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Flood Control Structures in the River Göta Älv to Protect Gothenburg City (Sweden) during the 21st Century - Preliminary Evaluation

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Abstract**—**Climate change would cause mean sea level to rise +1 m by 2100. To prevent coastal floods resulting from the sea level rising, different flood control structures have been built, with acceptable protection levels. Gothenburg with the River Göta älv located on the southwest coast of Sweden is a vulnerable city to the accelerated rises in mean sea level. We evaluated using a sea barrage in the River Göta älv to protect Gothenburg during this century. The highest sea level was estimated to 2.95 m above the current mean sea level by 2100. To verify flood protection against such high sea levels, both barriers have to be closed. To prevent high water level in the River Göta älv reservoir, the barriers would be open when the sea level is low. The suggested flood control structures would successfully protect the city from flooding events during this century.

Keywords**—**Climate change, Flood control structures, Gothenburg, Sea level rising, Water level model.

I. INTRODUCTION

IT is now recognized that increases in atmospheric concentration levels of greenhouse gases during the last century caused the global climate system to change (e.g. [1], [2]). Sea level rise, as one of main climate change features [3], increases risk of coastal floods influencing the human society and natural environments [4]. In 1953, about 2000 persons in England and the Netherland lost their lives due to the North Sea surge [5]. To prevent these kind of disasters, different flood control structures have been built (e.g., Thames barrier in London, UK, and Maeslant barrier in Rotterdam, Netherlands) to protect coastal population and ecosystem from flooding, and showed an adequate level of protection at least so far [6]. Most important issue to design and develop of flood barriers for the coastal zone is sea level rise [7] that will be accelerated during the 21st century [8].

The city of Gothenburg is located on south-west coast of Sweden, and a river "Göta älv", is running through the city towards the North Sea. The level of North Sea is the main factor affecting the water level in the Göta älv River within the Gothenburg city region. Hence, the sea level rising will increase risk of flooding in this region. By 2100, rise of 0.18 to 0.59 m is projected for the global mean sea level [8], while the sea level rising will be about 0.6-1.0 m in the sea bordering the south part of Sweden [9]. In addition, as a consequent of extreme weather conditions, a high tide in southern Sweden will be about +2 m above the current mean sea level [9] by 2100. Due to this high tide, most parts of metropolitan area in the city will experience flooding events; even the City Planning Office of Gothenburg (Stadsbyygnadskontoret i Göteborg) suggests +2.5 m above the current mean sea level as the safe level to set the shelter of especially important facilities for the end of 21st century [10]. Thus, the main managerial question in this area is: if flood control structures, such as Thames barrier in London, were built in the Göta älv River, how well would they work? And do they protect Gothenburg city from flooding events during the 21st century?

This paper examines hydrological possibility of flood barriers in the Göta älv River towards protecting the Gothenburg city from flooding events, mainly sea induced ones, during the 21st century. Three specific objectives are established to achieve the goal: (1) To determine the best places of flood barriers along the river (2) Outflow estimation from the gates of flood barriers; (3) Simulation and analysis of water level in the Göta älv River based on extreme weather conditions in today and 2100 under Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 and B2 storylines [11]. By providing the results of these objectives, the paper initially proves possibility of using flood barriers and their roles in protecting the Gothenburg city from floods during the next century.

II. THEORETICAL DESCRIPTION

Gothenburg is the second largest city in Sweden with about 940000 inhabitants in the metropolitan area (Fig. 1 (a)). The Göta älv River and its three main tributaries, called "Säveån", "Mölndalsån" and "Lärjeån", are running within the city. The study area for this paper is the Göta Älv River catchment between Kung älv in northern Gothenburg and the outlet of river to the North Sea (Fig. 1 (b)).

This area is about 255.7 km^2 that includes whole length of the Lärjeån tributary (about 16 km), 10 km length of Säveån tributary from Mellbydalen to the Göta älv River, and 3.5 km length of Mölndalsån tributary from Stensjön to the Göta älv River (Fig. 1 (b)). Main information about the Göta älv River and the three tributaries can be found in reports by the City Planning Office of Gothenburg [12].

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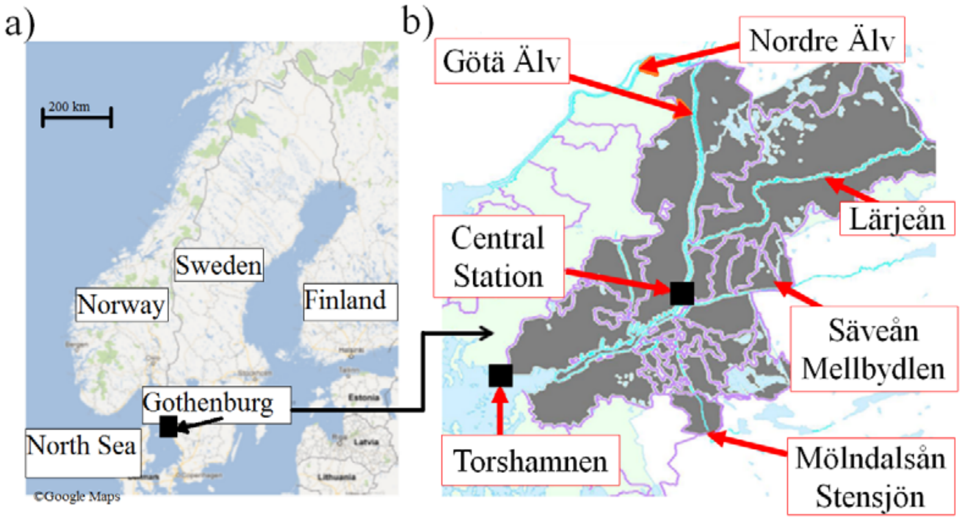

Fig. 1 (a) Gothenburg City location in Sweden and (b) Göta älv River catchment within Gothenburg city limits by grey color

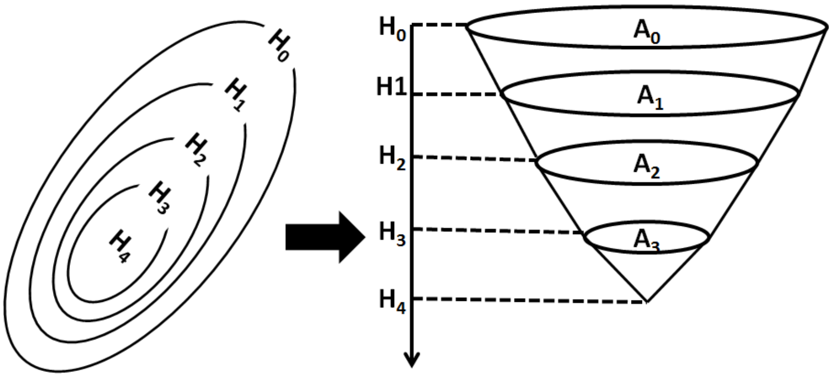

Fig. 2 Surface areas at counter levels and depth among them in order to use in trapezoidal rule

Hourly rainfall (mm) and temperature (°C) data for the period January 2005-May 2009 were obtained from Gothenburg centre station (Fig. 1 (b)). Measured daily discharge (m^3/s) at the Stensjön from January 2005 to December 2008 was used as contribution of Mölndalsån tributary discharge into the study area of this paper. Measured every 12 hours inflow data of Säveån tributary (m^3/s) to the study area was available for the period January 2006-April 2009 at the Mellbydalen (Fig. 1 (b)). Hourly sea level (cm) data from January 2005 to May 2009 measured at Torshamnen were used in this paper (Fig. 1 (b)). Based on available data, the highest sea level of +132 cm above the current mean sea level was observed in the year 2008. In addition, overlapping among all data was found for the data of year 2008. Hence, the data of year 2008 were considered as reference data to develop simulations by MATLAB Programming.

Two flood barriers are suggested by this study, one at the Göta Älv River upstream in the Gothenburg (hereafter, upstream barrier), and the other at the downstream close to the entrance point of the Göta Älv River to the North Sea (hereafter, Göta Älv barrier). The Göta Älv barrier protects the city from high sea levels by closing the barrier's gates. The upstream barrier drives the normal flow of Göta Älv River to the Nordreälv River (Fig. 1 (b)) for preventing the water level rising in the Göta Älv River when the gates of the Göta Älv barrier are closed.

Three main criteria of topology, geology, and river section characteristics were used to choose the best locations of barriers. The topology indicates the highest elevation in both sides of the river bank to prevent higher sea level rise into the city, and also increase the river reservoir volume between the upstream and the Göta Älv barriers (hereafter, Göta Älv reservoir). In general, the flood barriers are located on the river section where the both sides of river bank are made of rock to protect the barriers from settlement and erosion that often occur where the clay exist. The width and depth of river are the main river section characteristics in order to find the best location of barriers. The width of river affects the outflow from the gates of barriers, while the depth of river determines the reservoir capacity and provides shipping along the river.

The volume of Göta Älv reservoir was calculated by trapezoidal rule [13]. The rule is based on surface areas at two contour levels and the depth between them (Fig. 2). The equation of trapezoidal is as:

$$V_{i,i+1} = \left[\frac{A_i + A_{i+1}}{2}\right](H_{i+1} -)A_i \quad (1)$$

where, $V_{i,i+1}$ is the volume between H_i and H_{i+1} contour levels; also, A_i and $A_{i+1}$are the surface areas at Hi and H_{i+1} contour levels, respectively.

Outflow from gates of barrier controls water level at the barrier. The gates are closed when sea level is high. During closed gates, the water from rainfall-runoff as inflow to the reservoir makes the water level to rise ate the Göta älv barrier. When the water level at the barrier is higher enough than the sea level, the water level at the barrier is released to the sea by opening the gates. This releasing controls the water level at the barrier to be less than the safe level for protecting the city from river floods. Hence, outflow from gates, Q_g, depends upon the head (H_1*) between water level at the barrier, Y_1, and sea level, Y4, (Fig. 3 (a)) is very important for the barrier operation, and is expressed as [14]:

$$Q_g = K_A Y_4 b (2gH_1^* + V_1^2)^{1/2} \quad (2)$$

where, Q_g is in m^3/s, K_A is a value between 0.90 and 1.05, and it was considered 1.0 in this study, b is total opening width of river (Fig. 3 (b)), g = 9.81 m^2/s, and V_1 is velocity of water inside the barrier in m/s that comes from Q/A_s where Q is total runoff to the reservoir and As is the area of river section where the barrier wants to be located.

The water level model used in this study was as:

$$Q = \frac{dV}{dt} = \left((R.f_1) - \left(\frac{221.5+29\,(T+f_2}{365*24*1000}\right)\right)A + Q_m \; - Q_g \quad (3)$$

where, dV/dt is change in reservoir volume during time, R is rainfall in m/hr because precipitation was assumed as rainfall form, f_1 is future precipitation factor, T is hourly air temperature in °C, A is catchment area in m^2 that was equal to 255700000 m^2, whole catchment was assumed impermeable to calculate maximum runoff volume from rainfall towards the river, f_2 is future temperature factor, Q_m is inflow from Mölnadlsån tributary to the catchment in m^3/hr, Q_s is inflow of Säveån tributary to the catchment in m^3/hr, and Q_g is outflow from gates of barrier m^3/hr.

The performance of flood barriers was examined for three different operational scenarios. Scenario 1, today extreme weather conditions when future precipitation factor (f_1) is equal to 1 and future temperature factor (f_2) is equal to 0 in the water level balance model (5). Scenario 2, extreme weather conditions in 2100 under IPCC SRES A2 storyline, when f_1 = 0.15, f_2 = +3.5 and sea level variation factor, f_3 = 1.48 [4]. Scenario 3, extreme weather conditions in 2100 under IPCC SRES B2 storyline, when f_1 = 0.10, f_2 = +3, and f_3 = 1.48 [4].

III. RESULTS AND SIGNIFICANCES

Best place for the upstream barrier was considered at the separation point of main Göta älv River into Nordre älv and Göta älv River within the Gothenburg city limits, even the rocky parts are poor. The point is at the northern part of Jordfallen (Fig. 4 (a)). In the Jordfallen, elevation on the both sides of river bank is +2 m above the current mean sea level. Best place for the Göta älv barrier was assumed on the river section between Ryanabbe and Storabillingen areas (Fig. 4 (a)). The elevation of these areas is +6 m above the current mean sea level, and both sides are rocky. The width of river between areas is about 480 m and the maximum depth is 13 m that provide shipping across the barrier.

Whereas the upstream barrier is only for shifting the normal flow of Göta älv to the Nordre älv, the Göta älv barrier plays the most important role in protecting the city from flooding. Six piers with width of 20 m are suggested for the Göta älve barrier (Fig. 5). Thus, total opening width (b) of 360 m was used to calculate outflow from the gates of Göta älv barrier for all three operational scenarios (Table I).

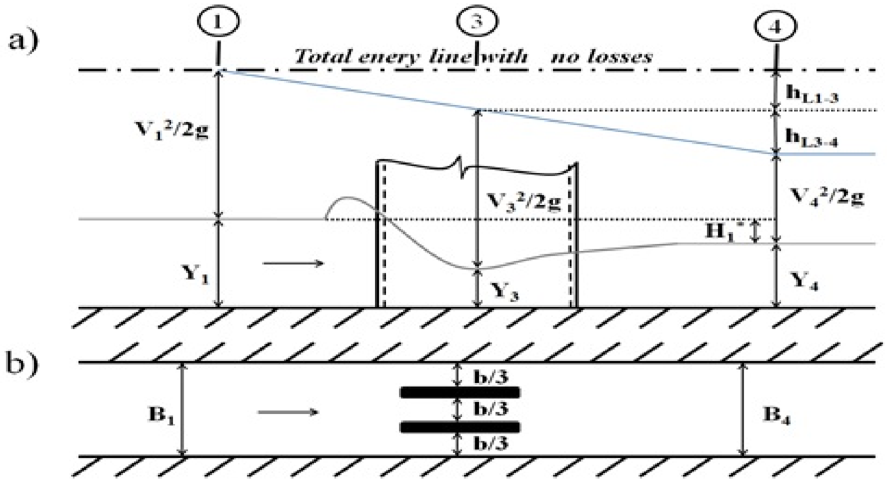

Fig. 3 (a) Longitudinal sections and (b) plan view of barrier

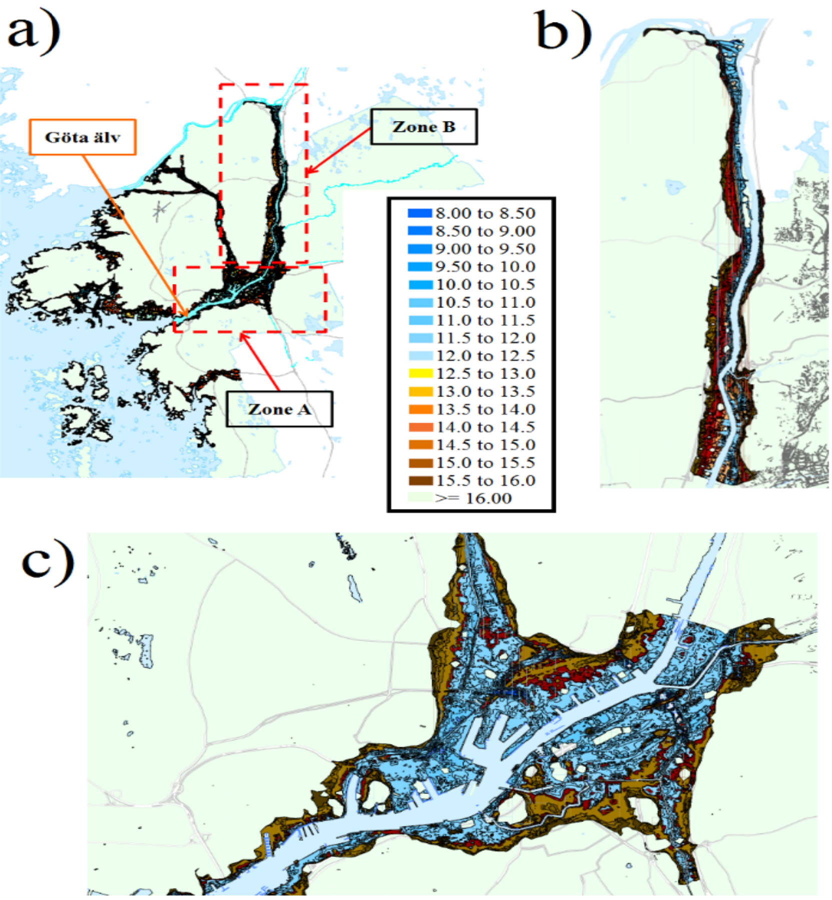

Fig. 4 (a) Bathymetric map of Göta älv reservoir developed by MapInfo, from +8.0 m (blue) to +16.0 m (brown), (b) Zone B and (c) zone A

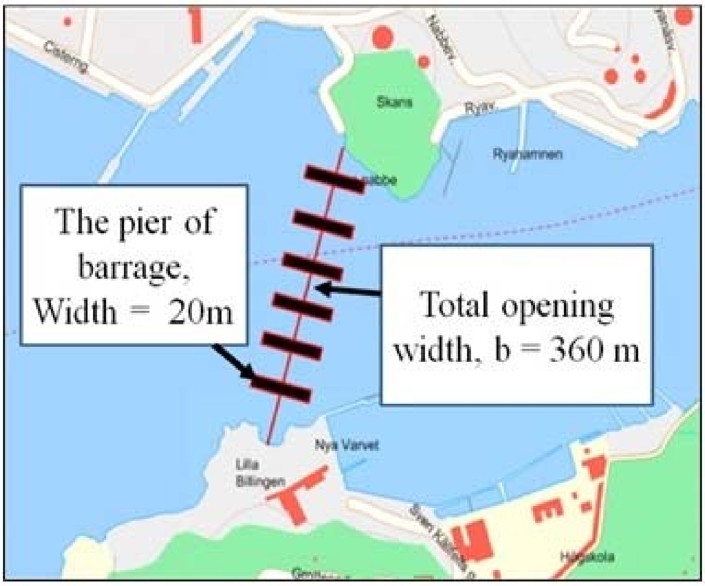

Fig. 5 Suggested piers and total opening width for the Göta älv Rive

TABLE I
TOTAL VOLUME OF GÖTA ÄLV RESERVOIR DEPENDS UPON DIFFERENT CONTOUR LEVELS (H), AND OUTFLOW FROM THE GÖTA ÄLV BARRIER BASED ON DIFFERENT HEAD BETWEEN WATER LEVEL AT THE BARRIER AND SEA LEVEL (H_1^*) FOR DIFFERENT OPERATIONAL SCENARIOS

Göta älv reservoir		Scenario 1				Scenario 2 and 3			
H (m)	Total Volume (106 m^3)	Y4 (m)	H1* (m)	V1 (m^2/s)	Outflow (m^3/s)	Y4 (m)	H1* (m)	V1 (m^2/s)	Outflow (m^3/s)
+1	5,40	0.4	0.1	0,800	230	0.5	0.1	0,044	250
+2	13,66	0.5	0.2	0,147	355	0.6	0.2	0,033	430
+3	28,27	0.6	0.3	0,127	520	0.7	0.3	0,023	615
+4	47,47	0.7	0.4	0,107	700	0.8	0.4	0,200	810

Results from water level model and sea level projections for all three different operational scenarios are represented in Fig. 6. For operational scenario 1 (Fig. 6 (a)), extreme sea levels (higher than the safe level) occurred twelve times in 2008 (Table II). By closing the gates of Göta älv barrier, the city was protected against these extreme sea levels adequately, and at the same time, closing the gates of upstream barrier controlled the water level in the Göta älv reservoir under the safe level (Table II). The maximum sea level was +1.32 m above the current mean sea level on 22nd of February 2008 between 15:00 and 16:00 when the water level at the Göta älv barrier was between -0.15 and -0.39 m under the current mean sea level. The maximum water level in the Göta älv reservoir was about +1.27 m above the current sea level, higher than the safe level, on 22nd of June 2008 at 23:00 when the sea level was about -0.02 m under the current mean sea level. This situation occurred when both barriers were closed; while due to the low sea level at the same time of this situation there was no need to keep the barriers closed. Thus, by keeping the barriers open, the runoff to the Göta älv River is released to the sea and there is not any high water level such this in the Göta älv reservoir.

Results from operational scenario 2 and 3 determined the water level in the Göta älv reservoir was always less than the safe level (Figs. 6 (b) and (c)); thus, there will no risk of river floods when the gates are closed. The maximum water level at the Göta älv barrier was estimated about +2.1 m above the current mean sea level on 22nd of June 2100 when the sea level was about +0.97m above the current mean sea level (Figs. 6 (b) and (c)). The highest sea level was estimated to +2.95 m above the current sea level for both operational scenarios 2 and 3 on 2nd of February 2100 (Table II) when the water level in the Göta älv reservoir was about +1.23m above the current sea level. Based on operational scenarios 2 and 3, eleven times of extreme sea level is predicted for 2100. By closing the both barriers, the city was protected against all these extreme sea levels. Based on operational scenarios 2 and 3, eleven times of extreme sea level is predicted for 2100. The risk of flooding events due to the extreme sea levels was higher than the risk of river floods because of heavy rainfall-runoff generation during the 21st century. In addition, the results showed that the extreme sea levels were observed in winter period, and extreme water levels at the Göta älv River occurred in early summer.

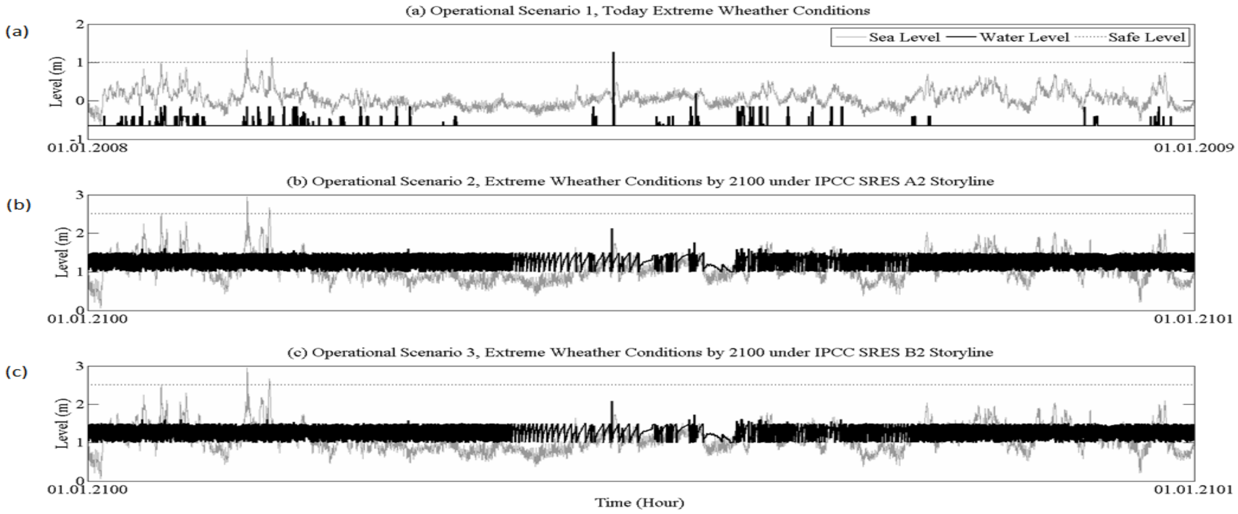

Fig. 6 Sea level against water level in the Göta Älv river reservoir for (a) Operational scenario 1, (b) Operational scenario 2, and (c) Operational scenario 3

TABLE II
SEA LEVELS (S.L.) HIGHER THAN SAFE LEVELS (SAFE L.) AND THEIR CORRESPONDING DATE, TIME AND WATER LEVELS (W.L.) IN THE GÖTA ÄLV RESERVOIR (ALL LEVELS ARE CONSIDERED FROM THE CURRENT MEAN SEA LEVEL = +10 M)

Scenario 1 (Safe L. = +1 m)			Scenario 2 (Safe L. = +2.5 m)			Scenario 3 (Safe L. = +2.5 m)		
Time	S.L. (m)	W.L. (m)	Time	S.L. (m)	W.L. (m)	Time	S.L. (m)	W.L. (m)
25.01.2008 07:00	1,01	-0,65	22.02.2100 15:00	2,95	1,28	22.02.2100 15:00	2,95	1,27
22.02.2008 15:00	1,32	-0,39	22.02.2100 16:00	2,95	1,36	22.02.2100 16:00	2,95	1,33
22.02.2008 16:00	1,32	-0,15	22.02.2100 17:00	2,71	1,09	22.02.2100 17:00	2,71	1,02
22.02.2008 17:00	1,16	-0,41	01.03.2100 20:00	2,51	1,48	01.03.2100 20:00	2,50	1,47
01.03.2008 20:00	1,02	-0,65	01.03.2100 21:00	2,61	1,01	01.03.2100 21:00	2,61	1,00
01.03.2008 21:00	1,09	-0.65	01.03.2100 22:00	2,65	1,22	01.03.2100 22:00	2,64	1,22
01.03.2008 22:00	1,11	-0,65	01.03.2100 23:00	2,66	1,35	01.03.2100 23:00	2,65	1,35
01.03.2008 23:00	1,12	-0,65	02.03.2100 00:00	2,67	1,47	02.03.2100 00:00	2,67	1,47
02.03.2008 00:00	1,13	-0,65	02.03.2100 01:00	2,66	1,21	02.03.2100 01:00	2,65	1,19
02.03.2008 01:00	1,12	-0,65	02.03.2100 02:00	2,56	1,15	02.03.2100 02:00	2,56	1,15
02.03.2008 02:00	1,06	-0,65	02.03.2100 03:00	2,55	1,31	02.03.2100 3:00	2,55	1,32
02.03.2008 03:00	1,05	-0,65	---	---	---	---	---	---

IV. CONCLUSIONS

This study examined hydrologic feasibility of using flood barriers for protecting the city of Gothenburg in Sweden from coastal floods due to the sea level rising during the 21st century. Based on IPCC SRES A2 and B2 storylines, the Gothenburg city will experience sea level rising about +1 m above the current mean sea level (+10 m) by 2100, while a high tide will be about +2 m above the current mean sea level. The results of water level model determined some sea levels higher than the city's safe level would cause coastal floods, in the absence of barriers. Two barriers, one in the northern Gothenburg area (upstream barrier), and another one at the outlet of Göta älv River to the North Sea (Göta älv barrier) were suggested as flood protection barriers for this study. In order to assure flood protection against the high sea levels, both upstream and Göta älv barriers have to be closed. The barriers would need to be open when the sea level is less than the safe level to prevent flooding from rainfall-runoff at the Göta älv barrier that surrounds most metropolitan areas of the Gothenburg city. Based on results of operational scenarios 1, 2, and 3, the flood barriers would successfully protect the city from flooding events during the 21st century.

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REFERENCES

[1] G.J. Boer, G. Flato, and D. Ramdsen, A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate to the twenty-first century. 2000, Climate Dynamics 16, page 427-450.

[2] J.F.B. Mitchell, Detection of climate change and attribution of causes. 2001, In Houghton, J. T. et al., (Eds.), Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge, UK, pag 695-738.

[3] UNFCCC, Climate change: impacts, vulnerabilities and adaptation developing countries. 2007, Bonn, Germany, pp. 64.

[4] Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal systems and low-lying areas. Climate change 2007: impacts, adaptation and vulnerability. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pag 315–356.

[5] L. Martinelli, B. Zanuttigh, and C. Corbau, Assessment of coastal flooding hazard along the Emilia Romagna Littoral, IT. 2010, Coastal Engineering 57, pag 1042-1058.

[6] R. J. Nicholls, Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. 2004, Global Environmental Change 14, pag 69-86.

[7] J. M. Smith, M. A. Cialone, T. V. Wamsley, T. O. McAlpin, Potential impacts of sea level rise on coastal surges in southeast Louisiana. 2010, Ocean Engineering 37, pag 37-47.

[8] G.A. Meehl, T.F. Stocker, W.D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, Z-C Zhao, Global climate projections. 2007, In: S. Solomon, D. Qin, Manning M et al., (eds) Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pag 433-497.

[9] SOU, 'Sweden facing climate change - threats and opportunities (Translation Journals style)'. Regeringskansliet, Sverige inför klimatförändringarna - hot och möjligheter. 2007, pp. 60.

[10] Gothenburg City Office, 'Extreme weather events : How well equipped is the Gothenburg? (Translation Journals style)'. Göteborgs Stadskansli, Extrema vädersituationer : Hur väl rustat är Göteborg?. 2006, pp. 63.

[11] IPCC. Emissions scenarios. 2000, pag 3-8.

[12] City Planning Office, 'Water so clears (Translation Journals style)'. Stadsbyggnadskontoret, Vatten-så klart. 2003, pag 25-50.

[13] S. C. Chapra, Surface-water quality modelling. 1997, McGraw-Hill, New York, ch. 3.

[14] L. Hamill, Bridge hydraulics. 1999, E & FN Spon, London, pag 178-181.