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NUMERICAL SIMULATION OF THE EXTRAORDINARY FLOOD OF THE SALADO RIVER, SANTA FE

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Abstract. Large areas of central and northern Santa Fe and the State Capital Santa Fe, have been recently a¤ected by an exceptional ‡ood of the Salado River as the result of extreme precipitations over the region during the …rst quarter of 2003. During April, between 300 and 400 mm of rain fell in Santa Fe city and surrounding areas to the north. By the night of April 29th 2003, almost one third of the city was under water. This communication presents the results of the numerical simulation of the event, in urban and suburban areas of Santa Fe city as well. The simulations were performed with a …nite element code based on the long wave mathematical model or shallow water equations. Among other capabilities, the code possesses a wetting/drying element algorithm, which confers more realism to the numerical computations. The aim was to simulate the e¤ect of the failure of a 150m reach of an un…nished levee that caused the rapid ‡ooding of lowland neighbourhoods, practically without warning. Numerical results reproduce ‡ood stages within the city during the ‡ood peak, adequatly well, capturing the catastrophic consequences of the collapse of the ‡ood-control structure..

1 INTRODUCTION

During the last 30 years, the State of Santa Fe has experienced noticeable changes on its precipitation regime, i.e. there has been a generalized increment of about 100 mm on the annual average rainfall all over the state. To give an example, the average annual rainfall for the city of Santa Fe, the State capital, was 983 mm for the series 1902-2000, amount that increased to 1082 mm for the series 1971-2000. In addition, another phenomenon is being more frequently observed throughout the State: extremenly intense and highly localized in space precipitation events that cause severe property damages and even losses of human lives.

The rainy season in the State, and for that matter in the city of Santa Fe, starts in October and extends until April of the following year. Close to 80 % of the total annual precipitation falls within that period. The rainy season of the water year 2002-2003 was one of the wettest on record. From October 2002 until March 2003, Santa Fe city received 21 % more rainfall than the average precipitation it gets in a whole year. This situation repeated all over the northern parts of the State saturating extended areas within the Lower Basin of the Salado River, hence reducing the water bu¤ering capacity of the basin to a minimum.

Santa Fe City, oriented on a predomintly N-S direction, is located on the wedge formed by the con‡uence of the Salado River on the West and the alluvial system of the Paraná River on the East (Figure 1). Its current population reaches approximately a half million people, a signi…cant proportion of whom occupy the ‡oodplains of the Salado and the Paraná rivers. In 1992, the city built several ‡ood-control structures on the Paraná River in the East part of the city, as well as along the Salado River on the West side of the city. The main ‡ood-control structure against ‡oods of the Salado River is the so-called Irigoyen levee, running for about 7 km and rising 5.2 m above ‡oodplain level. While the …rst two stages of the construction of the Irigoyen levee were accomplished, the third and last stage was never completed. The 3 km long third construction stage of the levee was meant to close a protective ring on the city's northwest side.

From April 21 to April 29, 2003, more than 400 mm of rain fell in some regions of the Lower Basin of the Salado River. The river quickly overtopped its narrow and wandering channel and spread over the ‡oodplain with unusual strength, destroying bridges and roads, and isolating some small towns in its run towards its outlet near Santa Fe city. The peak discharge through the bridge of the State Road No. 70 was estimated at 3600 m^3/s (the maximum peak discharge on record was 2700 m^3/s). During the night of the 29th of April, the failure of a 150 m reach of the un…nished Irigoyen levee resulted in the rapid ‡ooding of lowland neighbourhoods, practically without warning. Accustomed to coping with ‡oods where water levels rise steadily but slowly, people in this area faced a sudden increase of about 2 m of water in few minutes in some places. In the chaos of the …rst 24 to 48 hours of the ‡ood, an estimated 120,000 people were displaced. Schools, clubs, government facilities, churches, and non-pro…t organizations of the city sheltered about

50,000 people, and approximately 70,000 people are believed to have sought shelter with friends and family all over the city. One third of the city was under water at some point. The total loss of the flood is being estimated well above 1,000 million dollars, though a huge amount of that is being borne by individuals and, as such, is still unreported.

In this communication, numerical results of the simulation of the sudden flooding of the city of Santa Fe that took place during the last days of April are presented. The simulations were carried out using the TELEMAC-2D[1] code. The goal was to reproduce the propagation time of the water wave and the water level rise within city limits, not only to reproduce the natural phenomenon but also to demonstrate the capabilities of 2D computational tools for simulating a hydraulic situation that, in some aspects, resembles a dam break problem.[2]

2 GOVERNING EQUATIONS

The depth-integrated Navier-Stokes equations of motion, previously averaged over turbulence, known as the SWE, are expressed in Cartesian form as[3]

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = H \qquad (1)$$

The vectors U, F, and G can be expressed in terms of the primary variables, u, v and h as

$$U = \begin{bmatrix} h \\ uh \\ vh \end{bmatrix}; \quad F = \begin{bmatrix} uh \\ u^2h + gh^2/2 - 2h\nu_t\frac{\partial u}{\partial x} \\ uvh - h\nu_t\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \end{bmatrix}; \quad G = \begin{bmatrix} vh \\ uvh - h\nu_t\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \\ v^2h + gh^2/2 - 2h\nu_t\frac{\partial v}{\partial y} \end{bmatrix}$$

The source term H is given by

$$H = \begin{bmatrix} 0 \\ -g\frac{\partial \zeta}{\partial x} - \tau_{bx}/\rho \\ -g\frac{\partial \zeta}{\partial y} - \tau_{by}/\rho \end{bmatrix} \qquad (2)$$

In the above equations, $(u; v)$ are the depth-averaged velocity components along the streamwise and lateral horizontal directions $(x; y)$ respectively, t is the time, h is the total water depth, g is the acceleration of gravity, ρ is the water density, $(\tau_{bx}; \tau_{by})$ are the shear stresses components acting on the stream bed, ζ is the channel bed elevation, and ν_t is the turbulent eddy viscosity. For depth-averaged calculations, one often approximates the turbulent viscosity as $\nu_t \approx \alpha u_* h$, where u_* is the bottom friction velocity defined as $\sqrt{|\tau_b|/\rho}$. The constant α, that may range from 0.07 to 0.30, not only takes into account the mixing process due to turbulence but also the vertical flow inhomogeneities. To close the problem, the classical squared function dependency on the depth-averaged velocity is used to model the bed resistance

$$\tau_{bx} = C_F\rho|u|u; \quad \tau_{by} = C_F\rho|u|v \qquad (3)$$

Sometimes, the friction coefficient C_F is traditionally replaced by other coefficients such as the Manning or Chézy relations

$$C_F = g n^2 h^{-1/3}; \quad C_F = g C^{-2} \tag{4}$$

where n is the Manning roughness coefficient, and C is the Chézy discharge coefficient[4]

3 CODE DESCRIPTION

TELEMAC-2D was developed by the National Hydraulics Laboratory (Laboratoire National d'Hydraulique - LNH) of the Research and Studies Directorate of the French Electricity Board (EDF-DER). The software is imbedded in an integrated and user-friendly software environment, the TELEMAC system. TELEMAC-2D employs a fractional step method or splitting technique[5] to solve the governing equations (eqs. 1), where advection terms are initially solved with the Method of Characteristics (MOC),[6] and separated from diffusion and source terms, which are solved together in a second step. This is achieved for a space discretization consisting of linear triangles with three nodes.

The second step of TELEMAC-2D makes use of a time discretization of the predictor-corrector type and solves the resulting linear system with a conjugate gradient type method. In addition, the TELEMAC-2D code makes significant savings in both computational time and storage requirements through the use of an element-by-element solution technique. The matrices of the linear system are stored in their elementary form without full assemblage, that is the governing equations are formulated in a weak sense using the Method of Weighted Residual (MWR), where the water-depth and the velocity fields are approximated using the standard FEM basis functions

$$h \approx \sum_{j=1} h_j(t)\phi_j(x); \quad u \approx \sum_{j=1} u_j(t)\phi_j(x); \tag{5}$$

where N is the number of discrete points, and $h_j(t)$ and $u_j(t)$ are the nodal unknowns ($j = 1; \ldots; N$) of the water-depth and the depth-averaged velocity components, respectively, and $\phi_j(x)$ are the approximation functions defined over the finite elements. Then, the solution is advanced in two steps as follow:

- 1st step: The advection terms are solved with the MOC, that is, if the spatial coordinate is 'convected' along the problem characteristics, the convective terms disappear and the remaining problem is that of simple diffusion for which standard discretization procedures are optimal[6]

$$\frac{h^* - h^n}{\Delta t} + u^n \cdot \nabla h^n = 0 \tag{6}$$

$$\frac{u^* - u^n}{\Delta t} + u^n \cdot \nabla u^n = 0 \tag{7}$$

- 2nd step: The remaining terms are now advanced on the basis of the 1st step solution $h^*; u^*$. The mass conservation is, in consequence, discretized as follows

$$\frac{h^{n+1} - h^*}{\Delta t} + (h \nabla \cdot u) = S^n \tag{8}$$

where S represents source/sink terms, if any, and the non-linear terms are linearized mathematically to remove the need for an iterative solution of the Newton-Raphson type. For example, the non-linear term above is linearized as

$$(h \nabla \cdot u) = \tilde{h} \nabla \cdot \left[\theta u^{n+1} + (1 - \theta) u^n \right] \quad 0 \le \theta \le 1 \tag{9}$$

where θ is an implicit weighting coefficient bounded between zero and one, and the superscripts n and n + 1 indicate the time step level,[7] and

$$\tilde{h} = \begin{cases} h^n & \text{without sub-iteration loop} \\ h^{n+1} & \text{with a sub-iteration loop} \end{cases} \tag{10}$$

The momentum conservation equation is then advanced as follows:

$$\frac{u^{n+1} - u^*}{\Delta t} = -g \nabla H^{n+1} + F^n + \nu_t \nabla^2 u^n \tag{11}$$

where

$$-g \nabla H^{n+1} = -g \nabla (h^{n+1} - h^n) - g \nabla H^n \tag{12}$$

The resultant system of linear equations is solved with the GMRES solution algorithm (Generalised Minimum RESidual). Further details about the GMRES algorithm implementation can be consulted in Reddy and Gartling.[8]

4 DESCRIPTION OF THE MODEL AREA

The study area occupies about 88 km^2, extending 25 km on a North-South direction from 3 km upstream of the State Route No. 70 up to the discharge point of the Salado River on the alluvial system of the Paraná River. The average width of the floodplain along the modeled reach is 3.5 km. Included within the model domain are the lowland areas on the western part of the city, areas that belonged to the natural alluvial valley of the Salado River 40-50 years ago and today are occupied by densely populated neighborhoods. The limits of the computational domain and a satellite view of the city and its surroundings are shown in Figure 1.

One of the key issues on the present simulation was the bottom topography generation. This task was accomplished by combining data from different sources. The riverbed was constructed from bathymetric data while the alluvial valley was approximated by a constant elevation plane of 12.4 m. This approximation is considered adequate at this stage of the numerical simulations (efforts are underway to improve the representation of the valley topography). In tune with the objectives of the work, major consideration was given to the definition of the topography of lowland areas on the city western side, which has been generated from digitized maps of the Instituto Geográfico Militar. The model topography is also depicted in Figure 1. All elevations are referred to mean sea level.

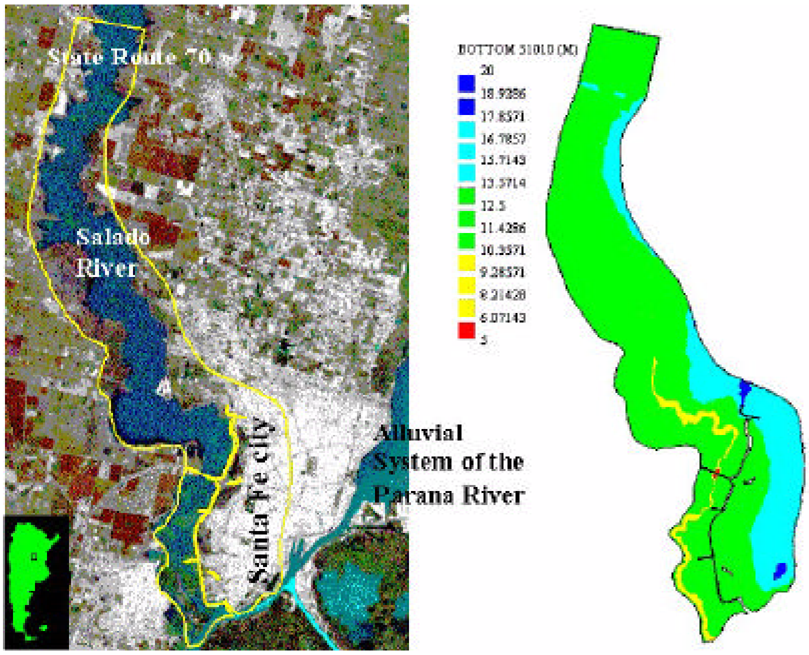

Figure 1: Located and topography of the study area

5 NUMERICAL RESULTS

The complete non-structured finite element mesh and a detail of it are shown in Figure 2. The total number of nodes and elements are 4190 and 7765, respectively. Linear triangular elements of different sizes and shapes were used, and meshes with different refinement as well. The zone around the Santa Fe-Rosario Highway bridge has been highly refined to model accurately the effects of the flow contraction and the superelevation of the water depth upstream of the structure (the bridge opening is 150 m while the width of the alluvial valley at the bridge location is about 2 km). Smaller elements were also placed at the location where water entered the city, called the gap hereafter, at the north end corner of the Irigoyen levee.

Velocity diffusivity is a critical TELEMAC parameter. This parameter fixes the constant viscosity coefficient (molecular and turbulent), and influences the shape and size of

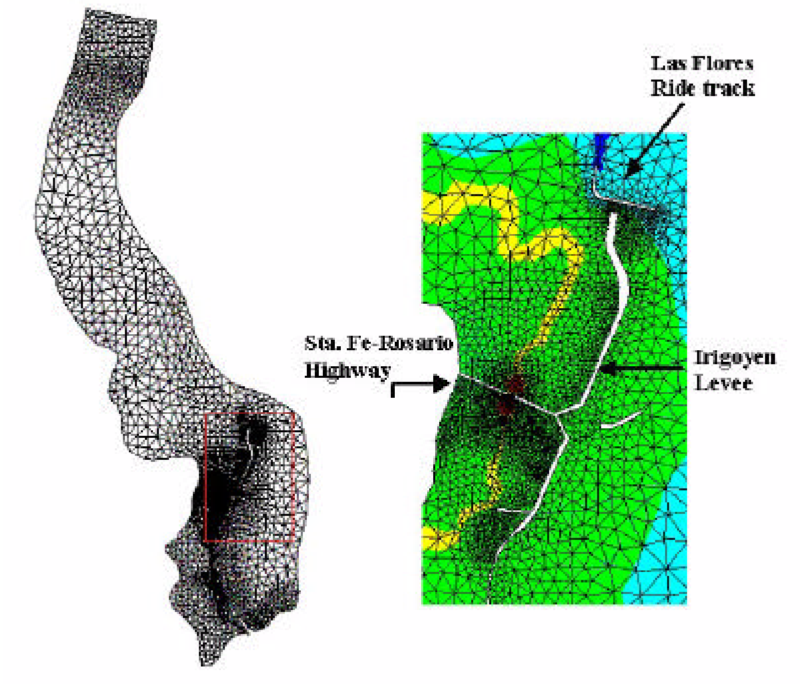

Figure 2: Finite element mesh

recirculations and the model dispersion. In the present application it was …xed at 0.1. Bed roughness was represented by Manning´s law with constant coe¢cients throughout space. No wind in‡uence was considered.

Two simulations were performed, a steady state and a transient simulation. The steady state was carried out with the aim of getting initial water depth values for the transient scenario. Boundary conditions were de…ned at the upstream and downstrem borders of the computational domain. Upstream, a piecewise constant stream‡ow condition was set until the ‡ow discharge reached the observed peak discharge value of 3600 m^3=s and the model converged to a steady state. The downstream boundary condition was de…ned as a constant water level of 14.2 m along the cross section. For the steady state simulation the gap area remained close, i.e. no water was allowed to enter the city.

Figure 3 shows the free surface at the end of the steady state simulation. Highlighted in the Figure are the protection levee on the west side of the city, other small altitude railway levees within the city, the State Road No.70 at the center of the model domain and the Santa Fe- Rosario Highway a few kilometers downstream. Notice the considerable water surface elevation di¤erence between upstream and downstream of the Santa Fe-Rosario Highway Bridge caused by the severe ‡ow contraction. The simulated di¤erence was 1.7 m while the observed di¤erence was estimated to be between 0.8 and 1.2 m. This discrepancy is in part attributed to the unaccurated representation of the alluvial valley topography adopted for the simulation. The numerical model is somehow "slower" than the prototype due to the mis-representation of bed topography. This, in turn, induces higher potential energy storage in detriment of kinetic energy, so that explains the discrepancy in the water elevation between upstream and downstream of the Santa Fe-Rosario Highway bridge.

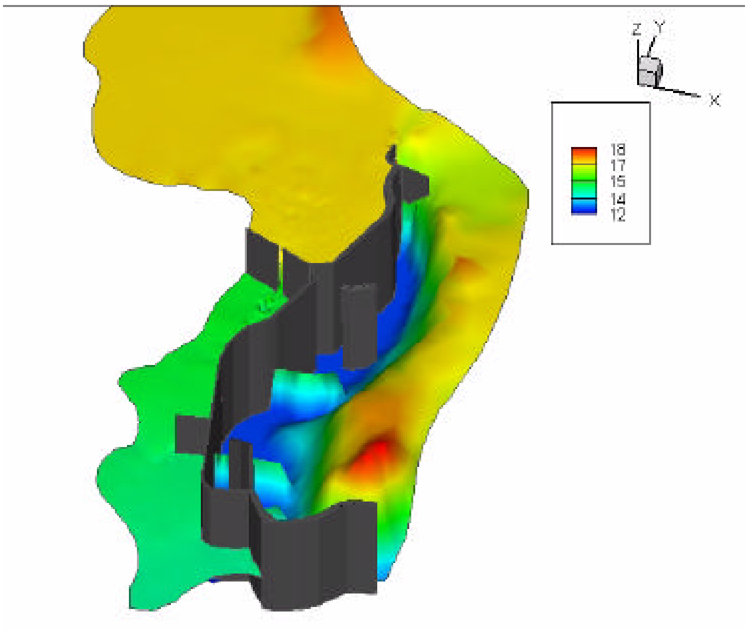

Figure 3: Free surface at the end of the steady state simulation

Boundary conditions for the transient scenario were set as those for the steady state simulation, constant discharge upstream and constant water surface elevation downstream. Free surface values from the steady state run were used as initial condition. All model parameters remained unchanged, except that the water wave was allowed to enter through the 150 m gap of the Irigoyen levee at its un…nished north end. The simulation time until the water reached its maximum level within the city, with a computational time step of 5 seconds, was 26 hours. The actual ‡ooding of the city took approximately the same elapsed time. The stricking aereal photograph of Figure 4 shows the extension of the area a¤ected by the ‡ood.

Figure 5 shows a sequence of the irruption of the water wave through the gap at 5, 25, 100, 200, 300, 400, 500 and 1000 seconds from the beginning of the simulation. The colour palette represents the magnitude of the velocity. In the contraction caused by the gap, the maximum simulated velocity reached 4.5 m/s.

It is interesting to analyze the temporal evolution of the water depth at the four points of the computational domain previously indicated in the Figure 4. Points #1 and #2 are located upstream of the Santa Fe-Rosario Highway, the …rst on the alluvial valley, the second inside the city behind the Irigoyen Levee. Points #3 and #4 are located

Figure 4: Aereal photograph of the western part of the Santa Fe city

downstream of the highway, on the alluvial valley and within the city, respectively. The almost horizontal lines in Figure 6 indicate simulated water depth in the alluvial valley upstream and downstream the Santa Fe-Rosario Highway. They are 1.7 m apart indicating the superelevation of the free surface caused by the tremendous contraction caused by the bridge. After about 26 hrs. of simulation, water depth at points #2 and #4 levels o¤ with the water level upstream the higway bridge, i.e. the water level within the city was much higher than in the river itself. Once water entered the city, it …lled up low elevation neighborhoods and remained trapped behind the levees that surround the city on the west and south borders. The situation was gradually alleviated when the Army blew up portions of the levee to allow entrapped water to ‡ow back to the river channel. This latter process was not simulated at this time.

6 CONCLUSIONS

This work shows the capacity of two-dimensional tools to deal with a study case that resembles in some sense a dam break problem. These tools are esential in cases where the ‡ood spreads over initially dry areas. The discrepancies on the free surface elevations at the Santa Fe-Rosario Highway bridge are somehow large. However, the results are good in reproducing the water wave evolution within the city. The maximum water elevation timing was also adequately represented. Work is underway to correct the representation of the bottom topography in order to improve model results.

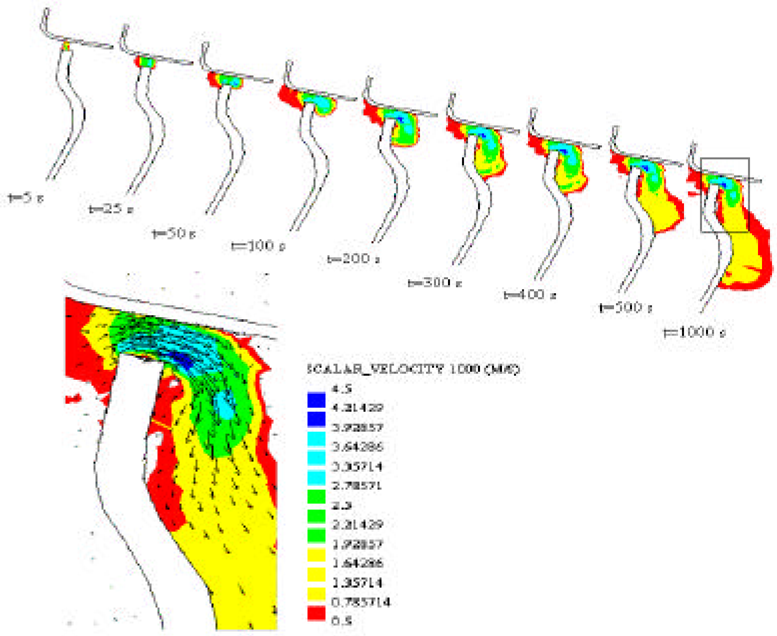

Figure 5: Water wave into the city

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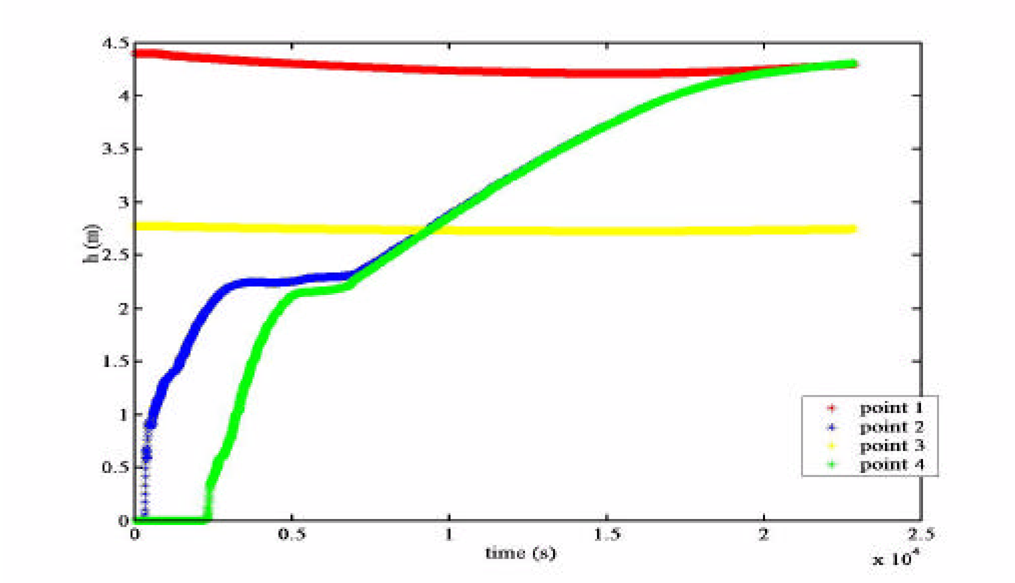

Figure 6: Water levels