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Inundation Maps for Extreme Flood Events at the Mouth of the Danube River

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Abstract

Hydrodynamic modeling is used to analyse the inundation behavior of St. George village during extreme flood events, in particular for a flood happened in spring 2006. The study reach, 4 km in length, is situated in the Danube Delta, at the mouth of St. George distributary and includes St. George village. Land and bathymetric surveys were used to create a digital terrain model (DTM) of the river channel and the village. By coupling the geometry with hydrologic data, a 2D hydrodynamic model was built up with the help of the CCHE2D code (University of Mississippi). The model is based on integrating Saint-Venant shallow waters (depth averaged) equations through finite-difference implicit numerical scheme. It was calibrated in terms of roughness coefficients on measured values of water surface elevation registered in the St. George port. Flood maps obtained from computations were compared to satellite images from the same days of the spring 2006 extreme event. Inundation behaviour of the St. George village was analysed for different scenarios of river hydrological and sea level (variable because of wind waves) conditions. Findings were compared with high water marks and inhabitants testimonials. The model proved that sea level has a higher influence upon the inundability of the area than the river flood events.

Keywords: Hydraulic Modeling, Finite Difference Method, Flood, Inundation Maps

1. Introduction

Considerable advance has been made the last decades in modeling the hydrodynamic behavior of rivers during the flood periods for predicting flow variable variation in time and space and obtaining flood maps. According to the variation in space of flow variables, models range in increasing order of complexity: from cross-section averaged-1D (used for long, straight reaches), to shallow water-2D [1], which are capable of reproducing more realistically spatially-distributed phenomena, such as the cross-stream component of flow, to 3D, capable of predicting secondary flows in meander bends and treat momentum fluxes varying in the vertical direction.

1D step-backwater models have intensively been used so far due to their advantages such as: computational simplicity and ease of parameterization, calibration facility (in terms of method and necessary data), accuracy when coupled with detailed topographic data [2], requirement of small computation times. However, when dealing with cross-section variation of hydraulic parameters (such as deltas or flood inundation prediction, estuaries, confluences/diffluences, braiding, recirculation zones, riffle-pool sequences, meanders, etc.) 2D models offer a better representation of the flow field and sediment fate. At the same time these models tend to require more computational time, be more data intensive, require distributed topographic and friction data and work with a much more complex grid (triangular or rectangular mesh with variable density most of the time). The 2D models also need distributed calibration and validation data acquired by using modern measurement techniques as well as remote sensing images. In terms of coupled 2D models, MOBED2, TELEMAC 2D (with its SISYPHE sediment module), CCHE2D, RMA2, River2D [3] etc. are some of the very widely used codes.

The aim of this study is to analyze the flooding behavior of a study area situated at the mouth of the south-

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ern distributary of Danube Delta, St. George, for flood events having return periods between 20 and 1000 years. For this purpose, a 2D hydraulic model was set up with the help of CCHE-2D finite difference code (University of Mississippi, USA). In this context, the objectives of present study are: 1) to extend the sparsely available measured values of hydrodynamic parameters over the entire study reach for discharge values in the (800-1600) m^3/s range; 2) to draw the flood maps and compare them with corresponding satellite images [4]; 3) to analyze the flooding behavior of St. George village and assess the risk factors under various scenarios such as: river flood events, sea level raise or sea storms (which lead to high waves and raised sea level at the downstream boundary of the study reach). The findings are helpful for local authorities in order to inform the population and take the appropriate defense measures in the future.

2. Site and Data

The Danube Delta is located in the north-western part of the Black Sea, between 44˚25’N and 45˚30’N and between 28˚45’E and 29˚46’E. The Romanian delta plain covers an area of about 5,800 km^2 (including water) (**Figure 1**). It has three distributaries (main branches), named from N to S: Kilia, Sulina and St. George. Delta apex is known as Ceatal Izmail.

About 20% of the Danube delta represents areas with negative relief (*i.e.* with an average level below the Black Sea-Sulina gauging system), about 54.5% of the Danube delta plain consists of areas having altitudes between 0 and 1 m above the sea-level and 18% with altitudes between 1 and 2 m. The reed plot swamp vegetation is predominant and it covers about 78% of the total area, while the salting vegetation covers about 6% of the total area. These two factors: flat terrain and compact vegetation (generally up to few meters in height) makes it almost impossible for the topographic surveys to be performed, and erroneous for the remote sensing topographic data acquisition (such as LIDAR, [5]).

Average multiannual (1960-2006) river flow near the Danube apex (Isaccea gauging station) is 6638 m^3/s with a maximum value of 16500 m^3/s (registered in April 2006) and a minimum value of 1970 m^3/s (registered in September 2003). The monthly multiannual average sea level has the same trend as the corresponding Danube flow, with amplitudes of 14 cm between high levels in spring and low levels in autumn [6].

Predominant winds are from the N and NE, and the most frequent induced wind waves recorded are from NE corresponding to the prevailing wind direction [7]. The mean maximum heights of wind induced sea waves in front of the Danube Delta reached even 7.0 m. The storm surges from N, NE, E and SE directions calls water level rises of 1.2-1.5 m. Therefore, water level at the mouth of the three distributaries has important variations, its average annual amplitude being of about 0.70–0.80 m. The Black Sea tide has small amplitudes of only 7 ÷ 11 cm [6].

Figure 1. Map of the Romanian Danube Delta with the three main distributaries (from N to S): Kilia (Romania-Ukraine border), Sulina and St. George.

In such conditions, flooding events in the Danube Delta occur when the water flow at the apex exceeds 10,000 m^3/s [8] and/or when waves from the sea are high. Most recent historic event (having a return period of approximately 200 years) took place in spring 2006. This paper focuses on St. George distributary, which is the most meandered (local meandering coefficient = 2.35) and conveys approximately 20-25% of the total Danube discharge. Top width varies between 150m and 600m, whereas the depth varies between 3 and 27 m beneath water level corresponding to the low flow regime. At its mouth, a secondary delta with conic entangled branches has been formed.

A study site was chosen at the mouth of this distributary. Its length is 4.3 km, minimum top width of 200 m in front of the St. George port and maximum top width of 600 m at km 1.5 from the mouth (**Figure 2**). Maximum depth along the study reach is of about 15 m (corresponding to an approximate average multiannual flow) near the port.

At km 8 from distributary mouth there is a gauging station (where flow is measured), and at km 4.3, in the St. George port, there is a level gauge (where water surface elevations are systematically recorded and flow data is obtained only through correlation). The flow hydrographs

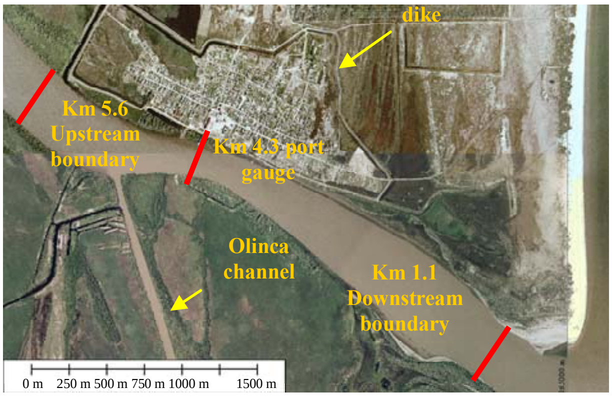


Figure 2. Study site. Arial photograph of Danube St. George distributary mouth and village surrounded by the flood protection dike.

recorded during the spring flood are shown in **Figure 3**; at the Delta apex (a) and for the study site (b). The study period is delimited (April 25th - May 3rd 2006). A rating curve has been derived at km 1.1 since sea level at the mouth is dependent of river inflow.

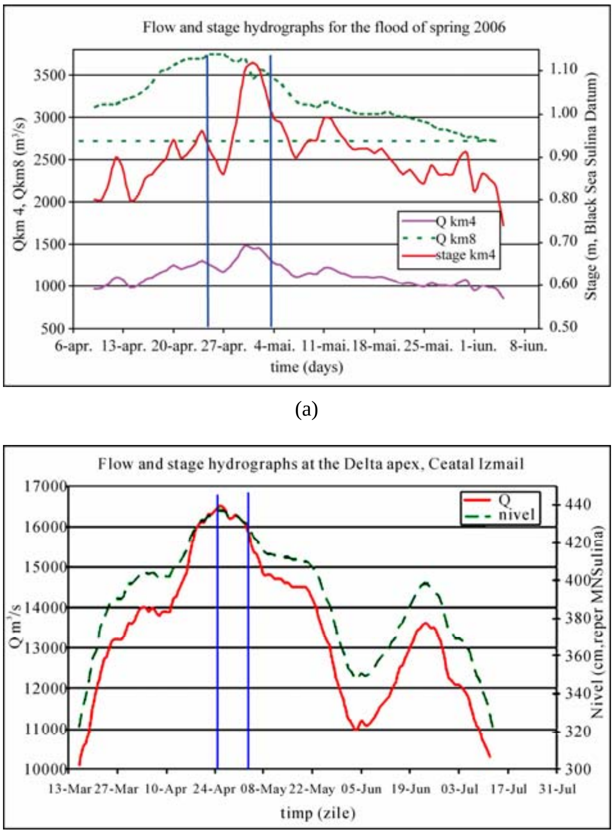
Bathymetric surveys were performed (using a Garmin 188 echo sounder) on a yearly basis (in July 2005, 2006 and 2007) along closely-spaced cross-sections (about 50 m). For the terrain part of the study area, recent topographic survey data (acquired with a Leica TPS 407 total station) were coupled with existent data (from detailed topo-hydrographical maps 1:25000) in order to obtain the digital elevation model (with a 20 × 20 m grid cell). The domain area was chosen to cover all inundated area in case of a 1000 year-flood event (**Figure 4**).

3. Method

In order to analyze the flooding behavior of the area the CCHE-2D software (Center for Computational Hydroscience and Engineering, University of Mississippi, USA), was used. The program integrates the shallow water equations by using the finite difference method.

Several meshes were created and tested for computational stability and accuracy. They were obtained by triangular interpolation of a plane, rectangular mesh over the topo-bathymetrical data. **Figure 5(a)** shows one of the meshes (with 25,000 = 250 × 100 nodes) used to represent the geometry of the domain in the hydrodynamic computations.

Different values of the Manning non-homogeneous roughness coefficient were tested in the model calibration process: 0.015 ÷ 0.02 s/m$^{1/3}$ for the St. George distributary channel, 0.2 ÷ 0.025 s/m$^{1/3}$ for the floodplain vegetated areas and 0.025 ÷ 0.03 s/m$^{1/3}$ for the village areas with houses (**Figure 5(b)**) [9].



(a)

(b)

Figure 3. Hydrographs of the 2006 spring flood; (a) Flow and stage at the St. George study site; (b) flow and stage at Ceatal Izmail (delta apex); the period between April 25th and May 3rd 2006 (with a maximum flow of 16500 m^3/s at delta apex) represents the studied flood event.

Steady flow regime computations were firstly run for 10 increasing inflow values covering the entire considered range. The model was calibrated in terms of roughness coefficient on registered water stages at the port gauge. Absolute maximum differences were less than few cm.

Unsteady flow computations were performed afterwards, for the spring 2006 flood event. As upstream and downstream boundary conditions (**Figure 5(b)**) were used the flow hydrograph and the derived rating curve at the mouth of St. George distributary, respectively.

Computed water surface elevation in the domain obtained from the steady flow computations were used as initial condition for the unsteady flow computations. Velocity, shear stress, water surface elevation, unit flow, Froude no. and eddy viscosity fields were inspected in the flow domain. Care was taken in the runs for the outflow to be equal to the inflow in the computation domain (no flow accumulations).

Computations were performed for different time steps, $\Delta t \in (1 \text{ s} \div 40 \text{ s})$ and a total no. of steps of 2,000, complying with the 2D Courant criterion (even though the

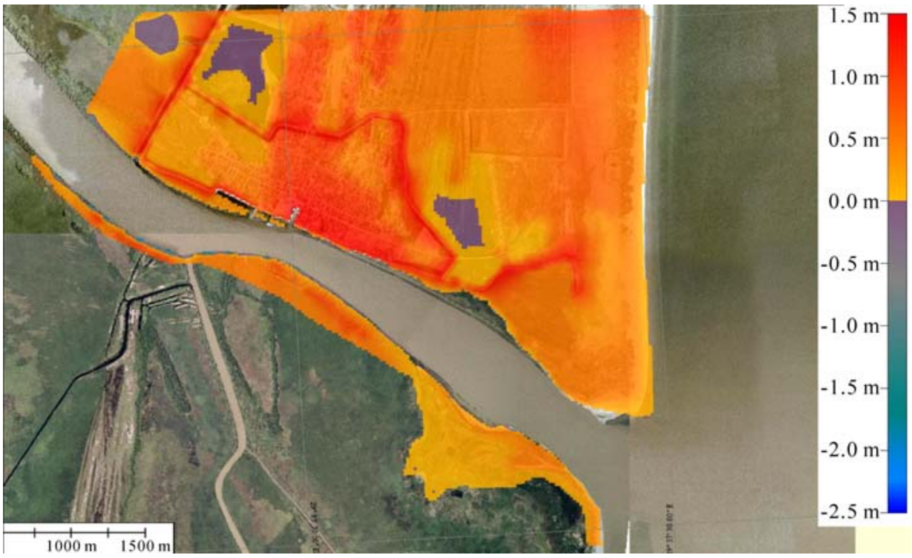
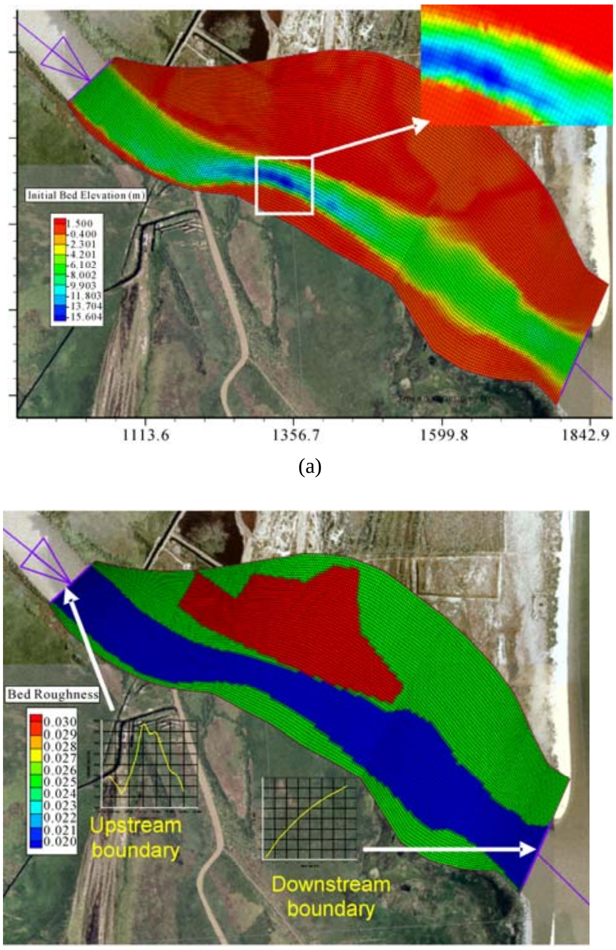


Figure 4. DTM of the study area (with a 20 × 20 m grid cell) displayed over the ortophotoplan.

numerical scheme is implicit). A trade-off value of 20 s per time step was chosen for the flow to pass a computation cell (of about 16 m ÷ 17 m), very close to the water flow physical time computed with the average distance and velocity. About 10,000-15,000 s were necessary to pass the warming-up period and for the instabilities to settle. The hydrodynamic parameters were computed with the *k*-*ε* turbulence model under two scenarios: with calm sea and with sea waves (of 30 cm and 70 cm in height).



(a)

(b)

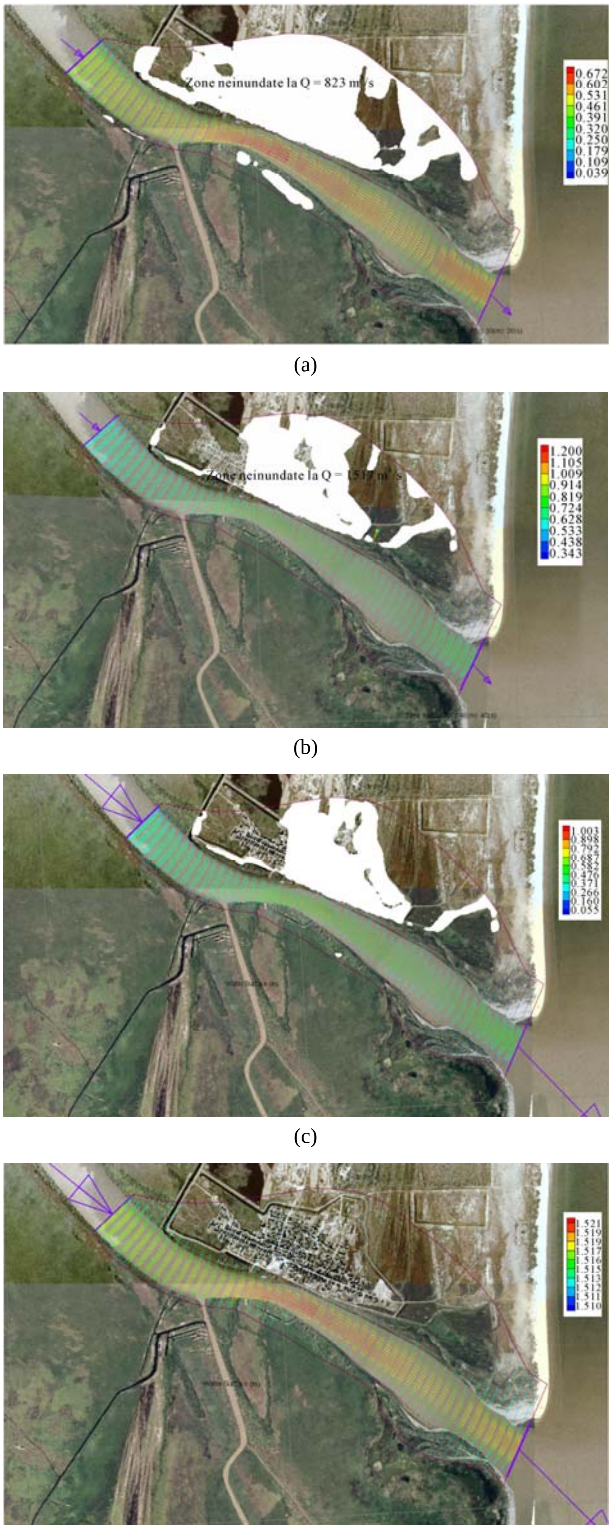
Figure 5. Examples of: (a) meshes; (b) roughness coefficient values and upstream and downstream boundary conditions-used in the unsteady computations.

4. Results and Discussion

Figure 6(a) and **Figure 6(b)** show two inundation maps obtained from computations performed under steady flow conditions for inflow discharge values of 823 m^3/s (the 20-year flood) and 1517 m^3/s (the 1000-year flood). In the first scenario, the absolute average downstream sea levels were of 61 cm (a) and 96 cm (b) respectively (according to the derived rating curve).

In another scenario, for which wind coming from the sea produces high waves, sea level increases with 30 cm in the case of the first discharge value (**Figure 6(c)**), and with 70 cm in the case of the higher discharge value (**Figure 6(d)**), worst case scenario, with river flood and maximum sea waves occurring simultaneously).

White areas in **Figure 6** represent dry, uninundated areas. One can see they are obviously smaller in case *b*) than in case *a*), whereas vectors and the legend colors indicate velocity distribution and its magnitude. By superposition of the inundation maps over the village maps one may see inundated houses. This result of the model is very useful for local authorities in case of such a flat



(a)

(b)

(c)

(d)

Figure 6. Inundation maps (white color means dry areas) obtained from computations performed under steady flow conditions. (a) Q = 823 m^3/s; (b) Q = 1517 m^3/s; c) Q = 823 m^3/s and increased sea level with 0.3 m; d) Q = 1517 m^3/s and increased sea level with 0.7 m high.

terrain, in order to draw flood risk maps and inform the population.

Maps of water depth may also be obtained from the model for the entire domain, in order to see the damage extent. Case d) actually has never been recorded; most of the river floods occur during spring (after defrost) or during summer, whilst most important icy north wind blows during winter.

Inundation maps have been recorded every 12 hours during the 9 days period of the 2006 spring flood event for which numerical simulations were performed, in order to get water boundaries. **Figure 7** and **Figure 8** show a comparison between satellite images (a) and computed inundation maps (b) from the same days. Satellite images are available from Romanian Space Agency, ROSA (http://web.rosa.ro/Inundatii_Aprilie_2006/inundatii_apr_2006.htm) for April 25, 26, 27, 30 and for May 02 and 03, 2006 (for the sake of simplicity, only two days are shown in this study). The flow hydrograph at km 4 from the river mouth is also shown, with highlighted instantaneous discharge values. Computations with a 20 s time step, for these 9 days, took about 8 hours on a standard PC with 2 GHz and 2 GB of RAM.

One can see in **Figure 7** and **Figures 8(a)** and **(b)** the same inundated areas from the E, N-E and N-W parts of the St. George village on the 30th of April, 2006, when the hydrograph reached its peak.

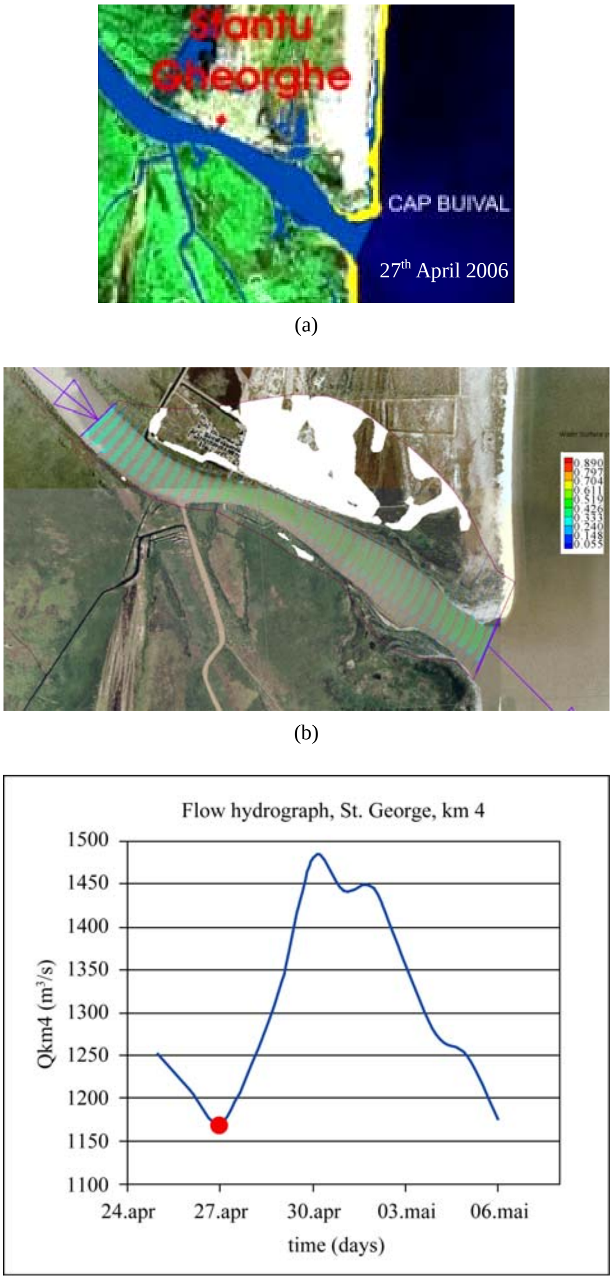
Measured high water marks found on site matched within few cm corresponding stages from computations.

5. Conclusions

2D hydraulic modeling is used to analyze the flooding behavior of St. George distributary mouth (estuary) and village from Danube Delta. St. George village has a history of frequent floods which endangered local fisherman community and the village touristic and cultural attractions. The 1.8 m in height dyke proved to be too low for the water level attained during several past important flood events and needs to be enlarged.

The site is very flat (maximum difference in terrain elevation is about 2 m) and covered with compact, tall vegetation which makes a challenge for topographic surveys to be performed. This is the first attempt to set up a 2D model for the area. Modeling such flat terrain is difficult, as results are very susceptible to small errors in measured land elevation or computed water level.

Present model was built with the help of CCHE-2D code (University of Mississippi) and calibrated in term of roughness parameter on water level recordings in the St. George port. Steady runs were performed for different upstream hydrological scenarios and downstream water levels (due to varying Black Sea wind conditions).



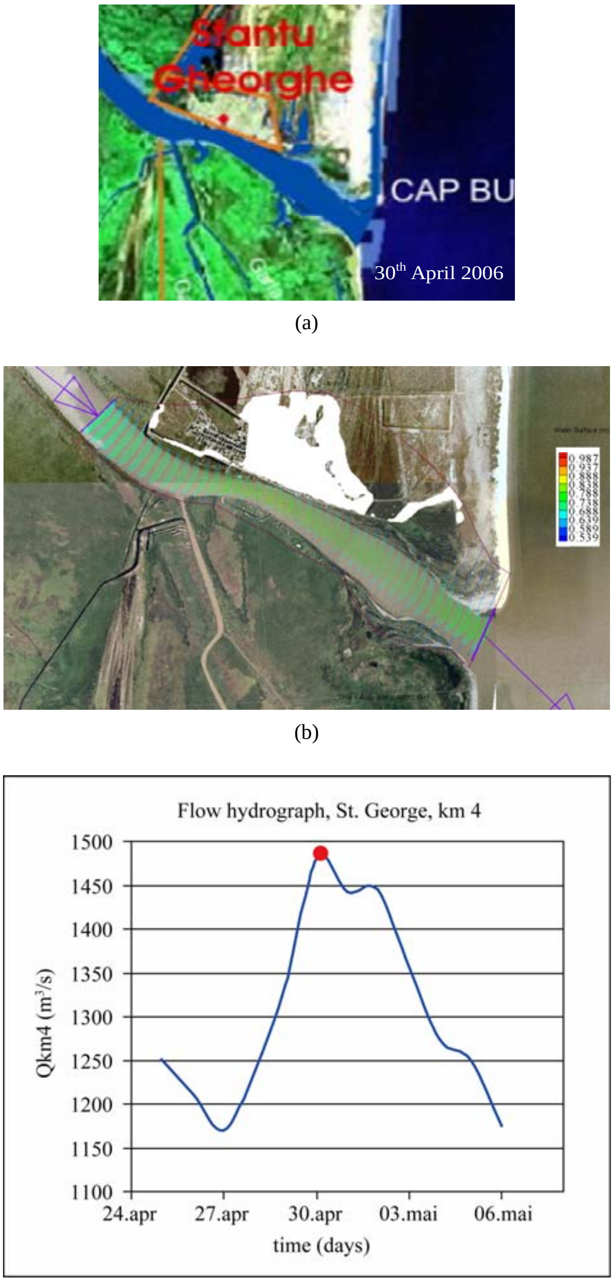
(a)

(b)

(c)

Figure 7. Situation on the 27th of April 2006 (a) satellite image of the study site (flooded areas in blue); (b) inundation map obtained the from the computations; (c) Inflow hydrograph with current day value (current flow value, Q = 1170 m^3/s on hydrograph).

The hydraulic model was set up and run under unsteady flow conditions too, for an extreme flood event happened in spring 2006. Satellite images from that period, showing inundation extent, were used as a qualitative comparison with the computed flood maps. Quantitatively, high water marks matched within few cm corresponding stages from computations.



(a)

(b)

(c)

Figure 8. Situation on the 30th of April 2006 (a) satellite image of the study site (flooded areas in blue); (b) inundation map obtained the from the computations; (c) Inflow hydrograph with current day value (current flow value, Q = 1481 m^3/s on hydrograph).

Computed hydrodynamic parameter values (water level, velocity in the grid cells) are very useful to draw flood risk maps and inform the population.

Computed water stage values and flood maps led to the conclusion that sea level has a higher influence upon the inundability of the study area than the intensity of the river flood events. Therefore sea storms (waves) and black sea level constant raise (due to climate variability and North Atlantic Oscillation–NOA, [10]) have a stronger influence on the flooding behavior of the St. George village. Worst case scenario of simultaneous 1000-year river flood event and maximum sea waves proved to be devastating for the village. For the first time, local authorities may use such a model as a prognosis tool in developing contingency and flood emergency plans and take the appropriate defense measures (such as enlarging the village enclosure dyke).

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