Chapter 8
Effects of Uncertain Control in Transport of Water in a River-Wetland System of the Low Magdalena River, Colombia

L. Alfonso and M. Tefferi

Abstract During the 2010 and 2011, extreme flooding events affected the low Magdalena River catchment, Colombia, with devastating consequences. This triggered the urgency of adjusting the new river basing planning framework for the country, in which the generation and use of flood risk maps, was lacking. Recent efforts include the generation of probabilistic flood maps, based on the generation of a hydraulic model and an uncertainty analysis related to the wetland-river connections. Although this effort is a step forward to the definition of design criteria for flood risk prevention measures and for the land-use planning process in general, an integrated vision is still missing. In particular, depending on the hydraulic and hydrological condition of the river-wetland system, the operation of the existing hydraulic structures is sometimes decided illegally by the water users with the strongest economical power and not by the local authority, with the consequent biased water use. The research objective of this study is to analyze the control strategy for the operation of hydraulic structures in the region of the Low Magdalena River, considering uncertain control due to self-operation of the structures by non-official actors. The study includes a literature review on existing methodologies and cases where control structures are significant and where conflicting interests are present. A number of different scenarios are analyzed different control scenarios are tested. The study uses the recently developed 1D–2D model of the region that simulates the Magdalena River Channel with side structures that replicate the river-wetland connections. Conclusions and recommendations of the study are drawn, as well as indications of activities for future research.

L. Alfonso (✉) • M. Tefferi
UNESCO-IHE Institute for Water Education, Delft, The Netherlands
e-mail: l.alfonso@unesco-ihe.org; teffe1@unesco-ihe.org

C. Ocampo-Martinez, R.R. Negenborn (eds.), *Transport of Water versus Transport over Water*, Operations Research/Computer Science Interfaces Series 58,
DOI 10.1007/978-3-319-16133-4_8

8.1 Introduction

Gates and pumping stations and other hydraulic structures are commonly used to control water systems in order to satisfy water quality and quantity demands of different actors. The need to fulfill the interests of different users considering the interactions between subsystems and the external disturbances has increased the requirements for a better control of the systems. The control of water systems aims at achieving their general operational objectives (i.e., supply drinking water, collect and treat sewage, drain rainfall runoff and prevent flooding), in the most cost-efficient manner. In fact, the control of water systems concerns the operation of regulating structures such as pumping stations, weirs and sluices, in order to make the system to meet the demands of the water users as well as possible.

However, in practice, this is not always the case. The Magdalena River, like many other rivers in the world, has diverse water users and interests that are conflicting. Examples are navigation, agriculture and pasture, flood control and fish production. Navigation in the middle and low Magdalena River is important because it is a way to connect important interior cities with the ports of Barranquilla and Cartagena. In consequence, dry periods or sediment deposits imply economic losses for ships that get stuck in bar sands along the river.

The wetlands in the Magdalena River are areas with a very important biodiversity in fauna and flora and with a high potential for fish, forest and crop production [1, 2]. The land is generally owned by a few influential families that develop it for agriculture and cattle [1, 8], who demand more land. Documented experiences [5, 8] show that they generally start land reclamation activities by themselves and decide on the operational status of gates installed for multiple purposes. The disconnections of the streams that link the river and the wetlands have affected the ecology and fish production of the region negatively. This is mainly because of uncontrolled human interventions and the lack of protection policies [9, 12, 13].

Flooding is also a great concern in the lower part of the Magdalena River. In particular, the communities of Sabanagrande, Santo Tomás, and Palmar de Varela in the department of Atlantico, located along a reach of 15 km on the west floodplain and 43 km upstream from the mouth of the Magdalena River into the Caribbean Sea. Several measures have been executed in order to reduce the flood risk in the municipalities of the study area. The main project took place in the year 2000 and comprised the construction of protection dikes around the wetlands. However, due to the conflict of interests existing in the area, the project was not entirely built as designed.

The variety of uses existent in the wetlands causes a complex conflict of interests. On the one hand, farmers and cattle breeders close the sluice gates that connect the wetlands with the river to keep their lands dry when the water level in the river is too high. On the other hand, fishermen open the sluice gates to allow the fishes pass to the wetlands area. There is no operational protocol for such structures and the authorities do not exert any control policy.

The level of income of the local community living in the study area is low due to limited job opportunities and lack of development of sufficient productive work sectors. The poor inhabitants of the towns of the region are engaged in agriculture, fishing and production of hand crafted bricks. Besides, large areas of the wetlands are utilized for producing a wide variety of crops and cattle breeding by investors.

This research focuses on the effects of uncertain control strategies into the landscape of the river-wetland water system in the low Magdalena evaluating different scenarios with modeling tools. By uncertain control strategies we want to take into account the nature of human decisions that are outside the technicalities of control strategies, in particular to the transport of water throughout control structures under extreme events.

This chapter is structured as follows: first, a descriptive section of the case study is presented, which includes the main hydrological features of the region, the characteristics of the flood defense measures and the socio-economical aspects that make control of water a difficult task. Then, a description of the methodology to take into account the uncertainty in the status of control structures on the estimation of flood inundation maps of the area is presented and the resulting maps and the corresponding analysis are reported. Finally, some reflections about the link between transport of and transport over water are made explicit, followed by the discussion of open topics that should be investigated in the future.

8.2 Case Study

The study area is on the lower part of the Magdalena River, and includes the wetlands of Sabanagrande, Santo Tomas, and Palmar de Varela in the department of Atlantico—Colombia (Fig. 8.1). The wetlands are located along a reach of 15 km on the west floodplain and are part of the so called sub-catchment of wetlands of the Magdalena River in the Atlantico department and receive their names from the municipalities where they are located. According to the environmental authority of the region, the study area is located in geomorphologic units that represent stripes of variable width where the river develops curves in the main channel due to the high fluvial dynamics. As a consequence of such dynamic, the stream creates and destroys islands, erodes the riverbank, modifies local flow directions and abandons sections that become wetlands when they are wide enough.

8.2.1 Hydraulics and Hydrology of the Region

Climate in the study area is characterized by warm temperatures all year long, with an average temperature of 27 °C and a high humidity, around 80%. Annual average precipitation is 1,060 mm and three different seasons can be identified throughout the year: rainy season (August–November), when approximately 53% of

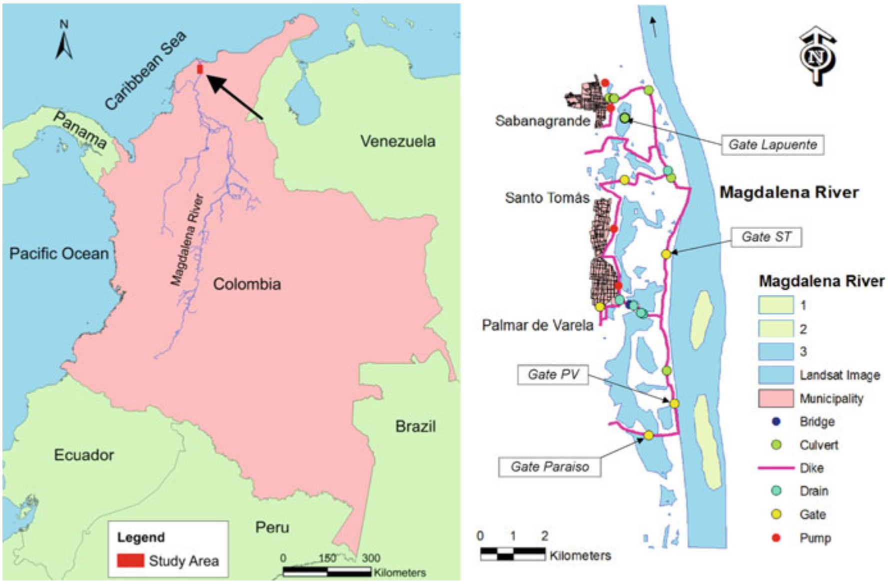

Fig. 8.1 Study area and location of flood defenses and hydraulic structures (adopted from [3])

the total annual precipitation takes place and dry season (December–March), when approximately the 8% of the total annual precipitation takes place, and transitional season, (April–July).

The wetlands of the lower Magdalena River (WLMR) form sub-catchments formed by multiple creeks that drain down to the river. Although this drainage occurs from both sides of the river, we focus the study in the west side along the last 115 km to its mouth in the Caribbean Sea. The system of wetlands can be considered as a subsystem that interacts with the Magdalena River and the runoff contribution from the afferent sub-catchments. The water level is mainly controlled by the fluctuations of the river and by the seasonal runoff that drains the sub-catchments of the system itself. Consequently, during the dry season, vast areas of the wetlands get dry. The sub-catchments that drain to the wetlands of the study area are the ephemeral creeks of Cañafistula and San Martin (Fig. 8.2).

The wetlands are hydraulically connected with the Magdalena River through canals, culverts that pass through the protection dikes, and directly when the river overflows its banks in low areas without dikes. The average annual discharge of the Magdalena River at its mouth is 7,100 m^3/s, typically having peak discharges during the months of June and November, being the latter the highest one.

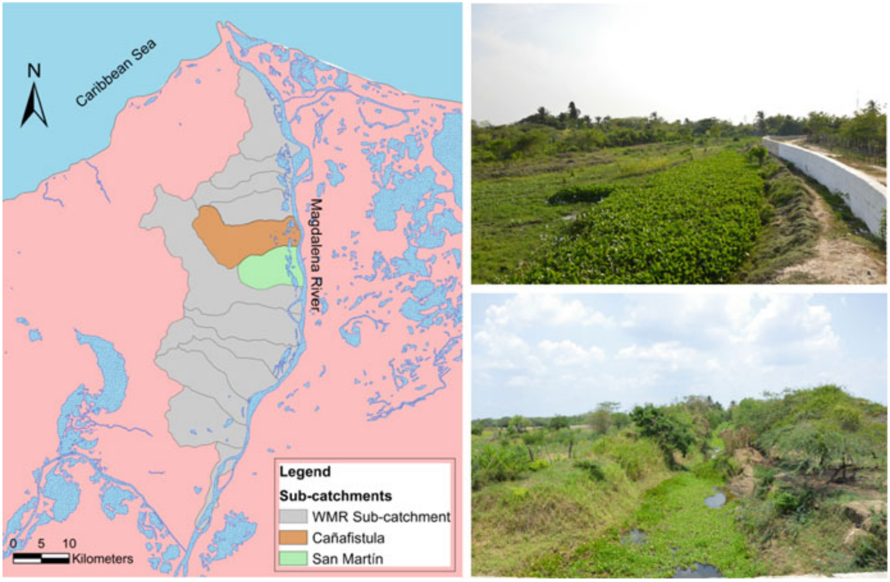

Fig. 8.2 *Left*: sub-catchment of the Magdalena River in the Atlantico department. *Top right*: San Martin Creek. *Bottom right*: canal between the Magdalena River and Santo Tomas wetland (adopted from [3]). *Photos*: Fabio Amador

8.2.2 Flood Defense Measures and Control Structures

Several measures have been executed in order to reduce the flood risk in the municipalities of the study area. The main project took place in the year 2000 and comprised the construction of protection dikes around the wetlands “to confine and regulate the water storage in the wetlands” [16]. However, due to the conflict of interests existing in the area, which is detailed further, the project was not entirely built as designed. To date, an important section of the dike in the municipality of Santo Tomas remains uncompleted.

Multiple hydraulic structures such as culverts, and sluice gates were installed in the dikes between the wetlands and the Magdalena River in order to keep them hydraulically connected, minimizing in this way the ecological impact on the ecosystems (Fig. 8.3). Flood protection measures and control structures affected considerably the hydrodynamic of the wetlands and caused a problem associated to pluvial floods in the towns as the dikes hinder the flow of the runoff to the wetlands.

Activities as agriculture, fishing, and hand-crafted bricks production are carried out in the wetlands as only way of survival for the poorest inhabitants of those towns. Apart from the locals, landowners of vast areas of the wetlands develop extensive crops and cattle breeding. The variety of uses existent in the wetlands causes a complex conflict of interests. On the one hand, farmers and cattle breeders close the sluice gates that connect the wetlands with the river to keep their lands dry when

Fig. 8.3 Example of gates for flood control. *Photo*: Fabio Amador

the water level in the river is too high. On the other hand, fishermen open the sluice gates to allow the fishes pass to the wetlands area. There is no operational protocol for such structures and the authorities do not exert any control policy.

8.3 Methodology and Main Results

Theoretically, well defined control strategies should lead to adequate performance of a water system. However, in practice, there are other aspects that are usually not considered on their initial design and that may impact greatly the system performance. An interesting example is the *control for citizen self-convenience* of the hydraulic structures in our case study, which are operated based on the expediency of a few persons in the community. This implies that the operational status of the structures is not known and therefore they are uncertain at any given time. A general definition of uncertainty in modeling is given by [17]: "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system". Uncertainty is a relatively new subject in the research field of hydraulic modeling [18]. In particular, we focus here on the effect of uncertain control strategies in flood hazards in the region.

The methodology, explained in detail in [7], consists of producing a set of maps to depict the areas that might be inundated by water under different scenarios, using hydraulic models. Each map is then compared with the observed flood extent and the models with the best performance are selected. The resulting maps are then integrated into a single one that represents the probability of being flooded given the considered scenarios. These steps are further explained in detail.

The method has been applied to the case study in the evaluation of the effect of the uncertainty in the estimation of the 100-year return period flow in the river [3] and the effects of the uncertainty derived from remote sensing topographical data of the Shouttle Radar Topographical Mission (SRTM-90) [15]. Although flood maps are affected by several other sources such as hydraulic and hydrological data quality, model structure and parameterization [3, 6, 10, 14, 15] uncertainty of control strategies is usually not taken into account. In brief, the method uses a Monte-Carlo procedure to produce a number of models that generate a number of deterministic flood maps for different combinations of operational settings of the control structures.

Models are simplifications of reality, in which processes that are not important are deliberately ignored and those essential of design or operation are implemented. The hydraulic modeling is carried out on a 20 km reach of the lower Magdalena River using the 1D Quasi 2D hydrodynamic SOBEK model. SOBEK is an integrated software package which enables to build complex models by dynamically integrating 1D components from SOBEK-Rural and 2D components from SOBEK Overland Flow. SOBEK 1D solves the De Saint-Venant equations through finite difference scheme.

The result of flood inundation modeling has to be verified by comparing to an existing observed flood extent map of the study area. In the lower Magdalena River, the inundated area obtained from the Landsat image of December 2010 flood event is compared with the model results. The Landsat image is a 3 band (RGB) image obtained from the NASA Landsat program 2010 scene LE70090532010341EDC00 [8]. This image was first classified using Multispec software to identify areas that are flooded from non inundated areas with the aid of supervised classification (Fig. 8.4). Then, the classified Landsat image is compared with the simulated results of SOBEK model using the measure of fit, defined by [10] as given below:

$$F = \left(\frac{A - B}{A + B + C}\right) * 100, \tag{8.1}$$

where A is the size of the flooded/wet area correctly predicted by the model, B is the size of the area predicted as wet by the model but actually is observed as dry/not flooded (over prediction), and C is the size of the area that is predicted as dry by the model but actually is observed as wet (under prediction). The measure of fit is proved to give good results for problems associated to flood inundation modeling and gives the opportunity to compare model predictions against observations [10].

The probabilistic flood inundation maps are then produced using the GLUE method [4], where every individual model is assigned a weight based on how well fits the observed flood extent, based on a Landsat image (Fig. 8.4). The next step is to compute the likelihood L_i weight of each simulation results in the range between 0 and 1. Likelihood is a measure of how well the simulated results obtained from a

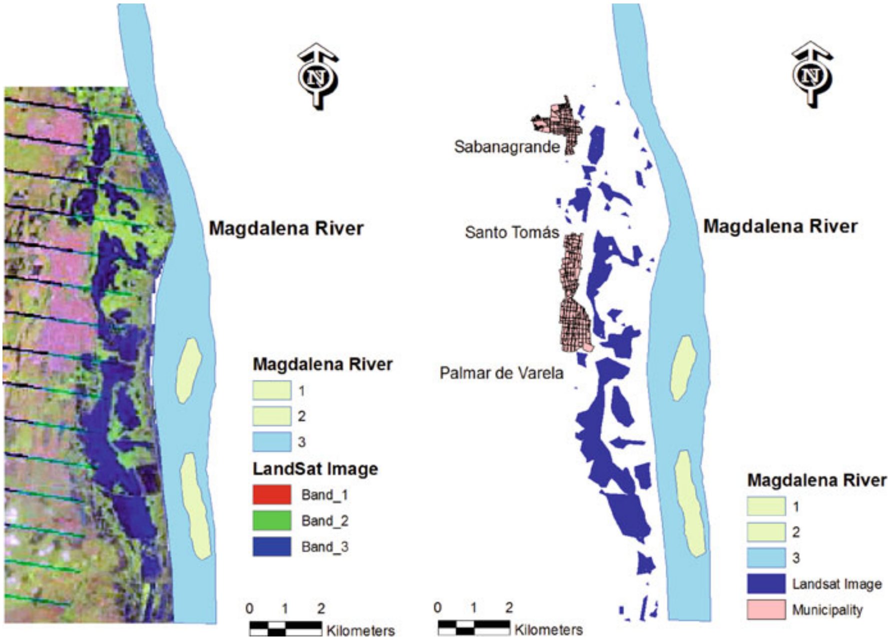

Fig. 8.4 Landsat Image of Dec. 2010 flood event (*left*) and its result after classification (*right*)

given combination of models, parameters and variables fits to the observed data and thus describes their degree of membership of the final acceptable solution. Given the measure of fit of (8.1), L_i is computed as

$$L_i = \frac{F_i - \min_i(F_i)}{\max_i(F_i) - \mathit{Min}_i(F_i)}, \tag{8.2}$$

where $\min_i(F_i)$ and $\max_i(F_i)$ are the minimum and maximum measures of fit found throughout the ensemble simulations. These likelihood values are used for generating uncertain probabilistic flood inundation map. A final model prediction is then generated by the weighted sum of the predictions from each simulation. For instance, given a weight L_i for each simulation i, and the simulation results for the jth model element (e.g., computational cell) of $W_i j = 1$ for wet and $W_{ij} = 0$ for dry, it is possible to develop an uncertain predicted flood inundation map using (8.3).

$$C_j = \frac{\sum_i L_i W_{ij}}{\sum_i L_i}, \tag{8.3}$$

where, C_j stands for a weighted average flood condition of the jth cell of the model [10]. The use of remote sensing data about the extent of inundation is a common practice to validate model-based flood maps. Conceptually, the evaluation of model results derived from an optimal parameter set is straightforward, and the performance measure given in (8.3) may be used.

8.3.1 Results and Discussion

As mentioned above, previous studies evaluated the effect of uncertain flow [3] and topography [15] in the flood maps of the region, including the probabilistic analysis of four topographical data sampling scenarios of 100 simulations each. The best model produced by the scenario with the higher number of behavioral models (those better matching the observed Landsat image in Fig. 8.4) was selected to run the possible 16 combinations of operational statuses of the four existing gates in the area, which can be either closed or opened.

The average inundated area resulting from the 16 maps is $10.7\,\text{km}^2$, with a minimum of $8.5\,\text{km}^2$, a maximum of $13\,\text{km}^2$ and a standard deviation of $2.2\,\text{km}^2$. The resulting probabilistic flood map is presented in Fig. 8.5, which has been build

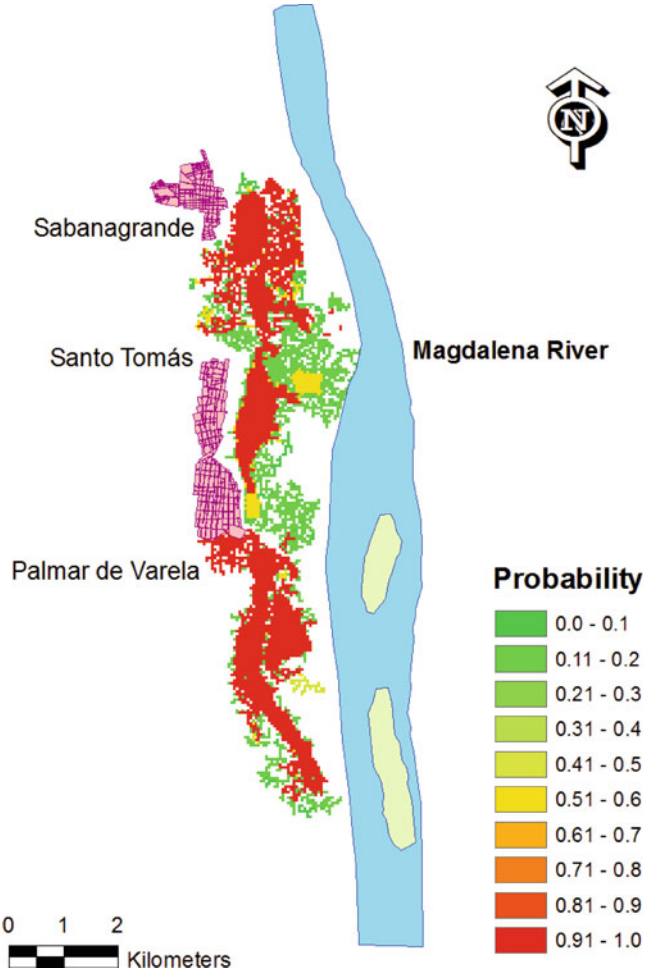

Fig. 8.5 Probabilistic flood map due to uncertain operation of gates

using the best model obtained regarding topographical uncertainty coming from SRTM data. It can be observed that, although the zones with higher probability of flooding largely match those areas in the observed Landsat image, there are important areas that can be flooded due to variations in the operational status of gates.

Another interesting analysis is to consider independent gate opening on the extent of flood inundation area. Results indicate that the inundation area does not change if the gates Lapuente or gate Paraiso (see Fig. 8.1) are operated, and that this is equivalent to the condition when all gates are closed. This leads to the conclusion that the operational state of both gates has no significant effect on the extent of inundation. On the contrary, the opening of gate Santo Tomás (ST) produces a significant increment in the inundation area, of about 5.0 km^2. A similar conclusion can be made for gate Palmar de Varela (PV), which generates an increase in the inundation area of about 3.0 km^2. Table 8.1 shows the total inundation area due to the individual gate opening, keeping the remaining gates closed, compared to the situation when all the gates are closed.

These results are evident when looking at the relative contribution of flooded area for different combinations of gate operation. Figure 8.6 shows the relative incremental flooded area from a number of gates operations combinations. It indicates that opening of either only gate Lapuente or Paraiso does not change the inundation area, which is equivalent to the condition when all gates are closed. This leads to the conclusion that the operational state of both gates does not have significant effect on the extent of inundation. On the contrary, the opening of Santo Tomás (ST) gate produces a dramatic boost in the inundation area. An analysis using different topographical model scenarios shows that this increment is between 3.1 and 5.2 km^2.

In conclusion, based on the results of the simulations, gate ST is the most important one as far as flooding is concerned and hence this particular gate should be closed especially during extreme flood events. This gate appears to be the critical one for fishing activities.

Table 8.1 Simulated inundation areas as a result of local control gate opening scenarios

Scenario	Gate	Status	Inundation area (km^2)
1	Lapuente	Opened	8.6
2	Paraiso	Opened	8.5
3	PV	Opened	8.6
4	ST	Opened	12.5
5	All	Opened	13.0
6	All	Closed	8.5

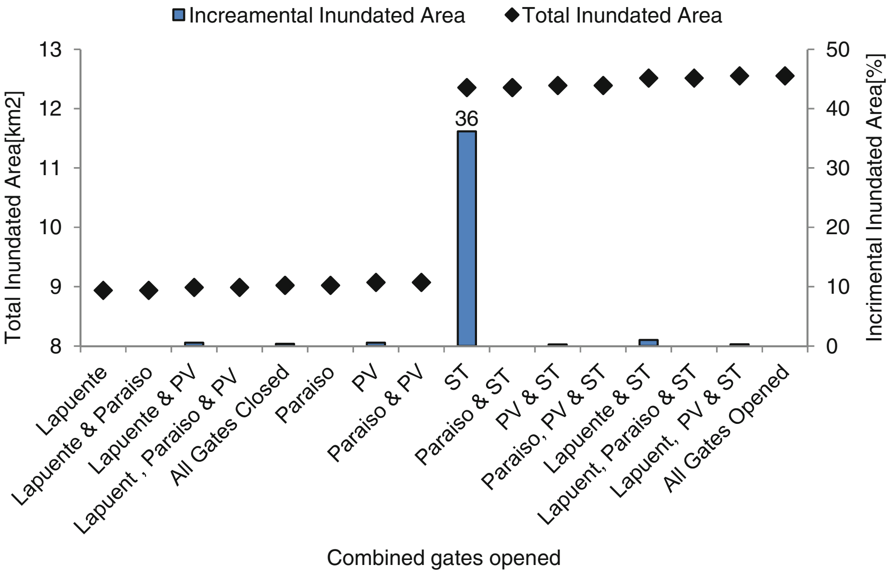

Fig. 8.6 Relative incremental flooded area due to different combinations of gate operations

Table 8.2 Inundation extent at different opening heights of gate ST

Opening height of gate ST (cm)	0	20	40	60	80	100	120	140	160	180	188
Inundation area (km^2)	8.8	9.9	11	11.7	12.2	12.5	12.6	12.7	12.9	13	13
Incremental area (%)	0	13	12	8	6	3	2	1	2	2	0

8.4 Linking Transport of and Transport over Water

All previous analysis have been done considering a binary status of the gate, either fully opened or closed, due to the computational effort required for the 2D model to perform a single simulation. However, the effect of multiple opening states is of interest, in particular because this is a feature of the anthropogenic interference in the status of the control structures by different water users with different water requirements, including transport of and transport over water. To this end, a sensitivity analysis of the status of the gate ST, identified as the most important in the context of flooding, is considered, assuming that the remaining gates are closed.

Table 8.2 and Fig. 8.7 show the flood inundated area as a function of opening height of gate ST at an opening step of 20 cm. As a result, the inundation area consistently increases as the gate opening goes up to 1.0 m. Interestingly, no

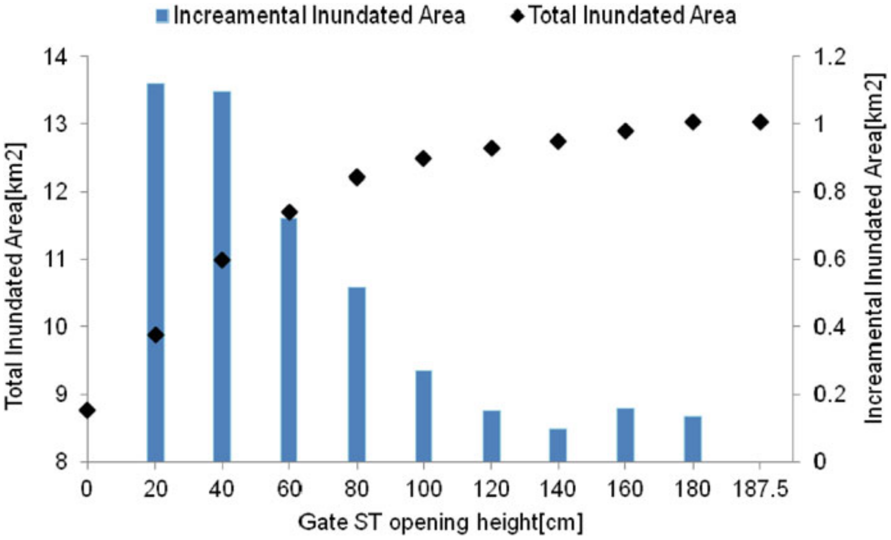

Fig. 8.7 Result of the sensitivity analysis using Gate ST

significant increase of such inundated area is observed beyond that value. In general, the smallest and the largest flood inundation extent are achieved when gate ST is fully closed and fully opened, respectively.

8.5 Open Topics

As demonstrated, uncertainty of social aspects can greatly affect the flood inundation area of controlled, regional and flat water systems. An open question is how to incorporate such a source of uncertainty within an integrated design of control strategies in these cases. Robust optimization could be a possibility, aiming at making the performance of the water system as independent as possible to uncertain variations of control structures.

From the practical perspective, it is well-known that the design of control and real-time control of water systems must take into account all user requirements when defining setpoints at different special and temporal scales and that this is a multi-objective optimization problem [11]. It is also known that robust solutions are obtained if uncertainty is accounted for when solving this kind of problems. In consequence, the use of the concept of robustness could be used as a global performance indicator of transport of/over water systems in further research.

8.6 Conclusions and Future Research

The present study has demonstrated that in a combined framework of control for transport of water and transport over water, different sources of uncertainty must be estimated and analyzed. In particular, sources of uncertainty of anthropogenic nature, such as the one presented, deserve as much attention as those sources that are traditionally taken into account and that normally receive more attention. Probabilistic flood inundation maps can be used to analyze the consequences in terms of transport of water and its implications to other uses, including transport over water, and, in consequence, they can be used as inputs in the design of robust control systems.

This research takes into account water to be transported through the river and through the hydraulic structures to allow for environmental, ecological and social purposes of some stakeholders, in the unusual case in which the stakeholders operate the structures at their convenience. It demonstrates that the current control condition may lead to different situations in terms of flood extension, which affect different water users. Although in the specific case of the WLMR one could argue that a strong implementation of control policies regarding the control of structures would be enough to improve the situation, this is not easy in practice, due to the peculiar social and political situation of the inhabitants of the region. Methodologies from social science are needed to approach the communities and communicate the implications of the current practice and the advantages of collaborative, organized control strategy with clear rules and responsibilities, presumably starting with basic school education.

This research focused on the particular situation of extreme flow conditions on the river. However, it is of interest to further investigate the possible effects of anthropogenic activities on control for the case of normal variations in the river, checking at other criteria beyond flood extension. For example, the effect of uncertain gate operation on the agricultural (transport of water) and fish production (transport over water).

In the context of this book, we can argue that the presented case and the proposed methodology not only addresses transport of water, occurring from the river to the wetland throughout hydraulic structures, but also other aspects, including transport over water. For instance, a fisherman that cannot navigate the wetlands when gates do not allow for water inflow from the river is a common problem in the considered case.

More than a method to bridge the gap between flow and transport, this chapter shows how significant the role of uncertainty is in the performance of control systems, in particular that associated to social aspects. In consequence, management policies aiming at improving these systems should explicitly consider them, in particular in the context of developing countries. We believe this research contributes with new perspectives ultimately leading to a unified management framework.

Acknowledgements This research was carried out for the ColCuencas project, funded by the DGIS (Dutch Development Cooperation)—UNESCO-IHE Programmatic Cooperation (DUPC). The authors would like to thank the Regional Authority of Atlantico CRA for delivering the data and to Fabio Amador, who built the initial hydraulic model of the region.

References

1. Aguilera M. La Mojana: Riqueza natural y potencial económico, In: Documentos de trabajo sobre economîa regional. Banco de la República, Centro de Estudios Económicos Regionales (CEER), ISSN 16923715, 2004;48.
2. Aguilera M. Ciénaga de ayapel: Riqueza en biodiversidad y recursos hídricos. In: Documentos de trabajo sobre economîa regional. Banco de la República, Centro de Estudios Económicos Regionales (CEER), ISSN 16923715, 2009;112.
3. Amador F. Development of a methodology for producing probabilistic flood maps of river-wetland systems: Case study of Magdalena river, Colombia. Master's thesis, UNESCO-IHE, 2013.
4. Beven K, Binley A. The future of distributed models: Model calibration and uncertainty prediction. Hydrol Process. 1992;6(3):279–98.
5. Cormagdalena and ONF Andina. Plan de Manejo de la Cuenca Magdalena Cauca. Informe Final Fase 4. Fluidis, 6003 - I04, 2007.
6. Di Baldassarre G, Montanari A. Uncertainty in river discharge observations: A quantitative analysis. Hydrol Earth Syst Sci. 2009;13(6):913–21.
7. Di Baldassarre G, Schumann G, Bates P, Freer J, Beven K. Flood-plain mapping: A critical discussion of deterministic and probabilistic approaches. Hydrol Sci J. 2010;55(3):364–76.
8. DNP and FAO. Programa de desarrollo sostenible de la región de La Mojana, Departamento Nacional de Planeacion y. Organización de las Naciones Unidas para la Agricultura y la Alimentación, Bogotá, 2002;567.
9. Galvis G, Mojica JI. The Magdalena river fresh water fishes and fisheries. Aquat Ecosyst Health Manage. 2007;10(2):127–39.
10. Horritt MS. A methodology for the validation of uncertain flood inundation models. J Hydrol. 2006;326(1):153–65.
11. Lobbrecht A. Dynamic water-system control: Design and operation of regional water-resources systems. Rotterdam: AA Balkema; 1997.
12. Munera M, Daza JM, Páez VP. Ecología reproductiva y cacería de la tortuga. Rev Biol Trop. 2004;52(1):229–238.
13. Naranjo L, Andrade GI, Ponce E. Humedales interiores de colombia. Bases técnicas para su conservación y uso sostenible. Bogotá: Instituto Humboldt y Ministerio del Medio Ambiente; 1999.
14. Neal J, Keef C, Bates P, Beven K, Leedal D. Probabilistic flood risk mapping including spatial dependence. Hydrol Process. 2013;27(9):1349–63.
15. Tefferi M. Ensemble simulations to estimate uncertainty associated with srtm topography and operation of hydraulic gates in flood inundation mapping: Case study of the lower Magdalena river in Colombia. Master's thesis, UNESCO-IHE, 2014.
16. Urquijo J. Study and design of hydraulic structures in the wetland system of Sabanagrande, Santo Tomás and Palmar de Varela (in spanish), 1997.
17. Walker W, Harremoes P, Rotmans J, van der Sluijs JP, van Asselt MB, Janssen P, von Krauss MP. Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. Integr Assess. 2003;4(1):5–17.
18. Warmink J. Uncertainty analysis of hydrodynamic river models. University of Twente, Enschede, The Netherlands; 2009.