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Tide Contribution in the Flood Event of Jeddah City: Mathematical Modelling and Different Field Measurements of the Groundwater Rise

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***Abstract*—**This paper is aimed to bring new elements that demonstrate the tide caused the groundwater to rise in the shoreline band, on which the urban areas occurs, especially in the western coastal cities of the Kingdom of Saudi Arabia like Jeddah. The reason for the last events of Jeddah inundation was the groundwater rise in the city coupled at the same time to a strong precipitation event. This paper will illustrate the tide participation in increasing the groundwater level significantly. It shows that the reason for internal groundwater recharge within the urban area is not only the excess of the water supply coming from surrounding areas, due to the human activity, with lack of sufficient and efficient sewage system, but also due to tide effect. The research study follows a quantitative method to assess groundwater level rise risks through many in-situ measurements and mathematical modelling. The proposed approach highlights groundwater level, in the urban areas of the city on the shoreline band, reaching the high tide level without considering any input from precipitation. Despite the small tide in the Red Sea compared to other oceanic coasts, the groundwater level is considerably enhanced by the tide from the seaside and by the freshwater table from the landside of the city. In these conditions, the groundwater level becomes high in the city and prevents the soil to evacuate quickly enough the surface flow caused by the storm event, as it was observed in the last historical flood catastrophe of Jeddah in 2009.

***Keywords*—**Flood, groundwater rise, Jeddah, tide.

I. Introduction

HISTORICAL events show that coastal flooding in the KSA especially the ones happened in Jeddah can have devastating social and economic effects. From the Arab News Journal [10], floods killed 123 people in the Red Sea city in 2009, about 10 people two years later and paralyses the city almost once a year.

A number of Saudi important Red Seaside towns are directly exposed to atmospheric and oceanic conditions that are in particular risk of coastal flooding. Here, storminess generating water setups, intense precipitation and subsurface water level rise are responsible for both coastal and fluvial flooding and is considered as the major threat to flood defence structures.

In Mumbai city - India, when a strong storm hits the region during the high tide season, the coastal band finds itself covered by water resulting from sea waves, tide and rainfall. The city drains become incapable to evacuate all the water in the right time. Jeddah does not appear the same case.

There are few research initiatives on the subject before this study, so it was not clearly evident and could not have demonstrated the tide contribution in flood event. However, the research studies conducted by Rezzoug et al. [1], [2] showed that the water level in the soil reaches the high tide level and in some cases reaches the tidal annual water level especially for fine soils (clay and fine sands).

Estuarine and coastal areas generally undergo the influence of tide, which generates cyclic pressure in the coastal banks, slopes, beaches, harbour buildings, dykes, wharfs and propagate through the large band along the shoreline. This band is relatively large and characterized by its low altitude (Figs. 1 and 2) in the case of Jeddah and its agglomerations. This explains the appearance and disappearance of the water surfaces where the land elevation is the low above sea level and some coastal sabkhas (Figs. 3 and 4) surrounding Jeddah city and its agglomeration along Red Sea shoreline band.

Daoudi et al. [3] and Ameur [4] have produced several valuable pieces of information that can be used as part of a geographical information system for monitoring the natural risks of the city of Jeddah. They stated that vulnerability of the city to the risk of flooding seems to have increased sharply following the uncontrolled and very rapid extension of the urban fabric but also to the irregularity of the annual precipitations. The authors did not however show the tide effect on the flood risks.

In this paper, the research methodology will involve mathematical modelling and in situ measurement results from three different sites.

II. Topographic Elevation of Jeddah City

Fig. 1 shows the location of Jeddah town on the Red Sea coast and give an idea about the width of the shoreline band, which is characterised by its low topographic elevation (0 to 50 m).

Fig. 2 shows a focused zoom on urban areas of Jeddah city that covers the shoreline band. This low elevation lets the city very sensitive to any fluctuation of the groundwater level. Consequently, any external additional water contribution creates a surface runoff in the city. The elevation map is made by an online software [5].

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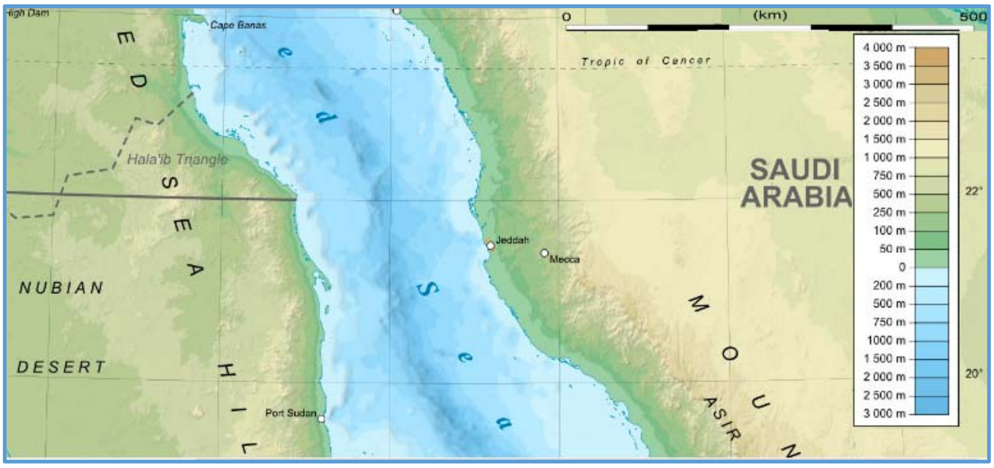

Fig. 1 Low elevation band along the Jeddah shoreline

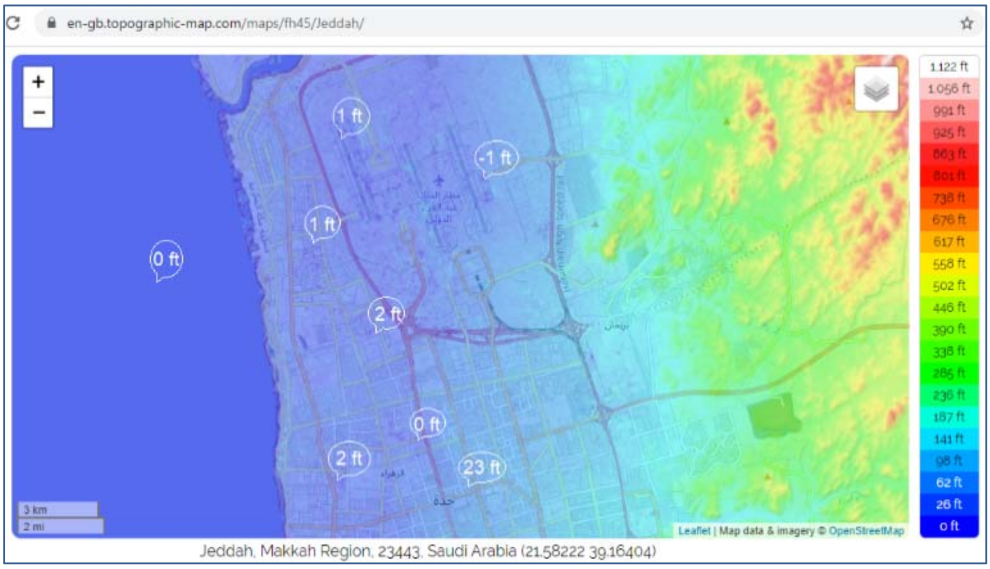

Fig. 2 Low topographic elevation of Jeddah city

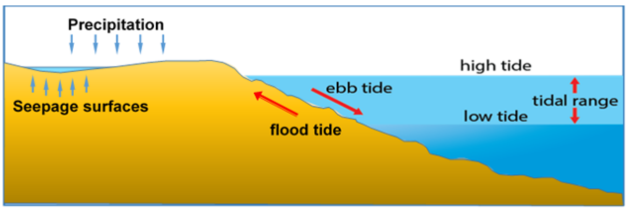

Fig. 3 Schematization of the seepage surface resulting from coupled tide with precipitation event

A. Tide Effect on the Groundwater Rise in the Shoreline Band

In the Red Sea, tide ranges between 0.6 m in the north, near the mouth of the Gulf of Suez and 1.0 m in the south near the Gulf of Aden. Jeddah coasts are affected by a tide of the same rage. The annual water level changes are significant. However, the mean sea level at winter is 0.5 m higher than in summer. During the high tide, the water seepages at the soil surface develop kind of thin surface ponds or sabkhas spreading over a few hundred metres (Figs. 3 and 4). One can see those water surfaces everywhere at Jeddah Airport especially during the high tide season.

Fig. 4 Water seepage on the surface near Jeddah airport

B. Geographic Location of the Tide Gauges Network in the KSA

Table I shows Saudi tide gauge stations network in the Red Sea with site names and approximate locations. The stations are installed by ARAMCO Oil Company in 2004 then maintained by the General Commission of Survey GCS from 2012, Abualnaja [6].

TABLE I
SAUDI TIDE GAUGE STATIONS NETWORK IN THE RED SEA

Location	Latitude	Longitude
Duba	27° 33’	35° 32’
Al-Wajh	26° 15’	36° 26’
Yanbu	24° 08’	37° 56’
Jeddah	21° 29’	39° 09
Al-Qunfuda	19° 07’	39° 09
Jazan (Jizan)	16° 53’	42° 32’

III. MATHEMATICAL MODELLING

Soil permeability, soil porosity and tide characteristics are the used parameters in the mathematical modelling of the water transfer from the sea seepage through the intertidal bank. This model is a non-linear flow equation with the solution describing the free surface flow going from the intertidal bank to the shoreline band. The oscillation of the tidal cyclic recharges through the soil bank produces a stable free surface flow in the shoreline band.

The piezometric water level in the shoreline band is therefore affected by periodical variations of tidal flow. Rezzoug et al. [1] proposed a global scientific approach that closely associates modelling, laboratory and in situ tests. The comparison of these approaches demonstrates a good overall agreement of results, the existence of a piezometric equilibrium level inside the bank higher than the mean tide level and often close to the high tide level depending on the soil characteristics. This approach allowed obtaining a set of original results, of great interest, leading to understanding the behaviour of the shoreline areas that have an intertidal interface with the sea.

A. Theory

The theory of saturated media, where the free surface is considered as the upper limit of the flow, is based on the description of the flow in the whole domain by [7]:

$$div\left(\bar{\bar{k}}\, gr\vec{a}d\ h\right) = S\frac{\partial h}{\partial t} \tag{1}$$

where $\bar{\bar{k}}$ is the permeability tensor in the sense of Darcy, h the hydraulic charge and S the coefficient of specific storage.

$$\frac{\partial^2 H^2(x,t)}{\partial x^2} = \frac{2n}{k}\frac{\partial H(x,t)}{\partial t} \tag{2}$$

where x is the horizontal axe oriented towards the sea and perpendicular to the shoreline and z is a vertical axe. $H(x, t)$ is the height of the free surface, n the effective porosity of the soil and t the time.

Equation (2) is known as Dupuit's equation of the free surface movement in nonlinear slow transient cyclic conditions.

B. Modelling Assumptions

The tidal excitation wave is complex, its pseudo-periodic character results from the superposition of oscillations of different periods (semi-diurnal or diurnal, lunar, annual). To reduce the complexity of the problem, we carry out the modelling with the following assumptions:

(i) periodicity of the tide by keeping only its main semi-daily sinusoidal component (of period T close to 12 hours), of amplitude A, of average level Hmoy (measured from an assumed substratum), and from pulsation ω supposed constant,
(ii) no fresh groundwater coming from the land side, just the sea water is considered in the modelling.
(iii) homogeneity and incompressibility of the soil in the bank,
(iv) non-permeable bedrock on which the bank rests,
(v) reducibility of the problem to a plane case; the generatrices of the slope are orthogonal to the direction of tidal wave propagation.

C. Simulation Scenarios for Varity of Soil Types and Boundary Conditions

The sinusoidal shape of the incident tide wave allows writing the boundary condition at the interface sea-land:

$$H(x = 0, t) = H_{moy} + A \sin \omega t \tag{3}$$

In the shoreline band, the damped oscillation of the hydraulic level H (x, t) of the free surface is a solution of (2) with (3). The groundwater level at x infinite on the landside is not imposed.

A semi-analytic solution offers results of a studied case scenario with the tide: amplitude A = 2 m around an average level of H_{moy} = 8 m. Fig. 5 shows the increase in the equilibrium level (defined as $\Delta Ne = Ne - H_{moy}$), function of the soil slope α for various types of the soil. In Table II, the soils used in the simulation are characterised by a range of values of the ratio k/n (in m/s).

TABLE II
VARIOUS TYPES OF SOIL USED IN THE SIMULATION SCENARIO

Soil Type	*k/n* Interval (in m/s)	
sands	3.3×10^{-2}	1.1×10^{-4}
sandy silts	1.4×10^{-4}	6.6×10^{-6}
silts	2.9×10^{-5}	1.0×10^{-6}
clays	1.2×10^{-5}	9.1×10^{-8}

In Fig. 5, the point (90°; 0.12 m) shows that for a vertical limit of the shoreline, the elevation of the water above the mean level of the tide is only ΔNe = 12 cm for the above defined tide, whereas it is close to 2 m (value of the amplitude A) in the case of small angles of the slope. This height is quickly reached in the case of fine soils as it is shown in Fig. 5.

In conclusion, the behaviour of the water level in the soil depends on the cyclic hydraulic regime created by the tide that alternating filling and emptying of the shoreline bank. The study showed the piezometric level in the shoreline band stabilizes round the high tide level in the most common cases of small inclination angle of the bank and in the cases of fine soils.

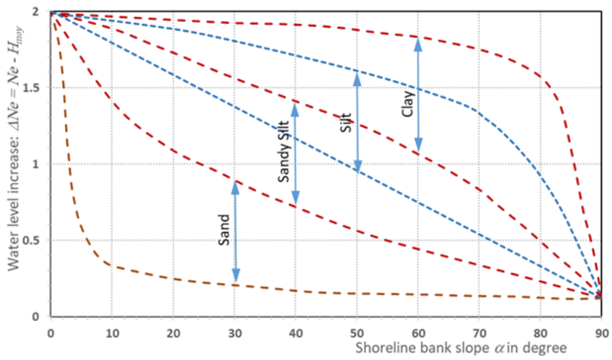

Fig. 5 Groundwater level rising versus the slope for different types of the soil

IV. In situ Measurements

Three different sites from the literature are presented here to showing the influence of the tide on the piezometric level in the shoreline band:

A. Les Sablieres Site on Loire Estuary – France

An estuary site called "Les Sablières", situated on the north intertidal bank of the Loire River, with simple geometry and easily identifiable boundary conditions, was chosen. It is a bank slope showing successive deposits of layers of medium compact sand and mud. The slope is about 1/5 protected by a riprap in natural stones.

The slope was alternately completely submerged during high tide, and completely emerged during low tide. The low sea discovers a muddy bottom crossed by resurgences and scour holes, through which the slope empties during the ebb tides. To monitor the free surface during the tidal cycle, piezometers are installed along a line perpendicular to the shoreline to measure the evolution of the groundwater level.

Rezzoug *et al.* [1] showed all the details of this in situ experimentation through a long process of comparison between lab experiments, in situ measurements and mathematical simulation. To summarize the obtained results, the free surface of the groundwater profiles give measured equilibrium level in the intertidal soil bank close to the annual high tide level. The in situ measurements confirmed therefore the results of the mathematical model shown above.

B. Metropolitan Area of Jeddah – KSA

Alsefry et al. [8] showed the data recorded in 2002 from 118 wells and evaluated them in order to assess the groundwater quality and quantity for identifying the groundwater rise. They prepared the groundwater level rise map, Fig. 6, through a simple probabilistic risk model. The authors summarise that the reasons of the groundwater rise within the metropolitan area of Jeddah city are due to leakages from water supply systems, exfiltration from cesspools, rainfall recharge, excess landscape irrigation, leakage from underground storage tanks, subsurface inflow from the eastern wadis and other hydrogeological parameters.

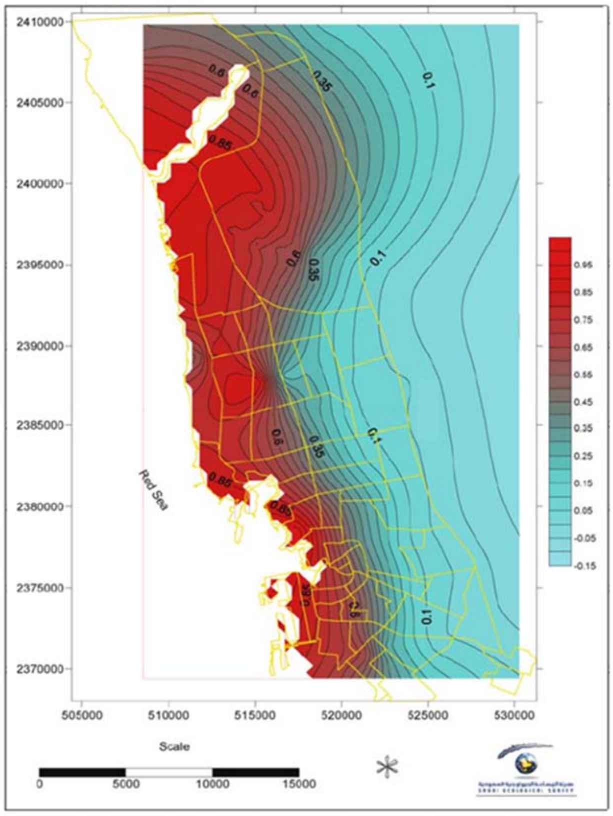

Fig. 6 Risk map for groundwater level [8]

Comparing this groundwater level map of Fig. 6 with the result obtained in [1], it is evident that the most important recharge is coming from the sea. The tide is therefore pumping water inside the intertidal bank and raises the groundwater level in the shoreline band to the annual high tide level.

C. Mangrove Forest in the Pacific Coast – Nicaragua

Calderón et al. [9] showed combined tide and precipitation effects on piezometer heads in the site of Mangrove forest during the dry season in the pacific coast of Nicaragua. The study showed that the hydraulic influence of seawater on coastal piezometers is controlled by the elevation of the water table and the tidal amplitude. These conditions controlling the shoreline areas are essential for the ecological and economic benefits. Fig. 7 shows sea tide and precipitation effects in hydraulic heads in piezometers located near the coast. Pb10 and Pb12 depict stronger tidal influence due to proximity to the shoreline; Pb11 is located further away and is more influenced by precipitation events.

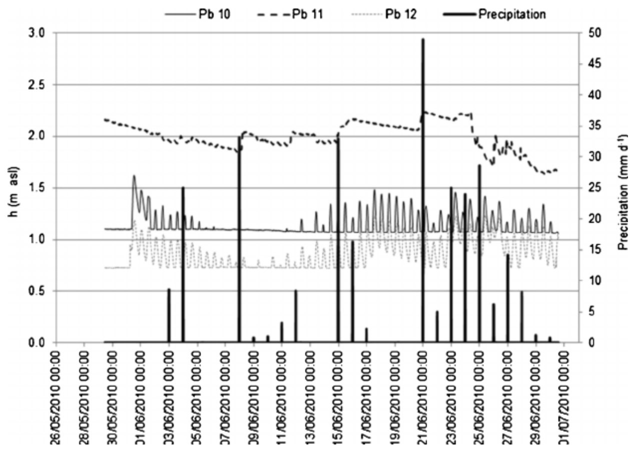

Fig. 7 Sea tide and precipitation effects in hydraulic heads [9]

V. Conclusion and Recommendations

The study raises two important factors that are effectively participating in the flood event of Jeddah city:

1) Tide charges the urban areas located on shoreline band and causes groundwater rising up to annual high tide level, and,
2) Low topographic elevation of the shoreline band accelerates the flood in those urban areas when the tide effect is coupled with strong precipitation storm.

The tide effect is important factor for Jeddah development authority to take into consideration in any risk prevention and/ or future planning and development in the urban areas. The tide factor was not explicit to the concerned authority. The small tide seems here to have significant effect. This factor has to be added to the list of other factors given by many authors in the literature, which are mostly caused by the human intervention like additional water supplies from surrounding areas due to human activities and lack of sufficient and efficient sewage system.

Future work plan could include at least these three recommendations:

1) Plan in situ measurement in Jeddah city and its urban agglomeration along the year to understand more the interactivity between the three parameters: precipitation events, tide recharge variation and the piezometric rise. It is important to understand the piezometer behaviour versus the highest tide coefficient dates and the annual full tide event.
2) Evaluate the flood risks and vulnerability with predicting possible flood risk indicators using a combination of more developed mathematical modelling and new in situ experimentations.
3) Develop Jeddah flooding risk maps with kind of elevation safety factors that helps the authority for new urban planning and development on those areas.

References

[1] A. Rezzoug, A. Alexis, and P. Thomas, “Ecoulement a surface libre dans un massif de sol soumis à la marée: comparaison théorie-experimentation”. Canadian Geotechnical Journal, NRC Research Press, 1999, 36 (1), pp.13-20.

[2] A. Rezzoug, A. Alexis, and P. Thomas, “Écoulement dans les talus intertidaux”. Journal de recherche océanographique. 19(3/4): pp.125–136.

[3] M. Daoudi, and A. J. Niang, “Flood Risk and Vulnerability of Jeddah City, Saudi Arabia”. Recent Advances in Flood Risk Management, 2019, DOI: http://dx.doi.org/10.5772/intechopen.82073.

[4] F. Ameur, “Floods in Jeddah, Saudi Arabia: Unusual Phenomenon and Huge Losses”. What Prognoses. FLOODrisk 2016 - 3rd European Conference on Flood Risk Management.

[5] Free online topographic maps visualization and sharing 2020, https://en-gb.topographic-map.com/maps/fh45/Jeddah/

[6] Y. O. Abualnaja, “Sea Level Activities in the Kingdom of Saudi Arabia”. Report Submitted to the Thirteenth Session of the Intergovernmental Oceanographic Commission (IOC), Group of Experts of the Global Sea Level Observing System (GLOSS). November 2009.

[7] H. Zaradny, “Groundwater flow in saturated and unsaturated soil”. Edited by R.B. Zeidler. A.A. Balkema, Rotterdam 1993.

[8] S. Alsefry, and Z. Şen, “Groundwater Rise Problem and Risk Evaluation in Major Cities of Arid Lands – Jedddah Case in Kingdom of Saudi Arabia”. Water Resources Management 2006. 20. pp. 91-108.

[9] H. Calderón, S. Uhlenbrook and W. Ruben, “Hydrological and Geomorphological Controls on the Water Balance Components of a Mangrove Forest During the Dry Season in the Pacific Coast of Nicaragua”. Wetlands 34(4), August 2014.

[10] Rainfall in Jeddah exceeds Nov. 2009 flood accumulation, Arab News Journal, 26/01/201, https://www.arabnews.com/node/366463