CO-219

# SIATL: WEB-BASED HYDROGRAPHIC NETWORK MODELLING

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## ABSTRACT

The Water-flows Simulator (SIATL) is a web-based, open access system that allows users to search and identify hydrographic features and to carry out the usual GIS navigation tasks on Mexico's 1:50000 hydrographic network. However, the core of the simulator is its network modelling capabilities which take advantage of the geometric network structure recently added to the country's hydrographic features. These modelling tools allow users to perform analysis in a simple and intuitive manner, including detecting rivers and streams from which water flow towards a point in the network, finding settlements lying in the path of a possible flood, and more. The simulator is aimed mainly at decision-makers, as an aid in planning, resource management and disaster prevention and response but it is open to anyone with an Internet connection. Users can also add comments and photographs, making it a tool with which society can contribute information to the country's hydrographic network, so that the knowledge about Water can be shared and increased.

## BACKGROUND AND OBJECTIVES

Water has always been one of the main topics in resource and risk management. Population growth, together with the prediction of more extreme weather events, intensify the need for tools that can help us make better decisions in water related issues, from optimal water use to how to deal with shortages and flood prevention. Helweg (1985) cites examples of flood-warning systems dating back to ancient Egypt (3500bc). Attempts at modelling hydrological processes can be traced back to the prediction of flood peaks in the 19th century (Mulvaney, 1851, cited in Anderson and Burt, 1985b). Besides flood forecasting, hydrological models include groundwater modelling, runoff modelling, water quality, etc. Anderson and Burt (1985b) classify hydrological models into three categories:

- Black-box models which establish a statistical relationship between input and output and include the unit hydrograph, extreme frequency analysis, regression analyses, and real-time forecasting.
- Conceptual models which are very simplified arraignments of a ‘few’ variables. They constitute an intermediate stage between black-box and deterministic models.
- Deterministic models which are based on complex physics and are data insensitive.

For Helweg (1985), hydrological models can be classified by discipline into

- hydrologic models, dealing mainly with river flow and basin modelling;
- hydraulic models, dealing with open channel flow, pipe flow and hydro-machinery;
- groundwater models;
- general simulation models, aiming at reproducing the dynamics of social systems like water demand;
- optimisation models, seeking to design the best system.

Detailed explanations about several hydrological models can be found in Anderson and Burt (1985a), Helweg (1985) and Maidment (1993).

The development of technologies such as Geographical Information Systems and the Internet as well as higher storage capabilities, provide new ways to simulate and analyse the present and possible future conditions of water resources so that water managers, emergency services and other policy planners can improve their decision-making processes.

In this context, one of the objectives of Mexico's National Institute of Statistics and Geography (INEGI) - as part of the National Statistical and Geographical Information System- is to generate National-Interest Information that will provide reliable instruments for policy-makers (INEGI, 2008). As one of the efforts that the Institute has implemented to achieve this, a new and improved 1:50000 scale hydrographic network map with geometric network characteristics like direction of flow and connectivity was developed and released in 2008 (INEGI, 2009). The aim of this redesign was to provide decision-makers with an interactive tool to aid them in water management tasks and for rapid-response services. Many other countries have designed and developed similar modelling tools like the United States Geological Service’s National Hydrography Dataset (NHD) and Canada’s National Hydro Network (NHN). The NHD is the surface water component of The National Map (USGS, 2010), a digital vector dataset designed not only for general mapping but also for the analysis of surface-water systems. The characteristics of the dataset that permit its use in analysis are the inclusion of the direction of flow and links to additional information (USGS, 2000). Natural Resources Canada (2010) produced the hydrographic information layer of the country's GeoBase initiative through the NHN project (GeoBase, 2010). In this case, the datasets are produced by federal, provincial and territorial partners selected to attain a homogenous data layer for Canada's water-surface system. The Network is designed for water flow analysis as well as for management and environmental applications. On the academic side, the INEGI also reviewed the work done at the Center for Research in Water Resources (CRWR), University of Texas at Austin, where they have developed several models to analyse surface- and underground water systems which include time series from hydrometric stations as well as software that allows for the integral analysis of drainage systems (Zoun, Schneider, Whiteaker, and Maidment, 2001).

Network problems originate when a situation can be described as flow through a network. Some problems that have network structure are those involving distribution systems, assignment and some planning problems like path analysis. There are different types of networks used to describe different types of systems. In the case of water resources, rivers are best represented by tree-like structures while urban water networks by grid-like ones (Figure 1). In the latter case, circuit-like structures could also be applied. For analysis purposes, a network may be assumed to be a static model while for planning, it may be seen as a dynamic one.

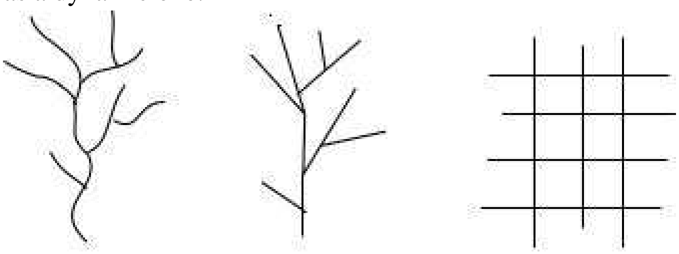

*Figure 1: Representation of different types of networks*

Thus, one way to perform analysis of the flow of water through a water basin is to use a Geographic Information System's capabilities to model the river system as a network structure that focuses on the connectivity –and not only on the physical shape- of the features (Heywood, Cornelius and Carver, 2002). The literature on network modelling in general is plentiful, mostly from the graph theory or the mathematical optimization points of view. Bazaraa et al. (1990), Bertsekas (1992), Dolan and Aldous (1993), Fang and Puthenpura (1993) or Jensen and Barnes (1980) can be cited among the many texts.

A network is composed of interconnected lines (arcs), each of which starts and ends in a point (start- and end-nodes). In two arcs that meet, the start node of one coincides with the end node of the second one; in addition to the location information of the arcs and nodes that conform the network, the arcs contain a direction of flow. In GIS terms, the relationship held by nodes and arcs is known as the network's topology.

Lupien et al., (1987) mention the following benefits in using a GIS environment to describe and analyse linear networks: a single model can be used to analyse different types of linear networks; digitising and editing tools help in the creation/updating of the cartographic side; data base management systems allow the assignment of flow attributes to the network topology; and the possibility of an interactive graphical implementation makes the models easy to use and interpret. They point out one limitation: the inability to change the flow characteristics during an analysis session. This can be overcome by allowing the flow to be a function of several variables, including those in the database and those produced during the session. They conclude that

"The GIS approach is to regard network analysis as one of many techniques for examining spatial relationships. In that context, a GIS is successful when it provides knowledge to its user, and when it makes available the tools needed to answer the questions raised by that new knowledge." (Lupien et al., 1987:1421)

Thus, giving the network a geometric structure allows users to simulate different scenarios thus permitting the users to consider how certain areas could be affected by extreme rainfall events in the shape of flash floods but also to detect which settlements could be affected by pollutants spilling into a river or to help in the planning for new infrastructure.

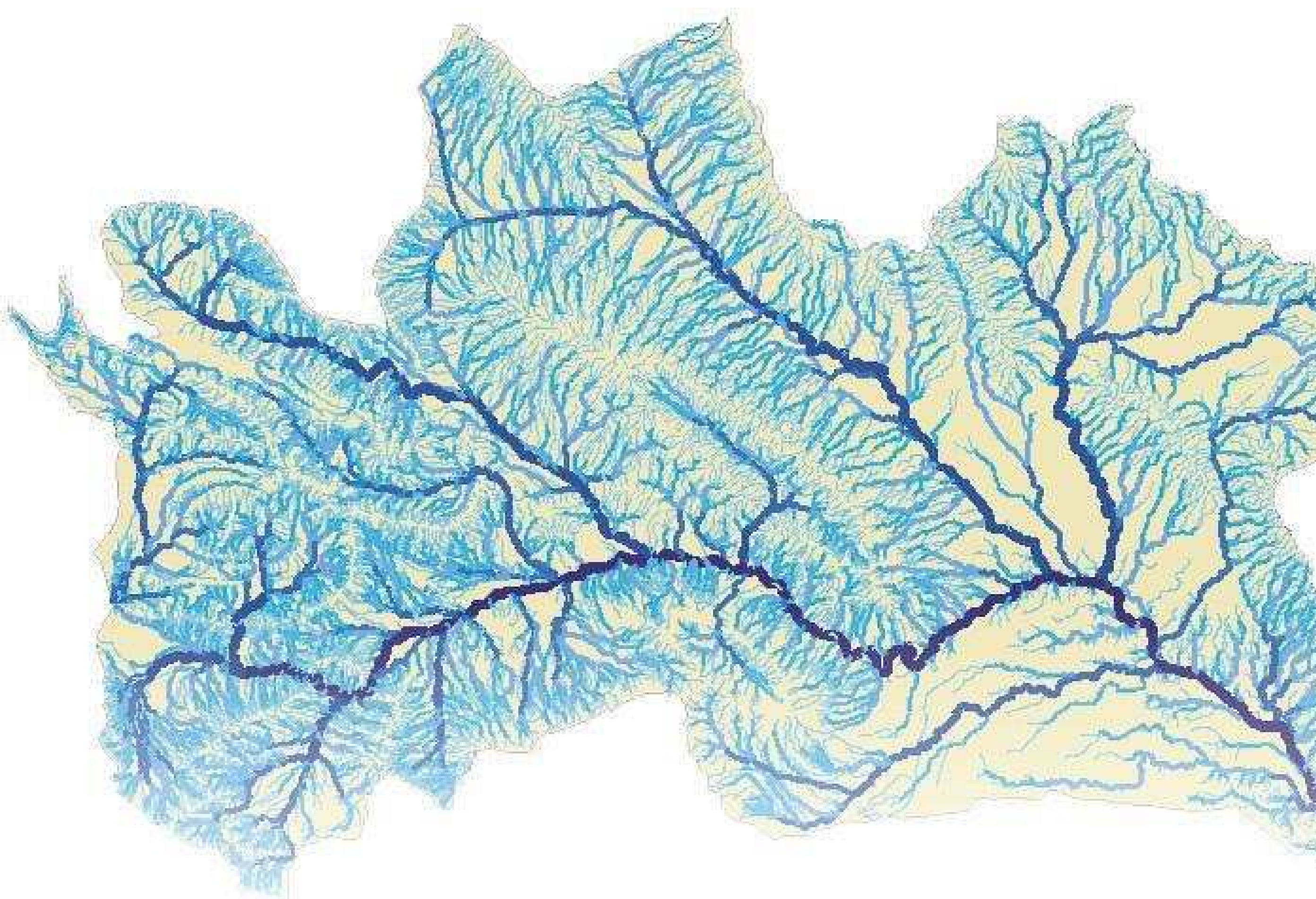

*Figure 2: Basin from the hydrographic network*

Once the INEGI had produced the new 1:50000 national hydrographic network as a dataset with a topology that would allow its users to model different scenarios, the Institute took a further step to take advantage of the new Internet technologies that allow users from all over the world to access information and software developments remotely by developing a web-based simulator (the Water-flow Simulator -- SIATL). This tool aims at giving users a platform to perform free consults of the hydrographic network via an Internet connection but in parallel it also allows them to construct different scenarios for decision-making through a set of network modelling routines included in the system. The simulator was rounded-up by the addition of capabilities to upload comments and photographs so that users can give their feedback to the INEGI and hence help the Institute to improve and add value to the national hydrographic network. Details on the network, the SIATL water-flow simulator and their development are given in the next section.


*Figure 3: The SIATL's interface*

**APPROACH AND METHODS**

As explained above, in order to provide decision-makers with an instrument to aid them in water management issues, including risk assessment and rapid-response planning, the direction taken by Mexico's National Institute of Statistics and Geography was to start by improving the 1:50000 scale National Hydrographic Network giving it the topological structure required to perform water-network analysis with the aid of the tools available now in Geographic Information Systems. To achieve this, a new digital network had to be derived from the Institute's 1:50000 topographic maps, whose previous datasets had not been designed with such analytical tasks in mind and thus did not have the data structure needed to perform them. Changing the existing dataset to add geometric network characteristics (connectivity, direction of flow, and junctions) implied using information taken from other sources like contour lines, geological and geomorphological features, soil and rock characteristics as well as the analysis and interpretation of aerial photographs and satellite images. Thus a project known as the "1:50000 Hydrographic Network Structuring Project" was conceived which aimed at the construction, improvement and strengthening of the new network (INEGI, 2009). The main objective of the project was to produce a dataset that was structured as a lineal network that would allow the users (mainly decision-makers at different government offices) to model the drainage in a water basin, for all the watersheds in Mexico.

The project was divided in two stages so that some of the network's improvements over the previous product could start to be used in the short term. The first of these stages took on the connectivity and direction of flow aspects while the second consisted in an inspection of neighbouring sub-networks and giving a vector data structure to the basin and sub-basin polygons. The first stage (also known as Edition 1.0) was released in 2009 while the second (or Edition 2.0) was released in 2010. The rest of this section describes the main points of the development of both the 1:50000 national hydrographic network and the SIATL Water Flows Simulator. Further details can be found in the technical document produced by the Institute, INEGI (2009)

As stated before, if the national hydrographic network was to become a useful tool for the decision-makers' hydrographic modelling and simulations, the Institute needed to construct a dataset that had the topological characteristics of connectivity and direction of flow used to represent the natural structures of rivers, streams and water bodies. To achieve this, the new network consists of two types of objects: lines of flow (arcs) and Drainage points (nodes). The nodes represent either the points where water accumulates in water bodies like lakes in endorheic basins or points where water disappears from the surface either from evapotranspiration or infiltration to the underground. Each sub-basin has to contain at least one drainage point. The arcs represent rivers, streams and irrigation canals; in addition, virtual arcs were drawn through those water bodies that have both a water entry and a water exit points to represent the flow of water throughout the whole sub-network. All arcs had to be assigned the correct direction of flow of the water running through them. While water in rivers and streams flows in only one direction, in some man-made structures like irrigation canals and pipelines, the direction of flow can be reversed. This case can be incorporated into a network model by assigning both directions to the arcs that represents such structures.

Each of the objects in the dataset (arcs and nodes) has two components: an attribute or descriptive component and a spatial or geometric one. Attributes correspond to those characteristics that describe or qualify the object and can consist of either qualitative or quantitative variables. The spatial component is the digital representation of the object that allows the distinction between them. Besides these components, the network's topology has to represent the actual flow of water through the network. Therefore, the spatial relationship between those elements that are connected in reality (e.g. a river with its tributaries and effluents) or those that overlay each other without being physically connected (like an aqueduct passing over a river or stream), has to be correctly preserved in their digital representation. Also, some models require that the discharge be considered to represent the branching complexity of riparian systems.

The basis for the new hydrographic dataset was the existing hydrographic network (at the 1:50000 scale), which had a vector data structure. Additional data from other sources, including maps at smaller scales, was used as support information. The project started with the extraction and inspection of the hydrographic features contained in the previous version of the network. This process revealed some of the problems that would have to be solved first: elements of many of the sub-networks that are connected to each other in reality, were incorrectly connected or not at all; the direction of flow could not be determined automatically from the way the line features had been traced because it had not been done in a systematic way (which was expected since the previous network was not designed with the objective of modelling); and the width of the lines was the same for all of them, regardless of the actual discharge of a given river, stream or canal.

From this analysis of the existing data, the specialists working on the project determined which arcs had to be joined in order to achieve the network's connectivity correctly, with the aid of satellite images, aerial photographs and the hydrographic division taken from the INEGI's 1:250,000 Surface Water Hydrologic Map. They also determined the direction of flow for all the arcs in the data set that represent rivers and streams by making sure the direction always follows the downwards slope of the terrain. Figure 4 depicts an example of the resulting network correctly connected and with the directions of flow assigned to each arc. Although canals are a very important feature for the representation of the country's water resources system, determining the direction of flow in them is complicated (the flow does not necessarily follow the slope of the terrain, water could be pumped upwards through them and they can have a reversible flow to suit irrigation needs). The scope of the project did not permit for the field-work necessary to determine the direction of flow therefore only the main canals -those whose exclusion would have interrupted the simulation of water flow in the network- were included at this stage.

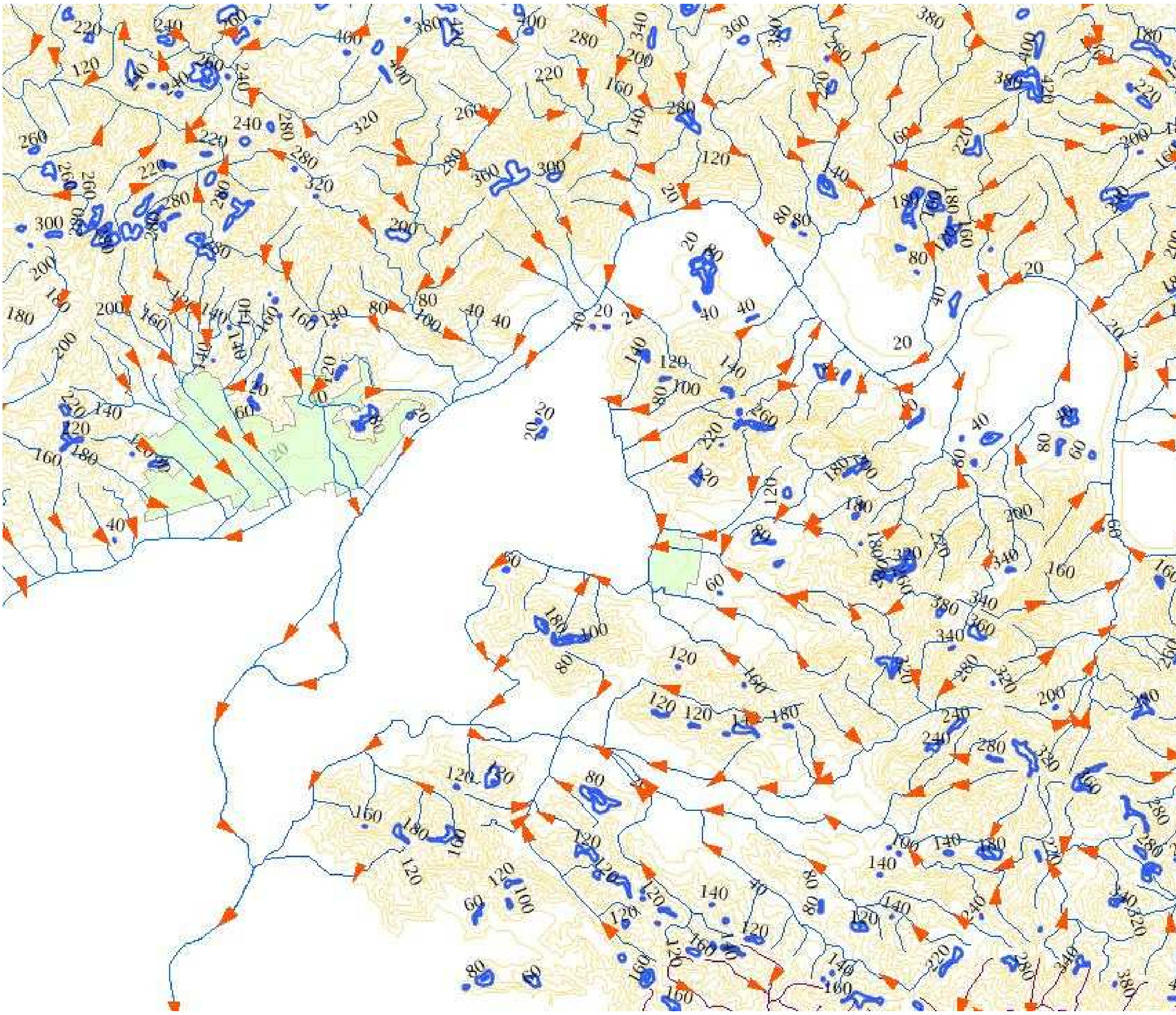

*Figure 4: Directions of flow in a basin*

The water-bodies were derived from the Institute's 1:50,000 topographic map. Due to the process used to create this map, there were some cases where one water-body was made up of several smaller polygons rather than by one larger feature. In these cases, the smaller polygons were merged together in an automated process so that the hydrographic network could have only one polygon for each water-body represented in it.

As was described before, implementing network simulation models requires that all the rivers, streams and canals that flow into a water-body converge. Since water-bodies at this scale are represented by polygons, the issue was resolved by tracing virtual lines through the centre of the polygons so that the lines 'flowing' into the water feature could be joined to the virtual line thus ensuring the connectivity of the network.

In summary, the "1:50000 Hydrographic Network structuring Project" took place in several stages over the span of three years and it involved over 120 persons, including technicians in the INEGI's 10 regional offices throughout the Mexico, supervised remotely by 17 experts at the Institute's central offices in the city of Aguascalientes. The resulting new network is made up by more than six million lines representing rivers and streams (both perennial and intermittent) as well as the main irrigation canals; it contains over 14000 points that indicate where the water disappears from the surface or where it drains into a water body or into a different sub-basin; and 976 polygons corresponding to the watersheds of the sub-basins. The lines that form the network are connected within each basin and their direction of flow was determined from the terrain's slope. Subsequently, polygons at the same scale for the 37 hydrographic regions and 158 basins were derived.

The objectives of promoting the use of the connected network and of providing decision-makers with a new tool were achieved with the Water-flow Simulator, SIATL. The ideas behind the project were that developing a web-based interactive system would mean that a larger audience could have free access to the hydrographic network while including network modelling capabilities in the system would allow users to set up and analyze different scenarios that could be used for decision-making. The SIATL can be accessed at http://antares.inegi.org.mx/analisis/red_hidro/SIATL/index.html using a web navigator like Chrome, Firefox, Internet Explorer, etc.

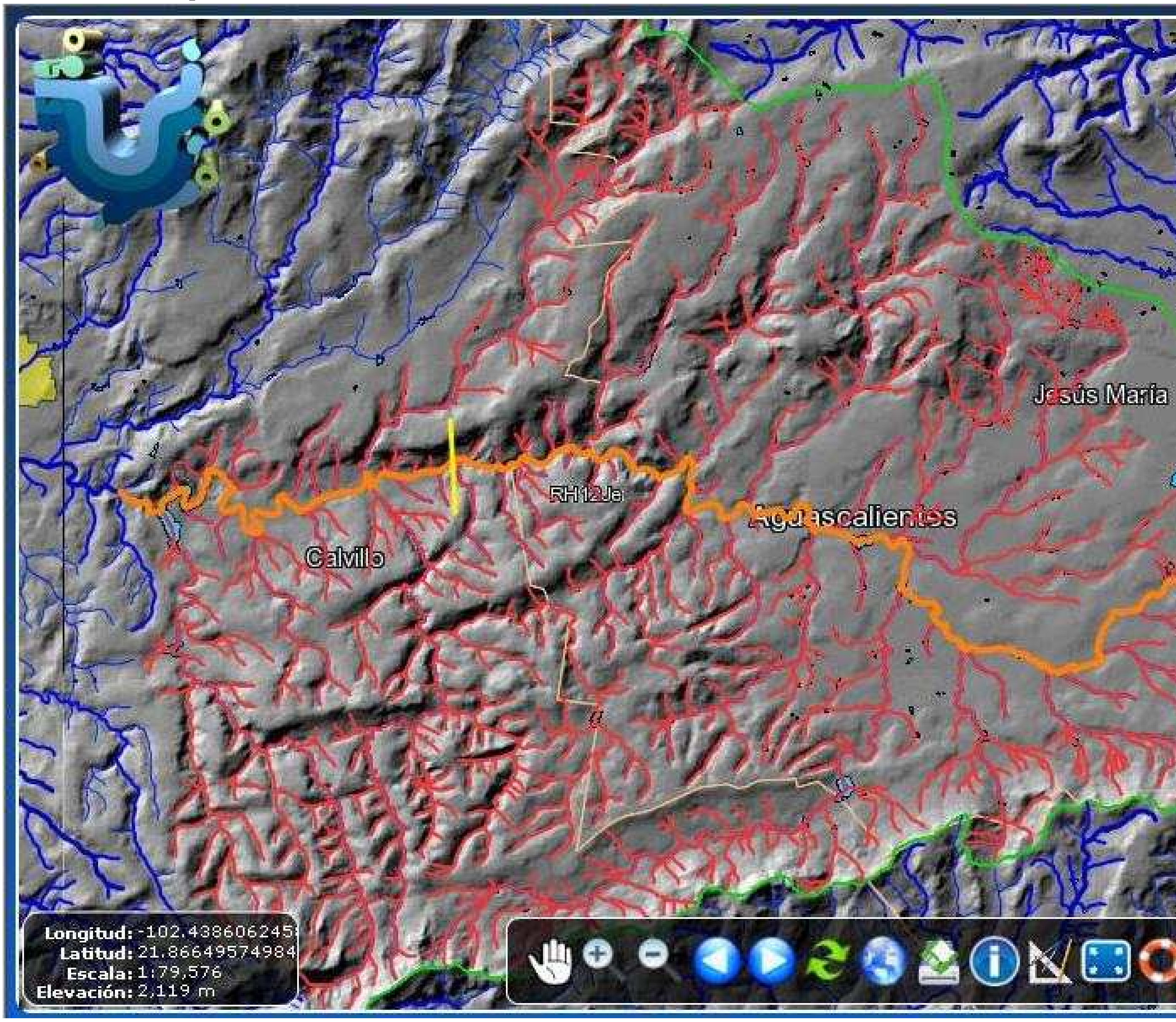


*Figure 5: Upstream function with flow lines and main stream selected.*

As a visualisation tool, the Simulator provides the user with the usual GIS-like capabilities: panning, zooming in and out, turning layers on and off (both vector and raster), including orthophotos and satellite images, etc. Searches can be performed on the following variables: political division, localities, sub-basin, hydrographic features and also by latitude and longitude coordinates.

However, the most important features of the SIATL are its hydromorphometric and network-modelling capabilities. These functions include: obtaining a stream's tributaries and distributaries so that the water flow trajectory can be visualised; morphometric indices like Strahler's stream order, drain stream level, arbolate sum, path length and hydrologic sequence identifier.

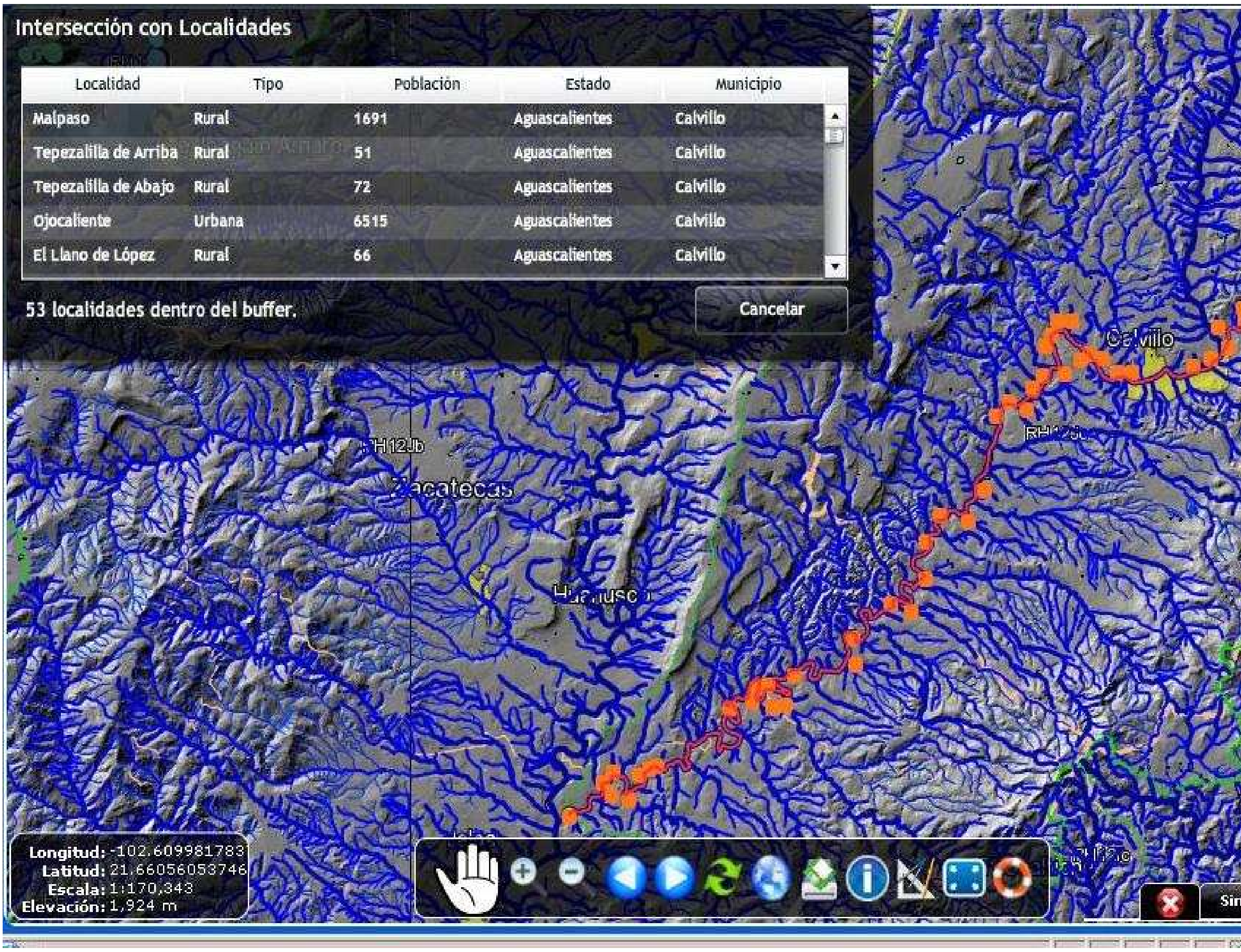


*Figure 6: Downstream function with cities within 100 meters selected.*

Additionally, the SIATL has some functions of morphometric indices like calculating the basin's mean slope as well as the main river-bed's, concentration times and elevation profiles; and obtaining those settlements that lie within a user-defined distance from a stream.

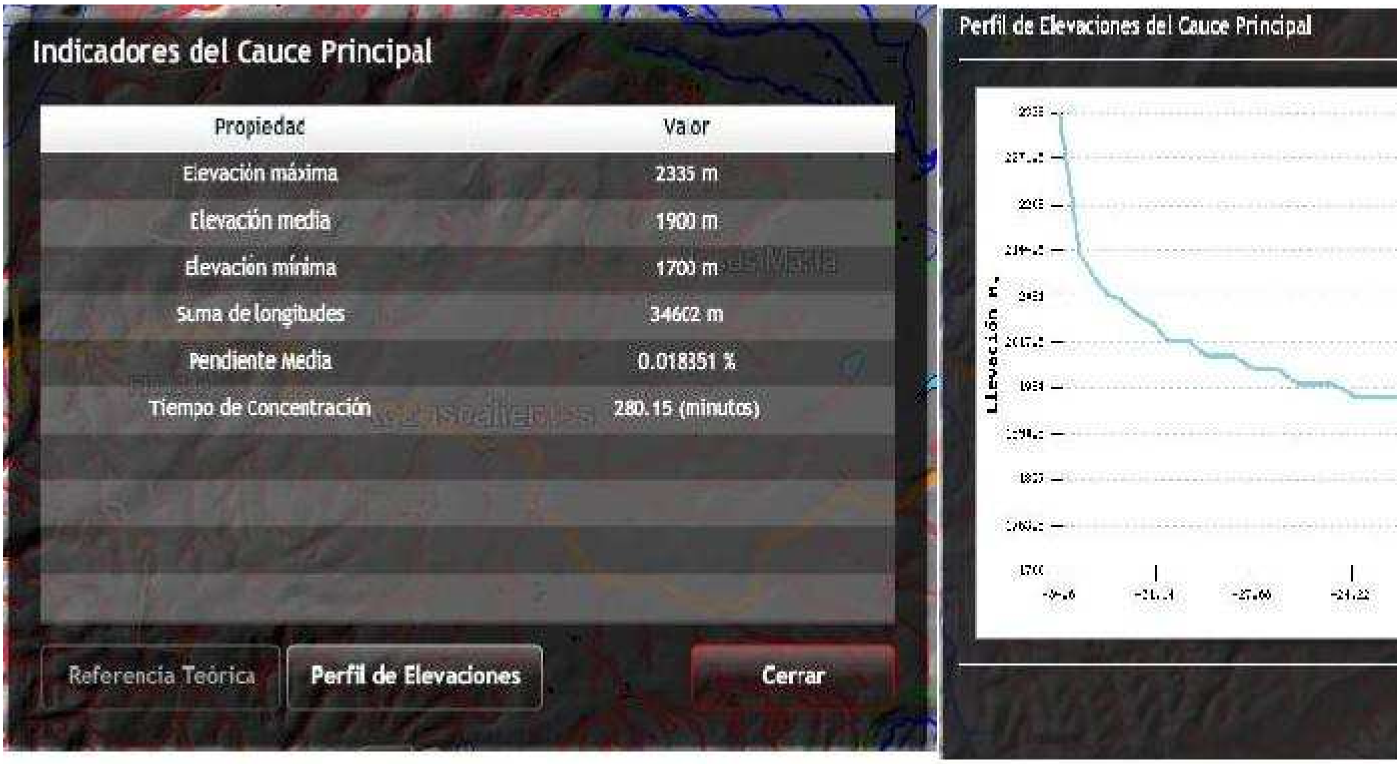


*Figure 7: Morphometric indices and elevation profile of main stream*

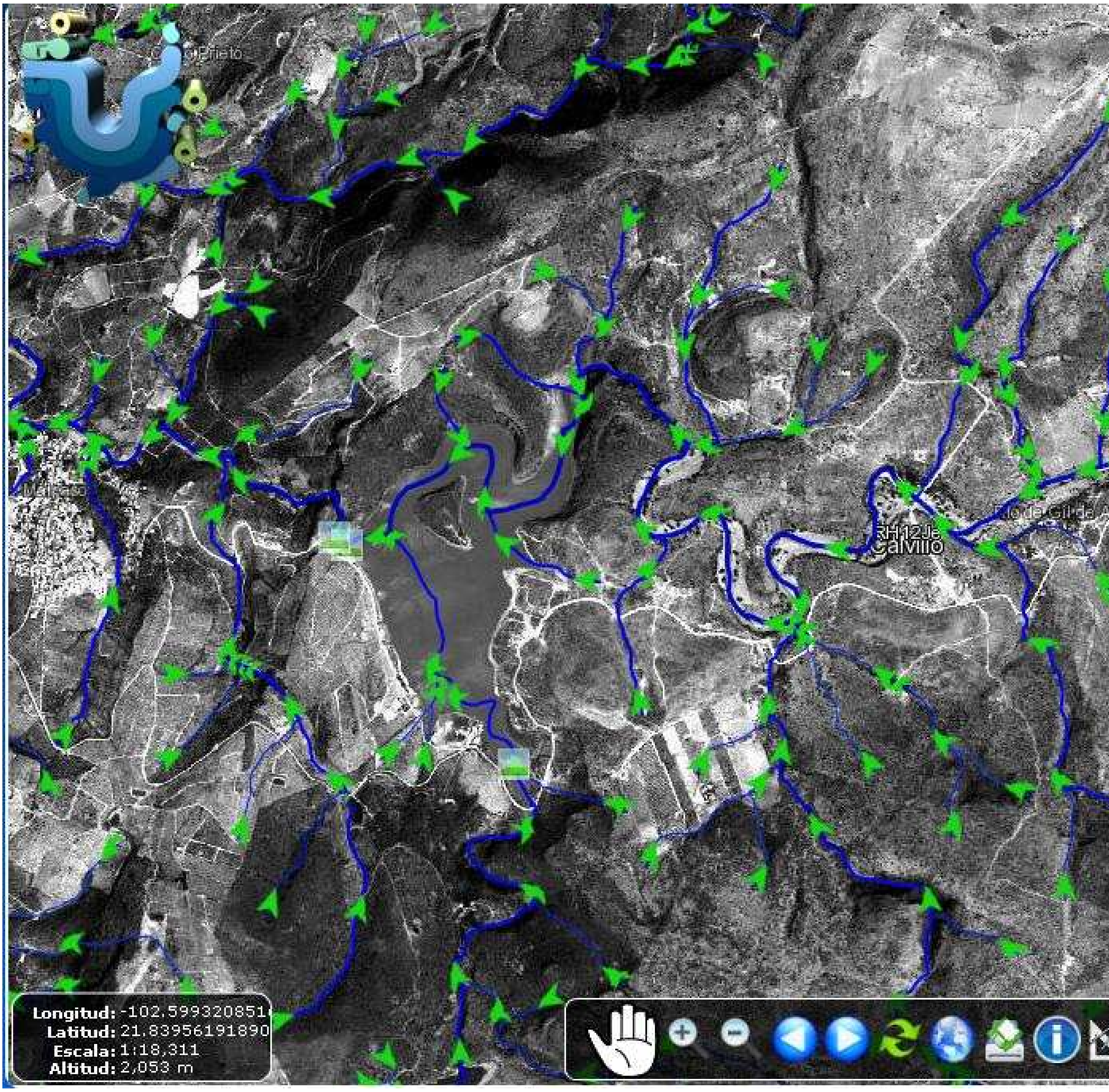


*Figure 8: Direction of flow displayed over an orthophoto*

The Simulator includes interaction features that allow users to send comments and corrections and photographs that are used to enrich both the hydrographic network and the SIATL. To ensure the quality of the product, user input is sent first to the Institute's experts so they can check it. If the comment is found to be relevant the corresponding modifications are made. In the case of photographs, these are added to the application once the quality and positional accuracy are verified.

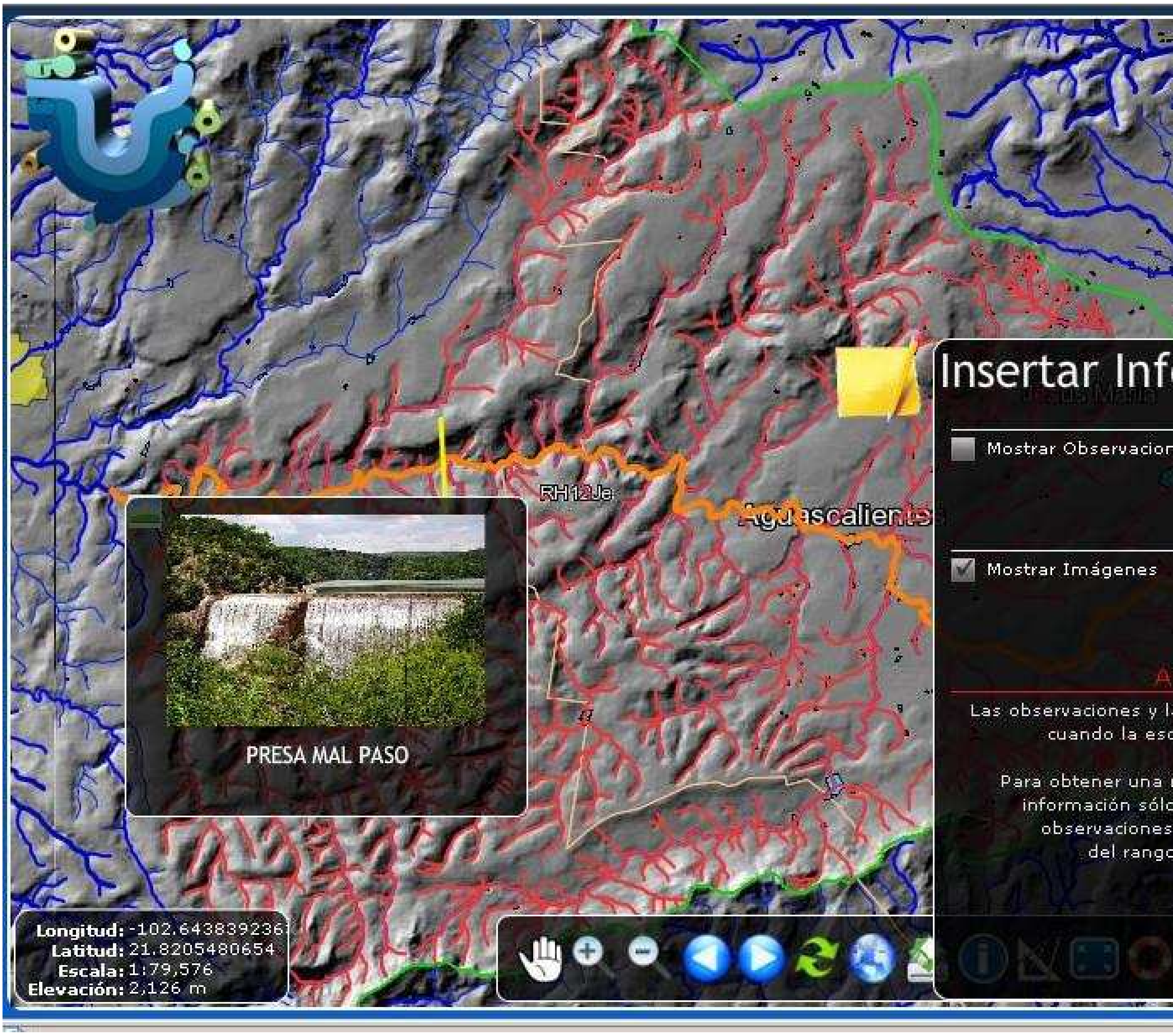


*Figure 9: Insert function to send comments and photographs.*

The design, development and analysis team is formed by four specialists and the software used for the application includes PostgreSQL (PostGIS), PLSQL, MAP SERVER, PHP and in-house programming for the backend and Flex AS3 and Java Script for the frontend.

**RESULTS**

On the one hand, the efforts to provide an underlying geometric structure to Mexico's 1:50000 National Hydrographic Network have helped it to become a much more successful tool for decision making since it is now possible to perform several types of modelling with it. On the other hand, the development of the Water Flows Simulator has added to the success of the Hydrographic Network as a policy instrument by giving decision makers a tool with ready-made modelling capabilities that is free and easy to access through the Internet. Through the routines described in the previous section, the SIATL acts not only as a visualisation tool but it also gives the specialised user the means to analyse the location of those populations that could be affected by contaminants spilling into a stream; which settlements could be affected or benefited by new waterworks (new reservoirs for electric generation or water supply, for example); or the towns and infrastructure (roads, bridges, telephone lines, etc.) that could be affected by floods caused by extreme rainfall events taking place in a catchment.

The SIATL water-flow simulator is also being used as support for the rapid-response programmes, providing information to the authorities in the aftermath of hurricanes Alex and Karl as well as tropical storms like Georgette, to plan for bridges crossing over rivers, and in improving the Digital Elevation

Models. The simulator importance is not limited to its role as a modelling tool. The SIATL has also provided the National Institute of Statistics and Geography with an instrument to improve its hydrographic data gathering and production processes by turning it into an easy to access instrument for public participation.

The general public can buy the dataset (either for the whole country or by individual sub-basin), along with its corresponding metadata and the Technical Description Document (INEGI, 2009), from any of the INEGI's Data Distribution Centres. The SIATL water flows simulator can be accessed freely on the Internet, as previously stated at http://antares.inegi.org.mx/analisis/red_hidro/SIATL/index.html .

## CONCLUSIONS AND FUTURE PLANS

Water and water related issues are an strategic theme in decision-making due to the problems that both its scarcity and excess can represent to the population. Providing the relevant authorities with a tool than can aid them in their management and decision processes is one of the tasks that the National Institute of Statistics and Geography must address.

So far, the SIATL has proved to be an efficient tool in spreading the use of the hydrographic network, in correcting and improving the network and as an aid for rapid-response programmes. However there is still room to grow. The future plans for the simulator include: adding historic precipitation data, time series from hydrometric stations, having 3D images and incorporating a probabilistic method to calculate discharge.

We expect that the number of people using it as a decision tool will increase in the future. Their feedback will help the Institute decide on the way forward for the hydrographic network and the simulator. Society's contribution to the knowledge-generation process is not only desirable but absolutely necessary and tools to integrate the public's contributions have to be devised. SIATL exemplifies one manner in which this goal can be achieved.

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