Towards Management and Regulation of Gravel Mining in Urban Areas of Santiago, Chile: Analysis of the sediment budget in Maipo River

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ABSTRACT

Gravel extraction from a natural streambed combined with changes in water resource usage may induce modifications of a stream's sediment transport characteristics. Reduced transport capacity and river bed overdraft can bring a system off its natural equilibrium, resulting in decreased sediment replacement rates downstream from the extraction area, which in turn may affect civil works founded in the river bed, as well as water catchment infrastructure designed upon minimum river stages. This work presents a methodology for estimating sediment production rates in the Maipo river (Central Chile) by means of a sediment transport simulation model and field data representative of current sediment and water use/extraction rates. The model is used to evaluate changes in sediment availability due to changes in gravel extraction rates and water use upstream of the urban area of Santiago. A first step toward integrated water and sediment management is proposed by means of coupling a management model with the sediment transport model in order to evaluate the economic impact of combined sediment and water use policy.

Keywords: Gravel mining regulation, Maipo River, Santiago, sediment budget, sediment transport.

1. Introduction

Aggregate extraction from river channels is a usual practice in Chile, based in the requirement of this material for different activities. The biggest demand comes from activities related to the construction field. One of the main sources of aggregates corresponds to rivers nearby to the cities, which represent the major sources of demand of aggregates (*Figure 1*). The importance of the alluvial aggregates is given by: 1) in general, there is a good access to the extracting area (roads and natural paths), 2) high quality of alluvial aggregate and a 3) broad particle size range, so that the requirement for mechanical size reduction is minor [5]. The sediment/aggregates generation processes are concentrated in the upper part of river (mountain river), from where the material is transported by the flow to the mean and lower part of the river. So is evident the high connection between the sediment transport process and the flow into the system.

Many rivers nearby big cities, having stable and considerable mean flow, present large extraction of water associated to consumptive uses (drinking water supply, irrigation, hydroelectric generation, etc.). Because of these uses many systems don't show a stable equilibrium in time in terms of sediment transport and streambed degradation/aggradation . Others authors have documented and described problems associated to the excessive exploitation of aggregates in rivers ([5], [6] and [7]). These problems are associated principally to streambed morphology modifications and to channel width variation in time. This modifications and their effects over flow behavior are far from restricted to a local scale, existing literature reports of cases for which the effect can reach several kilometers in both directions, upstream and downstream ([7], [1]). Some problems related to river behavior modification are: reduced sediment transport, decreased sediment replacement rates downstream from the extraction area, impact on civil works founded in the river bed (bridges, pipes, etc.) and water catchment infrastructure (lower streambed), impact on environment and ecosystems.

Considering the existence of several water and sediment extraction in different points throughout the river and all the structures supported in the banks and streambed, is necessary to develop a methodology to evaluate the effects of actions taken for one over the others, besides bringing forward the understanding on how new activities will alter the operational conditions of existing activities and industries in the short and long term. Therefore, this study is centered in the development of a tool, able to shed light over future interferences and problems associated with the changes and incorporation of further activities to the river system. With this is possible to obtain better information for the management and regulation of sediment extraction from river systems. So the study is focused in the linkage between a modified version of a Hydrodynamic and Sediment Transport Model (MOSSEM) with a Management Model, with the aim of evaluating several scenarios in rivers with high demands of water/aggregates. The Management Model is based on the river use optimization, considering all the users presents and their activities, and some external impacts as consequences of the morphology modification due extractions and the time evolution of the streambed.

Figure 1. (Left)Gravel extracted process industry. (Right)Gravel extraction pit on the Maipo river.

2. Management Objectives

The main management objectives include the determination of possible effects by new system users, and to estimate the costs and/or damages to the existing users on account of the new system operation. Another objective corresponds to the maximization of a general productive value considering the minimization of the associated effect of the different productive activities to the river, while some system constraints include water rights allocation, existing gravel extraction permits, and future possible water/aggregates extraction rights in the sector.

3. Model Development

The methodology is based in the linkage of a modified version of a Hydrodynamic and Sediment Transport model, MOSSEM ([4] and [1]), capable to calculate the time evolution of hydrodynamic characteristics, morphology modification and the sediment transport in the river from a particular state taking into account gravel extraction in specific zones, with a Management model developed by the authors, capable to identify and evaluate the interaction between different current and future extractions in the river. The Management model uses output information from the Hydrodynamic and Sediment Transport model, which is analyzed evaluating a main objective function for all locations of interest. With the information generated in all the numeric simulations, it is also possible to analyze the interaction and interferences between the different activities developed in the river system.

A schematic description of the whole model and the interaction between their different parts is shown in the *Figure 2*.

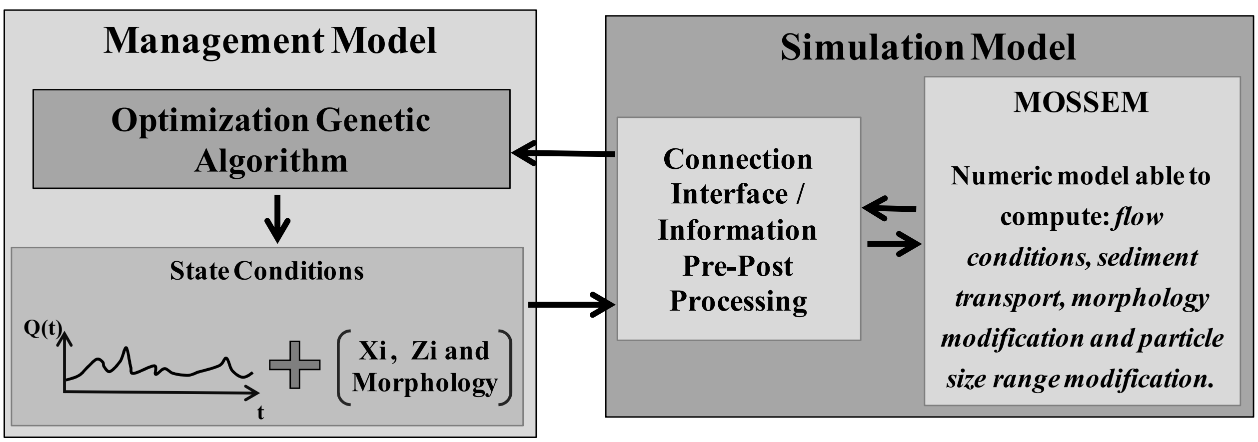

Figure 2. Description of Management model coupled with MOSSEM model.

3.1 Management model

The Management model has the form of a mathematical programming problem and has been implemented over a public domain Genetic Algorithm programmed in FORTRAN, which gives the possibility to interact within the modified MOSSEM model, and enables direct manipulation of the input/output data. The model considers a set of optimization and control nodes which corresponds to real zones on the river. These evaluation nodes are divided in 4 categories: Infrastructure nodes (type 1), water catchment and minor infrastructure nodes (type 3), existing gravel extraction nodes (type 4) and new possible gravel extraction nodes (type 2). The main variable for the model is given by the gravel extraction rates associated to the different potential extraction zones. Other relevant parameter corresponds to the maximum final streambed decrease permitted along the river, which is defined in terms of the river restoration time. This time is given by the decision-making criteria in order to define a wanted time scale to have a fully operative river system in a particular state condition. This aim has to be resolved previously, running several MOSSEM simulations to estimate the time restoration for a particular limit of streambed decrease.

The Management model solve the optimization problem,

$$\text{F.O.} \Rightarrow Max\left[\alpha B - (1-\alpha)C\right]$$

Where,

$$\text{Benefit}: B = \sum_{i}\sum_{t}^{N} \delta_i^{\,B}\, X_i\, b_i \quad ; \quad \text{Cost}: C = \sum_{i}\sum_{t} \delta_i^{\,C}\, C_i(\eta_i)$$

And,

$$\delta_i^{\,C} \in \{0,1\} \quad ; \quad \delta_i^{\,B} \in \{0,1\}$$

The decision variable $\mathbf{X}_i$ corresponds to the amount of aggregates extracted in the node **i**; η_i is the streambed level in node **i**; δ_i^C and δ_i^B are delta function for applying the costs or benefits, respectively, to the node **i**; $\mathbf{b}_i$ is the benefit per unit of $\mathbf{X}_i$ in the node **i**; $\mathbf{C}_i(\eta_i)$ is the function cost in the node **i** depending of the streambed variation (η_i) during the simulation. The α parameter corresponds to a weighting factor to focus the optimization in the benefits or the costs.

3.2 Hydrodynamic and sediment transport model (MOSSEM)

The MOSSEM model is capable to resolve stream fluxes together with the dynamics of sediment transport. The first version of this model (González [4]), includes three main parts: i) flux resolve, ii) calculate of bottom sediment transport with streambed evolution and iii) calculate of turbidity current and fine sediment deposition/resuspension. A newer version of the model (Abarca [1]) considers the variability of granular size distribution in an active superficial layer. A newer modified version of MOSSEM is developed to take in account the existence of gravel extraction zones and to include the removed mass into the zone mass balance and its consequential effects on the morphology evolution.

3.3 Linkage implementation

The global model is implemented to be run in cluster mode, using independent processors for each case of simulation with MOSSEM. The interaction between the Genetic Algorithm and MOSSEM is made by a third program developed by the authors in FORTRAN language, which is capable to interpret the instruction given by other programs and execute the run of MOSSEM. Also, this program performed the intercommunication between models and the backup of the output information for each simulation.

The use of a cluster mode to run the program permits the utilization of many computers as is necessary, to perform faster and bigger general simulations with the consequential information generation of greater quality to post-processing.

3.4 Model results analysis

The Management model has the ability to find the optimal solution for a given objective function, which can be posed to maximize the benefits, minimize the costs or find the best solution for a particular case in terms of gravel extraction rates in a defined river zone. Besides of finding an optimal, all the results generated in the search are archived for post-processing work, which analyzes statistically the behavior of the system in terms of finding possible interferences between different users, impacts on river behavior by particular modifications and increasing the knowledge about river morphodynamics.

4. Application Example

<u>Maipo River Description</u>

The Maipo river basin is the main source of water for the city of Santiago, (Región Metropolitana), yielding approximately 21 m^3/s of fresh water. This amount considers the water provided by the Maipo river, El Yeso reservoir and Laguna Negra (lake). Besides, there exists a great demand of water for irrigation in agricultural land (about 195.000 ha). Agriculture generates a mean demand of around 132 m^3/s ([2] and [3]). For management purposes the system is divided in 3 sections, besides the main tributary rivers (e.g. Río Mapocho). The study is focused in the First Section, which extends from the high Andes Cordillera in the limit with Argentina until the railroad bridge of Paine to Talagante (Lonquén). The First Section has 7 water extractions, which give rise to 10 main conduction channels and 4 river refill points (1 of rain water and 3 of hydroelectric power plants). The main water extraction is located in “La Obra” sector, and includes the “Independiente” catchment and “La Obra”. In this section of the river a “Junta de Vigilancia” (vigilance board), has control over the extracted flow volume and its distribution to the final users. Besides, there’s no strict control over the gravel/aggregates extraction, therefore excessive extraction is possible. Finally, the river and its tributaries are monitored by 13 flow gauging stations, of which 3 stations (Río Maipo en el Manzano, Río Maipo en San Alfonso, and Río Maipo en Las Hualtatas) are relevant in this study. Along the river 37 gravel extractions have been identified and coexist in the system 6 channel operation associations that regulate the extraction of water from the system and its latter distribution to different users.

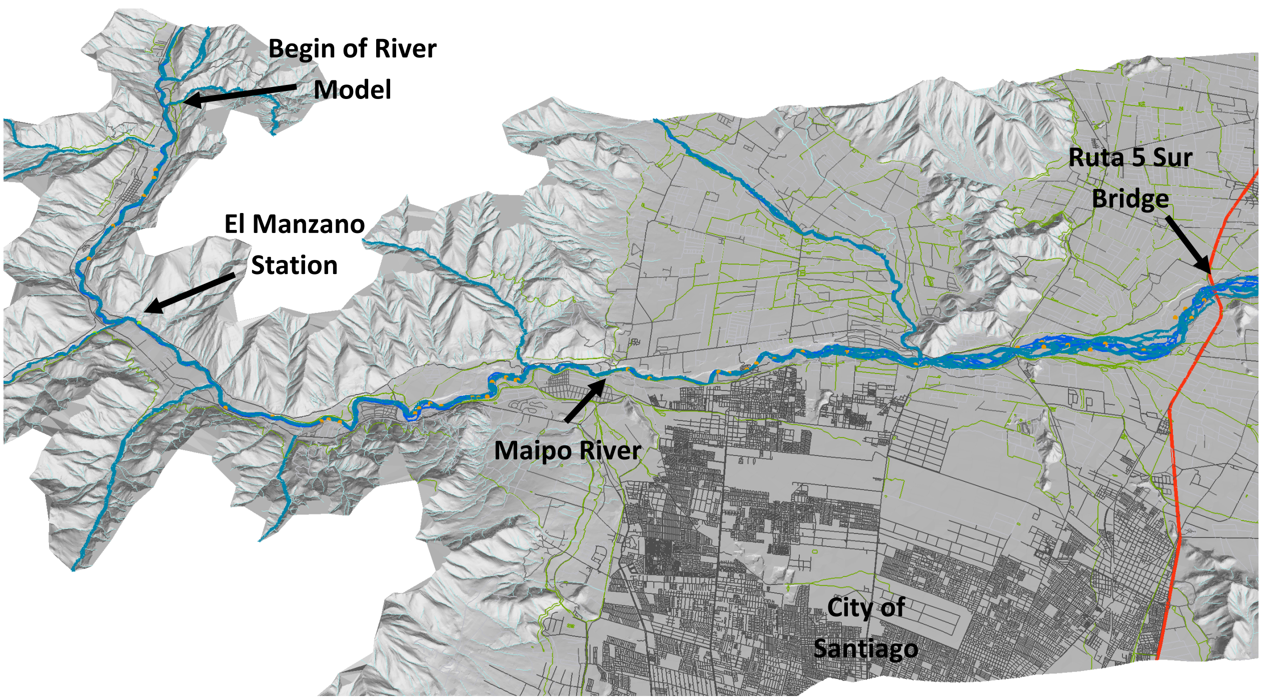

Figure 3.GIS data used to construct the morphologic model.

Application Description

The system can be described as a river with its mean condition established in the upper part of it. The rest of the system has inputs/outputs of series of water/aggregates. The application example considers around 42 kilometers of river for the morphologic model (*Figure 4*) and an annual flow time series that include high flow values (*Figure 4*). The morphologic model includes 408 transversal sections of the river and 69 nodes to be evaluated.

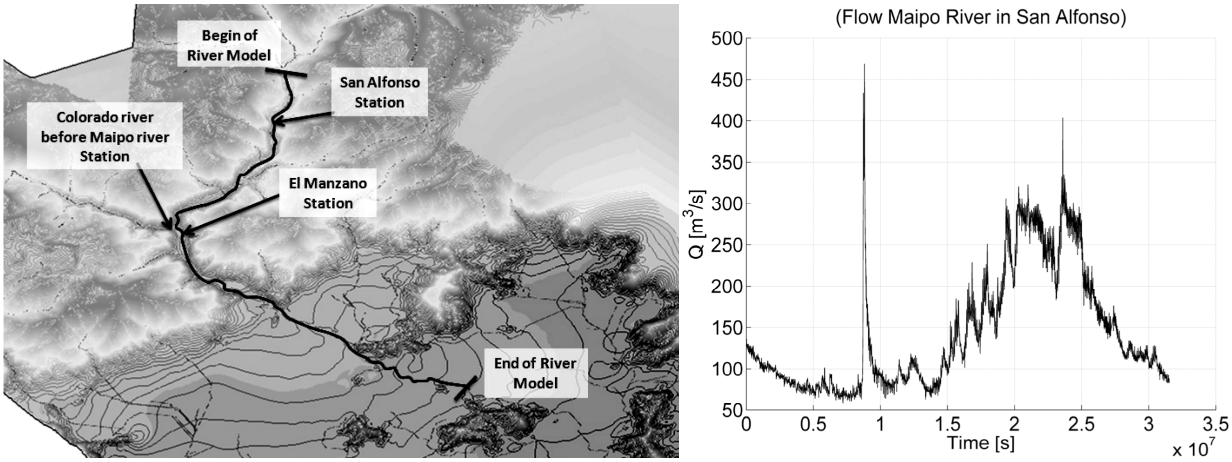

Figure 4. (Left) Morphologic model used in simulation (Right) Annual flow time series.

Moreover, the Maipo river gravel characteristics are considered through defined the material granulometry and incorporating this to the model.

5. Discussion

Several runs were made to evaluate possible new extraction zones, varying the initial model initial conditions, the number of nested process unit (CPU) for the calculus and the number of zones analysis. The results of all the runs had shown a convergence to a final solution in compliance with the required target.

Furthermore, given the structure of the Genetic Algorithm (GA), the convergence to the final solution is very sensitive to the established limits of the decision variables. Hence, dynamic limits were implemented to the decision variables in the GA. This allows to avoid long simulation times due to the need to have a wide range of variability for the decision variables,. It should to be noted that the application of dynamic limits reduces the simulation time, but using an update criteria closer to the limits may enlarge significantly the simulation time.

Finally, the great amount of information generated and stored during the simulation until reach the optimal solution permit the analysis of river system feasible domains, and in a future situation have a better knowledge about the river system behavior in terms of the management.

6. Future study extensions

Changes to the actual model are considered to improve the internal dynamic of the model and to reduce the time computation.

The incorporation of a heavy metals contamination dynamic module is in mind to evaluate the one of the most important problem in the Chilean mountain rivers due the mining activities existing closeness to the rivers head.

7. Acknowledgements

This research has been supported by “Risk Habitat Megacity” project, a Helmholtz Association initiative and coordinated by the Helmholtz Centre for Environmental Research – UFZ. We want to thanks to the Transport Processes in Environmental Flows research group for their support and help to deal with the numerical simulation issues.

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