models does not lie so much in their simulation capacity, as in the availability of the starting data, and in the filtering and verification of the same. Fortunately, the possibility of preparing a model adapted to the reality of each moment from the GIS initially implemented to manage all the information concerning the distribution network is becoming a priority objective.

The possibility of keeping the GIS connected with the SCADA thus allows to keep the model always updated, not only in terms of demands and state of the network elements, but also in regard to the calibration parameters, which can be reviewed as many times as necessary. In short, the simple fact of seeing that it is possible to keep a model permanently updated, opens the doors to their use not only in planning, but also in the daily operation of the networks and in making important decisions that may affect the distribution system operation.

2.1. Mathematical models applied to hydrological and hydraulic processes
A hydraulic mathematical model is an approximate scheme that reproduces the actual behavior of the physical system with greater or lesser reliability and that can be simulated using a specific computer program. The model is subject to the simulation program to be used, although in general, all are based on the abstraction of the real system to a set of elements of regulation and control. In this way the
engineer must interpret the existing hydraulic network and synthesize it in a model using only those elements that the simulation program is able to interpret.

Modeling is used to study situations that are hardly observable in reality, estimate the conditions of failure of a structure or simulate infrequent avenues. In this sense, modeling has turned out to be a very important piece of the design and monitoring of bioengineering techniques or actions in channels. However, modeling or simulations must have a calibration process, where variables such as roughness, runoff, etc. are adjusted. Either with measurements taken in the field or sensitivity analysis.

The preparation of the mathematical model requires gathering and processing a large amount of information. Various aspects inevitably break down when talking about modeling, among them the most notable is the concept of calibration. The calibration process is a part closely linked to modeling. While it is true that it is possible to make a model and not calibrate it, it is obvious that it will be of little use for practical purposes. Since the calibration process is a mere 'adjustment' process, it is possible to deduce that an uncalibrated model will have large deviations between the calculated values and the actual measured values (normally flow rates and pressures), due to which, it will not be feasible its use in most cases.

The numerical modeling of river hydrodynamics requires the use of hydraulic theory of free sheet flow and numerical methods to solve conservation equations. Any numerical model is a simplified representation of reality. A fundamental aspect of river flow models is the representation of riverbed topography and floodplains. There are numerical modeling tools that allow simulations with a one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D) approximation. In numerical modeling, each process that is relevant in the model should be explicitly included, and those that are not relevant should not be considered. However, in practice sometimes some processes that are relevant are ignored, and its effect is intended to be considered through a single parameter [11].

**SWAT Model (Soil and Water Assessment Tool)**

It is a basin or river basin scale model that has the ability to simulate both spatial heterogeneity and physical processes that occur within smaller modeling units, known as hydrological response units (HRU) for sustainable planning and management of the surface water resources of rivers.

SWAT has been declared by research as computationally efficient in its prediction, Neitsch et al. [12]. It has a reliability that was confirmed in several areas of the world. The SWAT model was applied on a large scale to assess hydrological processes in a mountain environment of the Indus River basin high by Khan et al. [13] and in other regions of Asia by Nasrin et al. [14] and [15]. It was tested and used in many regions of Africa by Fadil et al. [16], Ashagre [17] and Schuol et al. [18]. It was also applied to simulate the St. Joseph River Basin in the USA by [19]. They used the Swat model successfully to estimate the components of the water balance in southeastern Ethiopia [20] and in Nigeria by Adeogun et al. [21]. Ghoraba in [19] shows the global view of SWAT model components including input, output, the spatial datasets, and GIS parts and summarizes its methodology.

The hydrological cycle of the SWAT model is based on the equation of the water balance, which considers the unsaturated zone and the shallow aquifer on the impermeable layer as a unit. Equation (1) important for predicting the watershed used by SWAT.

\[
SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})
\]  

where \( t \) is the time in days, \( SW_t \) and \( SW_0 \) are the final and initial soil water content respectively (mm), \( R_{day} \) is the amount of rainfall on day \( i \) (mm), \( Q_{surf} \) is the amount of surface runoff on day \( i \) (mm), \( E_a \) is the amount of evapotranspiration on day \( i \) (mm), \( W_{seep} \) is the amount of water entering the vadose area from the soil profile on day \( i \) (mm) and \( Q_{gw} \) is the amount of return flow on day \( i \) (mm).
The model can estimate the surface runoff using the curve number method of the Soil Conservation Service (SCS), Arnold et al. [22]. This method is widely used for the prediction of the approximate amount of runoff from a given rain event. It is mainly based on soil properties, land use and hydrological conditions. The SCS curve number equation is

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)}$$

where $Q_{surf}$ is the daily surface runoff (mm), $R_{day}$ is the depth of the rain for the day (mm) and $S$ is the retention parameter (mm). The retention parameter $S$ and the prediction of lateral flow by the SWAT model are defined in equation (3):

$$S = 25.4 \cdot \left(\frac{1000}{CN} - 10\right)$$

where $S = \text{drainable volume of soil water per unit area of saturated thickness (mm / day)}$; $CN = \text{curve number}$.

SCS defines three antecedent humidity conditions: I - dry (wilting point), II - average humidity and III - wet (field capacity). The humidity condition curve number I is the lowest value that the daily curve number can assume in dry conditions. The curve numbers for humidity conditions I and III are calculated with the equations (4) and (5), respectively.

$$CN1 = CN2 - \frac{20 \cdot (100 - CN2)}{(100 - CN2 + e^{2.533 - 0.0636 \cdot (100 - CN2)})}$$

$$CN3 = CN2 \cdot e^{0.00673(100 - CN2)}$$

where $CN1$ is the number of moisture condition curve I, $CN2$ is the number of moisture condition curve II and $CN3$ is the number of moisture condition curve III.

The lateral flow is predicted by

$$q_{lat} = 0.024 \cdot \frac{(2SSC \cdot \sin \alpha)}{\theta_dL}$$

where $q_{lat} = \text{lateral flow (mm / day)}$; $S = \text{drainable volume of soil water per unit area of saturated thickness (mm / day)}$; $SC = \text{saturated hydraulic conductivity (mm / h)}$; $L = \text{flow length (m)}$, $\alpha = \text{slope of the earth}$, $\theta_d = \text{drainable porosity}$.

**HEC-RAS Unidimensional and Bidimensional Model: (Hydrologic Engineering Center - River Analysis System)**

It is a program whose main function is the delineation of flood plains, that is, to calculate the level of water in each cross section in the section of an artificial river or canal. The flow may be permanent or non-permanent. In addition to calculating the water levels in each section, HEC-RAS has the capacity to calculate other hydraulic variables such as the undercutting in the support elements of a bridge for the design of the foundation of the same, as well as the transport of sediments and pollutants [23]. HEC-RAS uses the standard step method to calculate the water levels in each cross section in the stationary flow. For these it is necessary to know the cross sections, the distance between the cross sections, the Manning coefficient in each portion of each cross section, the design flow (s) and the edge condition. If the flow is subcritical, the edge condition to be used is downstream; if the flow is supercritical, the edge condition to be used is upstream. In a section it is only necessary to know an
edge condition, unless the flow is mixed. In this case, one must have an upstream and other downstream edge condition [24].

The mathematical formulation of the HEC-RAS model in its condition of non-permanent flow and fixed bed, is given by the principle of conservation of mass (continuity) and the principle of conservation of momentum, both in one direction. These are expressed mathematically in the form of partial differential equations as indicated in equations (7) and (8) [23]. These equations are solved by the software through an implicit finite difference scheme.

\[
\frac{\partial A_t}{\partial t} + \frac{\partial Q}{\partial x} - q_1 = 0 \tag{7}
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA \cdot \left( \frac{\partial z}{\partial x} + S_f \right) = 0 \tag{8}
\]

where \(A_t\) is the total flow area, \(Q\) is the total flow, \(q_1\) is the lateral input flow per unit of width, \(V\) is average flow velocity, \(g\) is the acceleration of gravity, \(\frac{\partial z}{\partial x}\) is the slope of the water surface and \(S_f\) is the friction slope.

**IBER Bidimensional Model**

It is a numerical model of simulation of turbulent flow in free sheet in non-permanent regime, and of environmental processes in river hydraulics. The range of application of IBER covers river hydrodynamics, simulation of dam breakage, evaluation of flood areas, calculation of sediment transport and tidal flow in estuaries. The hydrodynamic module solves the depth averaged shallow water equations, also known as 2D Shallow Water Equations (2D-SWE) or two-dimensional St. Venant equations. These equations assume a distribution of hydrostatic pressure and a relatively uniform distribution of the velocity in depth, that is, the equations of conservation of mass and momentum in the two horizontal directions (9), (10) and (11) are solved [25]. The hypothesis of hydrostatic pressure is reasonably fulfilled in the flow in rivers, as well as in the currents generated by the tide in estuaries. Likewise, the hypothesis of uniform distribution of speed in depth is usually fulfilled in rivers and estuaries, although there may be areas in which said hypothesis is not fulfilled due to three-dimensional local flows or salt wedges. In these cases, it is necessary to study the extent of these areas and their possible impact on the results of the model [26].

\[
\frac{\partial h}{\partial t} + \frac{\partial hU_x}{\partial x} + \frac{\partial hU_y}{\partial y} = M_s \tag{9}
\]

\[
\frac{\partial hU_x}{\partial t} + \frac{\partial hU_x^2}{\partial x} + \frac{\partial hU_xU_y}{\partial y} = -gh \frac{\partial Z_x}{\partial x} + \tau_{sx} - \frac{\tau_{bx}}{\rho} - \frac{g h^2 \rho}{2} \frac{\partial h}{\partial x} + 2\Omega \sin \lambda \ U_y + \frac{\partial h r^e_{xx}}{\partial x} + \frac{\partial h r^e_{xy}}{\partial y} + M_x \tag{10}
\]

\[
\frac{\partial hU_y}{\partial t} + \frac{\partial hU_xU_y}{\partial x} + \frac{\partial hU_y^2}{\partial y} = -gh \frac{\partial Z_y}{\partial y} + \tau_{sy} - \frac{\tau_{by}}{\rho} - \frac{g h^2 \rho}{2} \frac{\partial h}{\partial y} + 2\Omega \sin \lambda \ U_x + \frac{\partial h r^e_{xy}}{\partial x} + \frac{\partial h r^e_{yy}}{\partial y} + M_y \tag{11}
\]

where \(h\) is the draft, \(U_x, U_y\) are the horizontal velocities averaged in depth, \(g\) is the acceleration of gravity, \(Z_x\) is the elevation of the free sheet, \(\tau_{s}\) is the friction on the free surface due to friction caused by wind, \(\tau_{b}\) is the friction due to the friction of the bottom, \(\rho\) is the density of the water. \(\Omega\) is the angular velocity of rotation of the earth, \(\lambda\) is the latitude of the point considered, \(\tau^e_{xx}, \tau^e_{xy}, \tau^e_{yy}\) are the horizontal effective tangential tensions, and \(M_s, M_x, M_y\) are respectively the source / sink terms mass and momentum, through which the modeling of precipitation, infiltration and sinks is performed.
Table 1. Comparison between the hydraulic models IBER and HEC-RAS

| IBER | HEC-RAS |
|------|---------|
| The best adaptation of the mesh allows faster models for the same precision in the channel. | Quick calculation for small models but it slows down a lot as we increase the model while maintaining accuracy, since the mesh's adaptability is lower. |
| You can see the result of the model as each step is calculated. | It is necessary to wait for the calculation to finish in order to see the results. |
| The IBER model has meshes with triangular or rectangular cells. Triangular cells allow more flow directions. | Square cells except in areas where breaklines are defined, which in many cases limits flow directions. |
| It allows different types of meshing (size, tailpiece error, divisions ...). | It only allows one type of mesh, except for the possibility of forcing mesh with breaklines. |
| Solve Saint Venant 2D equations. | Solve Saint Venant 2D equations. |
| Trapezoidal dam breakage or with the Spanish technical guide, it is necessary to calculate the breakage time or the basis of the breakage. | Several methods of dam breaking include a parameter calculator for each method according to the characteristics of the dam. |
| Total breakage of the dam from the beginning. | The breakage progression during the breakage time can be defined. |
| Visualization with colors and vectors to represent scalar and vector properties. | Visualization with colors and vectors to represent scalar and vector properties, also allows flow animations through the particle path (very visual). |
| Results in vertices and faces (the average of the vertices) of the mesh. | Results at each point of the model (calculates intermediate results between one point and another automatically). |
| You must add georeferenced image to see the orthophoto. | It has its own orthophoto viewer using several online services such as GoogleEarth. |
| You can see more results as specific flow or F of Froude and see its evolution over time or along the profile. | You can only see dimension, speed and draft and draw temporary graphs of flow and volume accumulated in a profile. |
| The volume dislodged by the break is consistent with the volume of the reservoir. | In much of the cases the volume dislodged is greater than that of the reservoir, which is an inconsistency that seriously questions the reliability of the model. |
| The results depend little on the size of the mesh. | The results depend a lot on the size of the mesh. |
| Output hydrograph consistent with the dislodged volume. | Output hydrograph consistent with the dislodged volume. |
| Hydrogram lamination in IBER is more pronounced and gives inconsistencies in the first profiles. | Hydrogram transmission is done almost without feeling the effect of lamination. |

3. Application and contribution of hydraulic models

In hydraulics, modeling is used to simulate real situations that occur in the prototype and whose behavior you want to know; Since the model and prototype are linked to each other, the observations and study of the model constitute the information necessary to understand the nature of the prototype, and must therefore be related. Because simulations occur under controlled laboratory conditions, hydraulic models have multiple applications. Hydraulic models are used to solve problems related to hydraulic structures, infiltration phenomena or stretches of rivers and recently with sediment transport.

The main characteristics of each of these groups are indicated by their names. Structural models are used to solve hydraulic problems in connection with a variety of hydraulic structures or certain parts of them, such as determining hydraulic capacity, reducing load losses in inlets to channels or pipes or in
transition sections; develop effective methods of energy dissipation in the stream, at the foot of the overflow dams or at the outlet end of the agarrings, thereby reducing erosion of the bed of river beds; determine discharge coefficients for overflow dams; develop the best design of dam weirs, siphons and wells and reservoir exit structures; design ports, including determining the best cross-section, height and location of the breakwaters, as well as the position and location of the entrance; design locks, including the effects on the boats of the established currents due to the operation of the locks etc. The infiltration model group is created for the study of infiltration phenomena in soils and granular media in general. This study also belongs to the study of infiltrations in the subsoil of a variety of dikes and embankments, in the vicinity of excavated holes for construction in granular soils, under or around structures founded on such soils.

Studies in river models are used to solve problems of regulation of rivers or hydro-energy developments, determine the time of displacement of flood waves by river channels, methods for the improvement of channels for flood transmission with less risk of overflow on the banks, the effects of river shortages, effect of dikes, retaining walls on the erosion of the beds, height of the backwaters caused by permanent or temporary structures, built in the middle of a channel; direction and current forces in rivers and ports and their effects on navigation etc.

4. Discussion and Conclusions
Despite the differences that occur between the models and the results obtained by some research such as [27] where they show the superiority of some models over others in different areas, this only shows that each one is good is specific areas. So the common work of the models could be an option to obtain a more inclusive and efficient model. As is the case of [28], which shows the efficiency of the work in common between the HEC-RAS and SWAT models for real-time flood forecasts.

The management and conservation of Hydraulic Resources is a topic of great interest to the country, so research focused on this line is of great importance. The use of GIS tools is an important support in applications that manage data of a spatial nature, since they provide specialists with visual information in different formats and allow their management and consultation.

It is important to highlight that the hydraulic modeling when representing the flow (three-dimensional) of a river or through a structure or soil with greater fidelity and detail than a simple theoretical calculation, increases the reliability of the projected structures. This means that the designs are more in line with the actual flow requests, which has a significant economic impact. On the one hand, the risk of designing a less resistant work that easily collapses with the consequent economic losses or worse, in human lives is reduced; while on the other hand the possibility of an oversized design that requires unnecessary investments is also reduced. In other words, hydraulic modeling is an important optimization tool for the design of hydraulic works. These models will arise when they lead to a more economical and safe solution or when they are essential. Cases have been seen in which, because of not making a model, the prototype - which is very expensive compared to the model - has been rendered useless in a relatively short time since the phenomena cannot be anticipated in advance and corrected in advance. In this sense, we must be aware of the need to make a hydraulic model when circumstances warrant.

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