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Hydrogeological changes in coastal aquifers due to sea level rise

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Abstract

Global warming and climatic changes can lead to sea level rise (SLR) of dozens of cms over upcoming decades, along with groundwater permanent reserve losses (PRL). This study focuses on understanding the processes and estimating groundwater losses. A case study for such phenomena is Israel's Coastal aquifer. PRL estimation methodology is based upon a simple hydrogeological conceptual model. The results lead to estimation of two main components of an aquifer's PRL, and to key factors that can enhance or mitigate these losses. Such recommended measures as high-resolution topographic mapping and improved monitoring of sea level have been noted.

1. Introduction

1.1. Sea level changes as a result of natural factors

Natural factors influence sea level rise (SLR) in a non-uniform way. Such geological processes as tectonic activities, including earthquakes, can supply material from below the oceans by means of eruption or intrusion of material from the earth's mantle, leading to the formation of new islands, contributing to a rise in sea level. On other hand, formation of tension faults can open canyons, rift valleys and augment deep relief, expanding the volume as well as the geometry of ocean and sea areas, resulting in a lowering of sea level. Natural processes can simultaneously supply material and reduce the water reservoir—thus raising seawater level, or enlarge the oceanic and sea volumes—lowering sea level [1].

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Another natural cause for change of sea level is glacial isostatic adjustment (GIA). This factor can cause continental sinking in one area but a non-uniform rise in other areas [2].

An additional natural factor that can influence rise in sea level can result from coastal erosion. The alteration of lithological material at the stratigraphic front of a coastline transfers masses of eroded material from the shoreline front downwards to the sea bottom as well as upwards to form new inland ridging along the resultant coast [3,4]. Sedimentilogical changes can damage natural environments along the shoreline [5], and may alter boundary conditions of hydrogeological systems connected to the sea.

It is therefore critical to determine what natural effects SLR might have, when they might occur, how significant they might be, and what their impacts might be upon groundwater and other natural resources, and the ambient environment of a shoreline.

1.2. Sea level changes as a result of anthropogenic factors

Beside natural processes, adverse anthropogenic effects can change the SLR. Over-use of fossil fuels produces immense amounts of gases which build in the atmosphere to produce a "greenhouse effect", contributing to atmospheric warming [6]. The latest reports of the World Meteorological Organization (WMO) and the United Nations Programme for the Environment (UNPE) indicate a sharp increase in world ambient temperature of between 1.4 and 5.8 °C by 2100 [7,8]. Ocean and seawater temperatures may also increase significantly by 2100. This global warming could be responsible for climatic change that may lead to atmospheric instability by increasing the number and intensity of storms and hurricanes, amplifying inland intrusion of larger and higher seawater waves.

Another anthropogenic factor that can change the environment, enhancing or mitigating SLR is the over-exploitation of confined aquifers, which can cause long-term sinking of continental masses in some areas but rises in others. Another factor is the construction of dams. This reduces quantities of water and sediment flowing from the continent into the sea. On the one hand, this can diminish SLR by reducing inflowing volume of water into the sea. In USA, 11–13% of the total annual river runoff is presently sequestered behind large dams. Along the Mediterranean Sea's catchment area, such construction chiefly affects locally important alluvial discharge of such streams as the Rhone, Elbre and Nile. Discharge from the Nile has been reduced by more than 80% since the recent construction of a major dam. Reduction of sedimentation in deltaic regions can lead to severe erosion of coastal areas. Construction of dams can reduce sedimentation which could also lead to increased erosion, causing further regression of the seashore and a rise in SLR. The results of erosion could lead to further seawater intrusion that can damage coastal water resources and precious ecological and archeological sites, with adverse ancillary consequences on tourism and other economic concerns. The concern is thus the ultimate impact as regards SLR and intrusion of seawater into the continent [1,9–12].

1.3. SLR measurements and trends

The Inter-governmental Panel on Climatic Changes (IPCC) attributes the majority of recent SLR to thermal expansion of ocean water (steric effect), resulting from global warming and subsequent melting of glaciers ([1,13]; Table 1).

The multitude of these natural and anthropogenic factors, along with the complexity of SLR measurement leads to uncertainty in accurately forecasting future SLR. Reports

Table 1
Rate of SLR from various references

Data information about global sea level rise (SLR)			
Sources	Region	Date used (years)	SLR (mm/yr)
Gornitz and Lebedeff (1987) and IPCC	Global	1880–1982	1.2 ± 0.3
Millinan (1992)	Mediterranean Basin	<1991	1–2
Shennan and woodworth (1992)	Northwestern Europe	<1991	1.0 ± 0.2
Zerbini et al. (1996)	Genoa	1884–1988	1.3
Nichollas and Hoozmans (1996)	Marseille	1885–1992	1.2
Gornitz (1995)	Eastern USA	<1994	1.5
Topex—Poseidon satellite	Global	1993–1998	2.5
Shirman (2001) [14]	Tel Aviv–Ashdod	1990–2002	$20–25 \pm 10$
Rosen (2002) [5]	Hadera (Israel)	1992–2002	11 ± 5

based on pre-1990 data indicate SLR of around 1–1.5 mm/yr. Later reports have been based on data between 1992 and 1998. Latest reports of the IPCC, based on data from the Topex—Poseidon satellite measurements and other facilities indicate that seawater warming is causing a rise in SLR of more than twice that noted in previous measurements (Table 1). Other recent reports in various areas in the world indicate SLR of between 5 and 20 mm/yr. This has been especially noticeable in the coastal areas of the Mediterranean Sea, measured over recent years (1992–2002). The focus has been upon the center and eastern portion of the sea, including the Israeli coasts of Tel Aviv, Ashdod, and Hadera. This trend has also been noted in other areas in the world. It is felt that SLR of between 50 and 100 cm could be expected by the end of the 21th century ([1,5,10,13,14], Table 1). Owing to non-uniformity, measurements in other areas of the world could also indicate trends in which no change at all are observed, or indeed, where sea levels might be dropping.

1.4. SLR and sea intrusion

Rising ocean levels will enhance processes already on-going throughout the world, which include submergence of large portions of shallow relief areas in estuarine and deltaic areas of Pacific, Indian, and other ocean coastal islands. In Europe, this could include the swamping of shallow areas of the Netherlands, and some estuarine regions of the British Isles, which could include such large cities as London, as well as the Camargue area in France. In the US, coastal cities such as New York, Boston, Miami, and New Orleans, etc. could be threatened [1,9]. A further question is not whether sea levels will rise, but rather how a change in sea level might alter the profile of coasts as regards coastal lithology, the integrity of coastal groundwater resources, and the ecology of the coastal environment [15]. Particular attention should be paid to coastal areas with low relief, where high waves could lead to significant inland damage. An extreme case, which occurred at the end of 2004, was the tsunami that struck coastal areas of the Indian ocean, leaving an apocalyptic disaster of more than a quarter of millions people dead and more than 1 million homeless in many countries [12,16].

SLR could enhance seawater intrusion and inundation along the Mediterranean Sea's constricted basin. This basin is home to a population of around 500 millions habitants, having 45,000 km of coastline with numerous deltaic and estuarine areas in which a multitude of natural resources, such as groundwater and historic archeological sites, could be threatened [17,18].

1.5. The need for a conceptual models to assess the permanent losses involving SLR

One of the attempts to develop a conceptual model to assess permanent losses that might result from SLR has been the DELFT3D three-dimensional model, which is used to estimate changes to be expected in the extent of seashore regression when considering lithology, stratigraphic parameters, and changes in tidal levels. The DELFT3D model can yield an approximate assessment of future coastline changes. The model indicates that even shorelines having a significant slope will suffer regression; a rise in sea level of 1 m could bring about an average regression of 100 m for a coast composed of sand, but only about 60 m where the coast is composed of harder material. The model further predicts a worldwide coastal regression of 10–100 m by the end of the 21st century. However, there is presently no model which can forecast SLR with an acceptable degree of accuracy, and which highlights the adverse effects SLR could have upon coastal groundwater reserves, lithology, stratigraphy, archeological remains of early coastal civilizations, ecological biota, and other environmental aspects [5,11,19].

1.6. Objectives

The purpose of this study is to present the basis for a simple hydrogeological conceptual model relating seawater intrusion to SLR. Such a model ought to estimate groundwater losses that can occur owing to the SLR, which may take place over coming years. The study also focuses upon potential environmental changes and adverse effects which may occur along the sea shore in general, in the eastern portion of the Mediterranean Sea, and in particular, along Israel's coastal plain, which includes the Coastal aquifer, considered here as the case study. Recommendations are also made towards preventing, mitigating, or overcoming possible adverse effects.

2. Methodology: a conceptual model of SLR and methods for assessing permanent reserves losses (PRL)

2.1. Assessment of PRL due to lateral seawater intrusion

Fig. 1 presents a visualization of scenarios which could lead to permanent storage loss, including loss resultant from SLR. For the purpose of making approximate estimations it is assumed that seawater intrusion in all such cases will take a linear form, and will intrude at a constant rate into porous aquifer media.

The initial case is represented in Fig. 1 by position O. Maximum seawater intrusion, called the "toe", is noted by the letter "I". I_0 stands for the initial point of interface (toe) of seawater and fresh water along the seashore, and I_1 represents the actual situation. Over "T" years, assuming over-pumpage continues at the same rate as today, the toe will advance to position I_2. In this case, OI_0I_2 encompasses a cross-section representing the area that will be filled by seawater. Estimation of total permanent loss of aquifer reserves is thus obtained by multiplying this area by aquifer porosity for a lateral unit width of seashore.

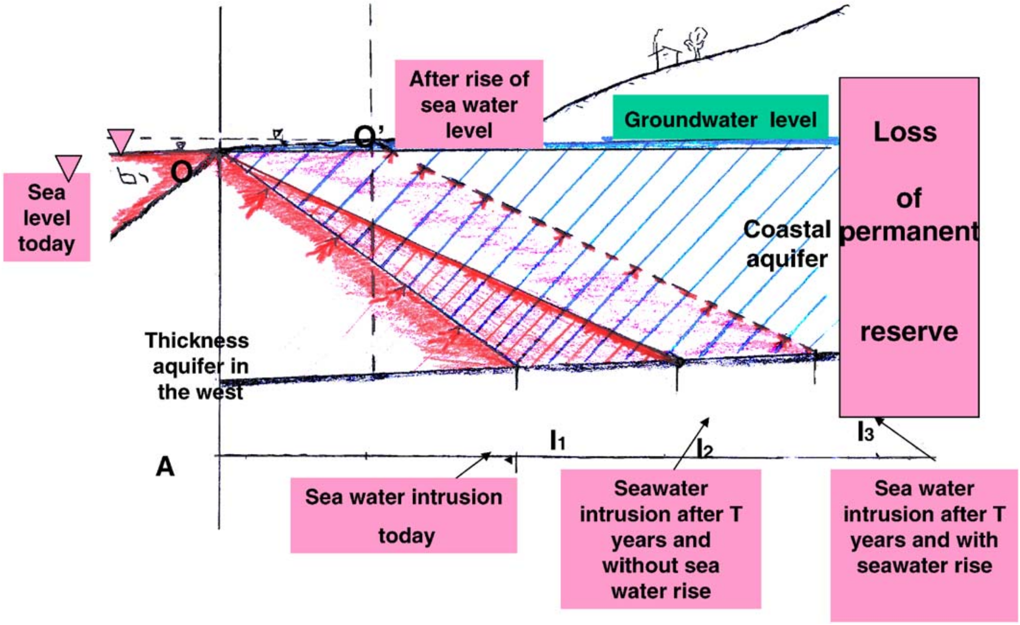

Fig. 1. Conceptual illustration of seawater intrusion, SLR and PRL.

In the case of SLR, the shoreline moves from position O to position O' (the new groundwater drainage basin basis). It is then assumed that the toe of additional intrusion into the aquifer with depth is represented by line $O'I_3$.

For purposes of calculation, assumptions must be made concerning aquifer geometry, the shape, and movement of the seawater fresh water interface, in order to consider the ultimate figure formed by $OO'I_3I_0$, as a trapezoid, composed of a triangle OI_0I_2 and a parallelogram $OO'I_3I_2$. The latter is, in fact, the area which will be filled by seawater due to SLR. Therefore, the area filled by seawater in the absence of SLR is the area encompassed by the triangle OI_0I_2 whilst the total area filled by seawater which includes SLR is represented by the trapezoid $OO'I_3I_0$. Subtracting the triangular area from that of the trapezoid enables estimation of the area of the remaining parallelogram, $OO'I_3I_2$. It is important to note that the ultimate size of parallelogram $OO'I_3I_2$ is a function of the distance inland which seawater intrudes along the coastal surface, itself a function of the relief slope of the coast. The calculation of permanent loss of storage capacity to the aquifer as a result of SLR can be made by multiplying the area of parallelogram $OO'I_3I_2$ by the porosity of the aquifer (Fig. 1).

2.2. Assessment of PRL due to change of drainage basin basis and of the groundwater head profile

An additional loss of fresh groundwater head can result from the change in the groundwater drainage basis to the sea, from position O to O' (Fig. 2). This can be shown by comparing the groundwater water head profiles in the both cases on the same graph. When considering the profile of groundwater head (dh_f) above sea level in a steady-state

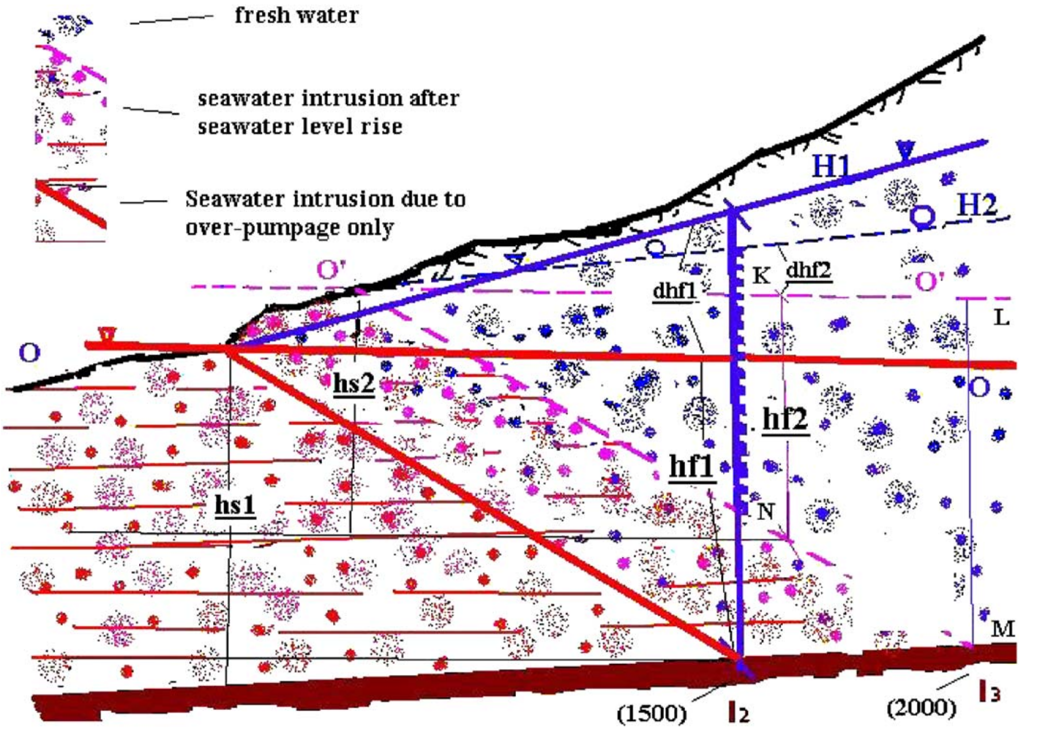

Fig. 2. Illustration of changes in drainage basin basis and groundwater profile heads.

situation where seawater is in equilibrium with fresh groundwater as formulated by Ghyben-Hertzberg law [20], one gets equation

$$h_s\,\rho_s = H_f\,\rho_f = (h_f + \mathrm{d}h_f)\rho_f \tag{1}$$

with the following equalities:

$$h_s = h_f \text{ and } H_f = h_f + \mathrm{d}h_f, \tag{2}$$

where ρ_s the density of the Ocean/Mediterranean seawater (1.02/1.035 g/cm^3); ρ_f the density of fresh water (1.0 g/cm^3); H_f the fresh head between groundwater head profile line and seawater interface; h_f the fresh water head between the interface line and seawater level and h_s is the seawater head between the interface line and seawater level.

From Eqs. (1) and (2), groundwater head above sea level is equal to

$$\mathrm{d}h_f = [h_s(\rho_s - \rho_f)]/\rho_f. \tag{3}$$

In this study it is assumed that groundwater head profiles are linear from distance I_0 to the eastern border of the aquifer, respectively, for the two groundwater drainage basin bases (O) and (O'). The above-noted formula and the considered assumptions enable calculation of groundwater head and delineation of a profile of groundwater head for each drainage basis case. For drainage basin basis O, the groundwater head profile $H1$ predicted for the coming T years results mostly from over-exploitation; for drainage basin basis O', groundwater head profile $H2$ includes SLR (Fig. 2).

Each groundwater head profile line is based upon two points: one point is at groundwater head 0 at distance 0 from the initial seashore location (Fig. 2); the second point is at groundwater head (dh_{f1}), I_2 m from the initial seashore, where, dh_{f1} is obtained by use of the Ghyben-Hertzberg law in formula (3).

After SLR, the maximum seawater intrusion will reach I_3 m from the initial seashore (Fig. 2). In this case, the two points that defines the groundwater head profile $H2$ are the groundwater head 0 located at position O' m from the initial seashore, and the groundwater head at distance I_2 m from the initial seashore. At this distance, in this case, only a portion of aquifer thickness (h_{f2}) is saturated with fresh water (Fig. 2). The fresh water height at this point (h_{f2}) is equal to the length included between the new seawater interface level and the new sea level. Here, (h_{f2}) is estimated by the geometric proportional triangles law. Utilizing Eq. (3), the groundwater head (dh_{f2}) corresponding to this column of fresh water h_{f2} can be estimated. This value determines the second coordinate that enables the drawing of groundwater profile line $H2$ as presented in Fig. 2.

For estimating groundwater losses after T years with and without SLR, profiles $H1$ and $H2$ are presented on the same graph and compared up to a distance of I_2 m from the initial seashore. For one unit of seacoast, a volume of groundwater loss can be estimated by multiplying each surface of the triangle included between the groundwater head profiles $H1$ and/or $H2$ and the appropriate seawater level, and the porosity of the aquifer (Fig. 2).

These estimated permanent reserve losses can be enhanced or mitigated by natural or anthropogenic factors that can lead to a change of the hydrogeological characteristics of the aquifer along its sea border.

3. Case study: estimation of the potential PRL of Israel's coastal aquifer due to SLR

3.1. Hydrogeology of Israel's coastal aquifer

Israel's Coastal aquifer extends from the Mt. Carmel horst/graben in the north to the Sinai and the Gaza Strip Authority in the south, and from the foothills of the central Mountain aquifer on the east to the Mediterranean sea coast on the west (Fig. 3). The aquifer is approximately 150 m thick along the seacoast and feathers out to a few meters along its eastern border at about 10 km from the seashore. The aquifer is composed of numerous sandstone and calcareous sandstone layers, having high conductivity, silt and "hamra" layers having moderate permeability; and impermeable clay wedges which are often found within the aquifer's stratigraphy, up to 5 km from the seashore. These impermeable clay layers subdivide the aquifer into subaquifers. Some of the deepest clay layers become thicker towards the sea, thus disconnecting the subaquifer segments below them from the influence of seawater [21]. Those portions of the Coastal aquifer with low slopes and a higher probability of influence by seawater intrusion are the upper subaquifer segments, ("A" and "B" in Fig. 4). Owing to this lithological characteristic of the aquifer, rise in seawater level will have greatest impact upon these upper layers in low topographic areas, generally in deltaic areas where streams enter the sea, for example, the areas of the Ayalon and Yarqon Streams near Tel Aviv (Fig. 5).

Assessment of the "toe" or the maximum distance from the seashore into which seawater intrudes the aquifer is delineated by the deepest incursion of the "seawater interface", the plane separating seawater from fresh water of the aquifer. On average along the length of the Coastal aquifer, this "toe" intrudes around 1000 m from the seashore

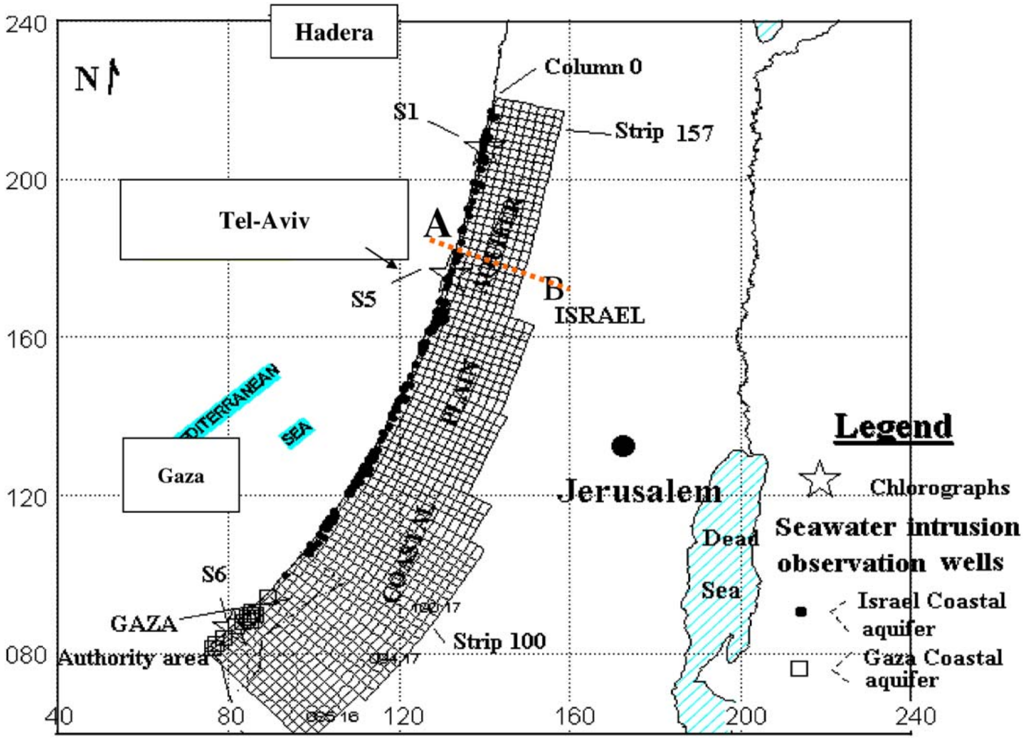

Fig. 3. Location map of Israel's Coastal aquifer and seawater intrusion network.

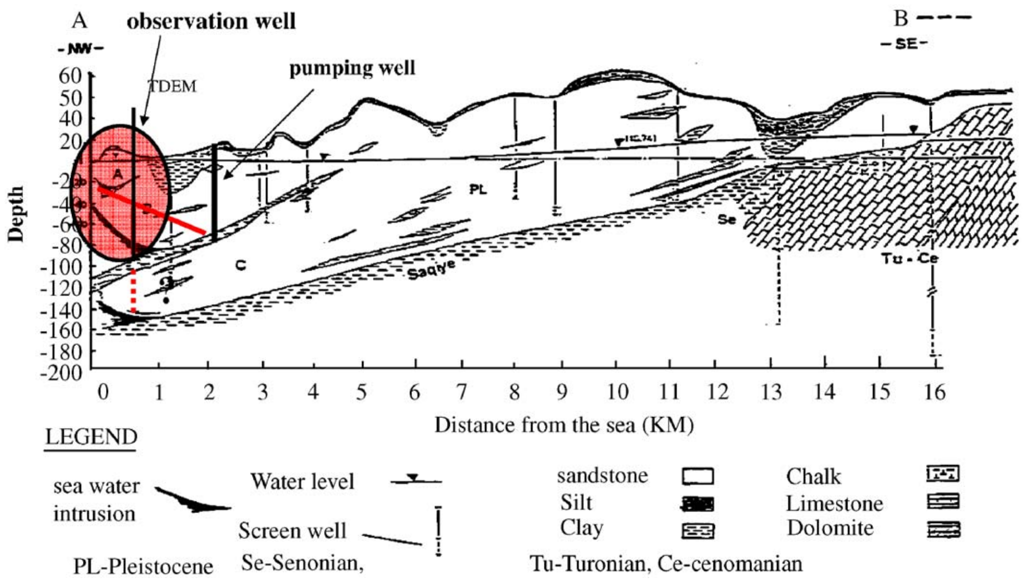

Fig. 4. Hydrogeological cross-section of Israel's Coastal aquifer (from: Tolmach, 1979).

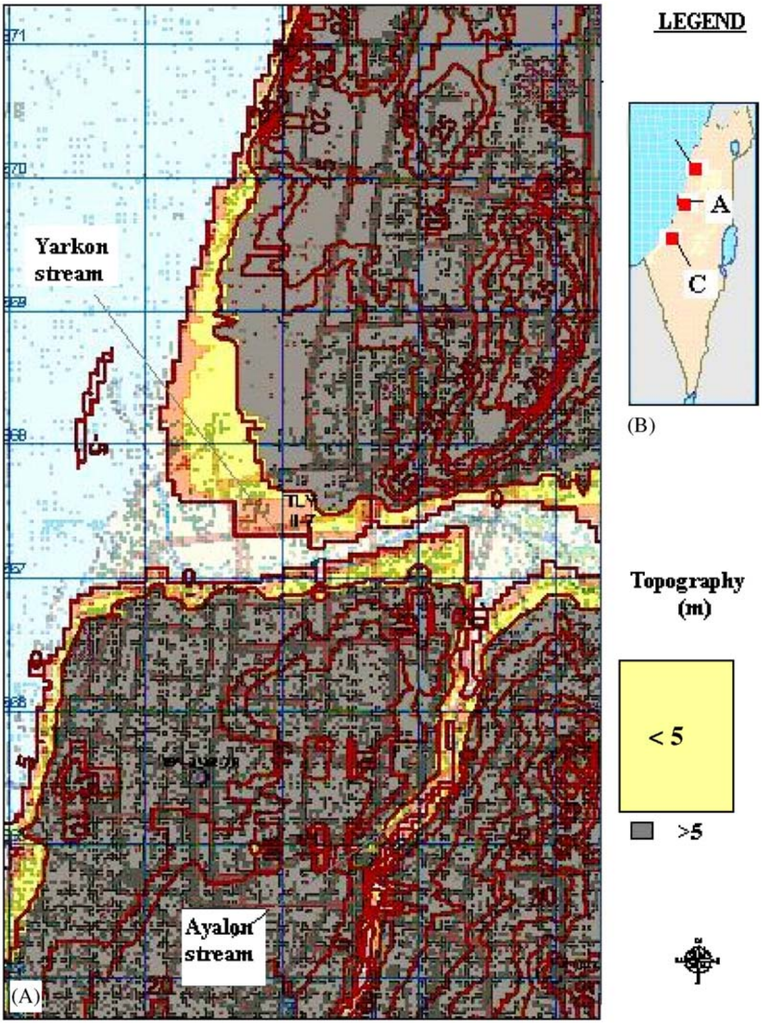

Fig. 5. Deltaic area of the Ayalon and Yarqon Streams near Tel Aviv metropolitan area.

(Fig. 6). Where seawater has intruded deeper into the aquifer, a significant number of pumping wells have become salinated and closed as sources of drinking and even of irrigation water [22,23]. Over recent years, owing to overpumpage, the quality of aquifer water has deteriorated, mostly as a result of seawater intrusion. Of the wells in question, 13% exceed standard limitations for acceptable domestic water supply and usage, characterized by more than 600 mg/l Cl and more than 70 mg/l nitrates [22], and are thus useless for drinking water.

In high-pumpage areas, water levels have dropped, and formed cones of depression. Water levels in the central portion of these cones of depression have dropped to -1 to -3 m below sea level. These cones of depression can be found mostly 1–3 km from the coast. Thus, intrusion of seawater more than 1 km from the sea can produce significant damage to the Coastal aquifer's water reservoir hydrology ([23]; Fig. 3).

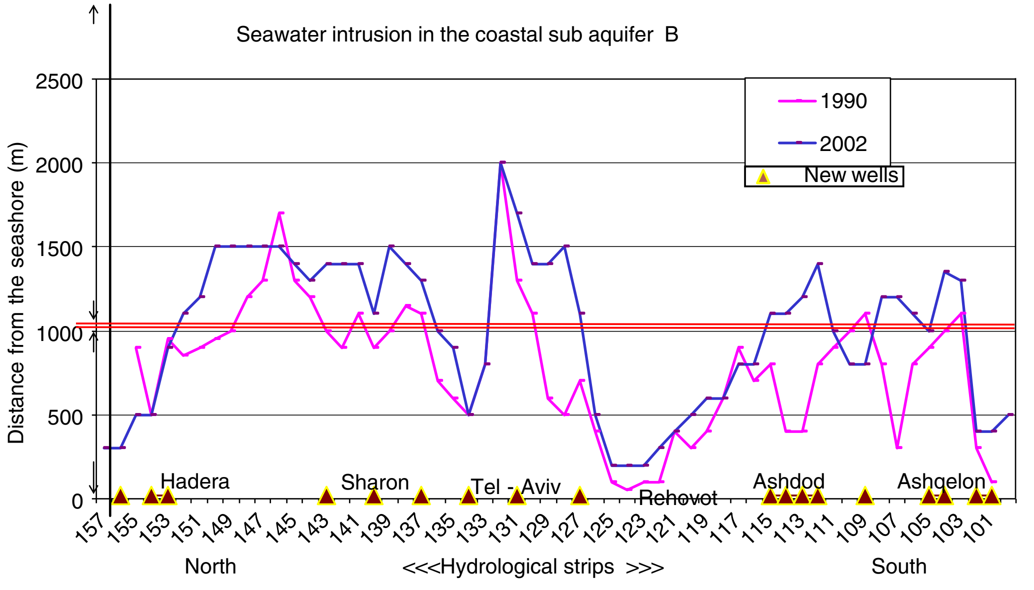

Fig. 6. Seawater intrusion in 2002 in the upper sub-aquifer (B) of the coastal aquifer.

In order to mitigate the negative impact of seawater intrusion, pumpage levels have been reduced, and fresh water has been recharged into the aquifer from a variety of sources. Two of those sources are treated effluents, characterized by salinities greater than around 200 mg/l Cl, while background fresh water is less than 100 mg/l. This recharge has contributed to a rise in groundwater level, but also to a rise in ambient salinity of Coastal aquifer water. However, the rate of rise in salinity from these recharge sources is small compared to the potential impact of salinity rise due to seawater intrusion. Therefore, a rise in seawater level is of critical importance.

3.2. Estimation of permanent storage losses of Israel's coastal aquifer due to sea rise

3.2.1. Estimation of permanent storage loss of Israel's coastal aquifer due to lateral movement of seawater

Based on the approach illustrated in Fig. 1, an estimation of PRL resulting from SLR has been assessed. In Table 2, data related to scenario *A* involves a case where virtually no SLR occurs. Scenario *B* represents a case where SLRs approximately 10 cm over 50 years, not far from the previous IPCC estimation (Table 1). Scenario *C* is a case in which SLR approximately 50 cm over 50 years, based upon recent measurements (since 1992), dealing with the Mediterranean Sea coast ([11]; Table 1).

To calculate these losses, it has been assumed that seawater intrusion is linear, intrudes at the rate of approximately 10 m/yr, and that aquifer media porosity is approximately 25%. In the case of Scenario *A,* seawater intrusion is illustrated with a toe located at I_1, approximately equal to 1000 m from the seashore (Table 2). Fifty years from now, on the assumption that overpumpage continues at the same rate as today, the toe will have advanced 500 m, to position I_2, approximately 1500 m from the sea shore (Fig. 1 and Table 2). Estimation of permanent loss for 1 km of seashore is thus obtained by

Table 2
Data and permanent reserve loss (PRL) due to lateral sea water intrusion in the upper coastal aquifer under various SLR scenarios

Scenarios		Thickness of the western border of the aquifer (m)	Sea water intrusion (m) for the case of a topographic shoreline with a slope of		Total permanent reserve loss (PRL) in an aquifer with porosity of 0.25 (MCM)	Additional PRL due only to SLR (MCM)
		1%	1%	1‰		
Without seawater rise	A	100	1500	1500	18.7	
With seawater rise of	B	100.1	1510		19.0	0.2
10 cm		100.1		1600	21.2	2.5
With seawater rise of	C	100.5	1550		20.1	1.3
50 cm		100.5		2000	31.2	12.5

MCM, million cubic meters; SLR, sea level rise; PRL, permanent reserve loss.

multiplying area OI_0I_2 by aquifer porosity 0.25. The estimation of permanent reserve losses then comes to 18.7 million cubic meters (MCM) per km of shoreline (column 5 in Table 2).

In the case of Scenarios B or C, sea level rises from position O to position O', Assuming the coastal plain to be flat, figure $OO'I_3I_2$ can be considered a parallelogram representing the area which will be filled by seawater due to linear movement of the seawater/fresh water interface, as illustrated in Fig. 1. In this case, the permanent loss of storage capacity to the aquifer as a result of a rise in sea level is calculated by multiplying the area of parallelogram $OO'I_3I_2$ by the porosity of the aquifer. For a 50 cm SLR, for a topographic slope of coastline of 0.001, the additional seawater intrusion into the aquifer would be a further 500 m. Then, $OO' = I_3I_2 = 500\,\text{m}$, while $O'I_0 = 100.5\,\text{m}$, and $I_0I_3 = 2000\,\text{m}$ (Table 2). Results given in column 6 of Table 2, indicate that for a shoreline having a topographic slope of 0.001, for a SLR of 50 cm, the additional permanent reserve loss of the aquifer would be about 12.5 MCM/km of shoreline (Table 2).

It has been assumed here that the basis slope of the aquifer is negligible, and the change in thickness of the aquifer along the coast will not have an appreciable effect in this stage of calculation upon final permanent loss of storage capacity of the aquifer. The more significant influence is the seawater intrusion into the uppermost layer of the Coastal aquifer, where the direct connection between seawater at the coastal aquifer seems most plausible.

3.2.2. Estimation of additional PRL for Israel's coastal aquifer owing to a change in groundwater head profile, owing SLR

As illustrated in Fig. 2 in Methodology Section 2.2, the additional loss of fresh groundwater owing to SLR is due to the shift in the basis of drainage of groundwater to the sea, from position O to O' (Figs. 1 and 2). This is on the assumption that groundwater head profiles for the two drainage basins are linear from 0 to 10,000 m from the seashore, a point which is found near the border of the active eastern portion of the aquifer.

In a steady-state situation between fresh groundwater (with $\rho_f = 1.0\,\text{g/cm}^3$), and the Mediterranean Sea water (with $\rho_s = 1.040\,\text{g/cm}^3$), Eq. (3) leads to a groundwater head

Table 3
Data base related to the old and new groundwater drainage basin basis after a SLR of 0.5 m

Groundwater level related to Ghyben-Herzberg (m)		Saturated aquifer thickness above seawater/fresh water interface (m)		Aquifer thickness related to distance from the sea (aquifer basis slope of 1%)	
After seawater rise of 50 cm	Before seawater rise	After seawater rise of 50 cm	Without seawater level rise	Aquifer thickness (m)	Distance from the seashore (m)
—	0	—	~0	100	0
0	—	0	—	95	500
2.1	3.4	53	85	85	1500
3.2	>3.4	80	No seawater intrusion	80	2000

(dh_f) above Mediterranean sea level by mean of Eq. (4) such as

$$dh_f = h_f\,0.04. \tag{4}$$

The key data given in Table 3 enable calculation of the groundwater head in order to draw the profile of the groundwater profile heads for each drainage basis: $H1$ and $H2$. The calculation of a new groundwater drainage basin basis can then be made presuming an SLR of 0.5 m for an area having a topographic seashore slope of 0.001 and an aquifer basis slope of 0.01 (obtained by averaging information from hydrogeological cross-sections of Israel's Coastal aquifer from Tolmach [21]).

The groundwater head profile line, $H1$ is based on two points: one is at groundwater head 0 at distance 0 from the initial seashore location (Fig. 2 and Table 3); the second is at the 3.4 m groundwater head (dh_{f1}), 1500 m from the initial seashore. This 3.4 m value is the groundwater head required to maintain and stabilize seawater intrusion in a steady-state situation at this distance from the seashore. This value is obtained by use of the Ghyben-Hertzberg law of formula (4), where $h_{f1} = h_{s1} = 85$ m (Fig. 2 and Table 3).

For a SLR of 0.5 m, maximum seawater intrusion will reach 2000 m from the initial seashore (Fig. 2 and Table 3). The two points defining the groundwater head profile line H2 are the groundwater head 0, located 500 m from the initial seashore, and groundwater head dh_{f2}, corresponding to $h_{s2} = h_{f2} = 53$ m, at a distance of 1500 m from the initial sea shore. The fresh water height h_{f2} corresponds to the thickness of seawater included between the seawater interface level and the new sea level, estimated by the geometric proportional triangles law. By use of Eq. (4), the groundwater head corresponding to this column of fresh water is equal to 2.1 m. This value determines the second coordinate, enabling location of the second point, and the drawing of groundwater profile line $H2$ (Fig. 2 and Table 3).

To estimate the situation of groundwater after 50 years with and without a rise in seawater level, profiles $H1$ and $H2$ are presented on the same graph as regards their initial coordinates from the seashore and towards the eastern limits of the aquifer (Fig. 7). For 1 km of seashore, the volume of water is estimated by the multiplication of each surface of the triangle formed between groundwater head profiles $H1$ and $H2$, respectively for an aquifer width of 10,000 m ($H1$) and 9500 m ($H2$), by an aquifer porosity of 0.25 for the

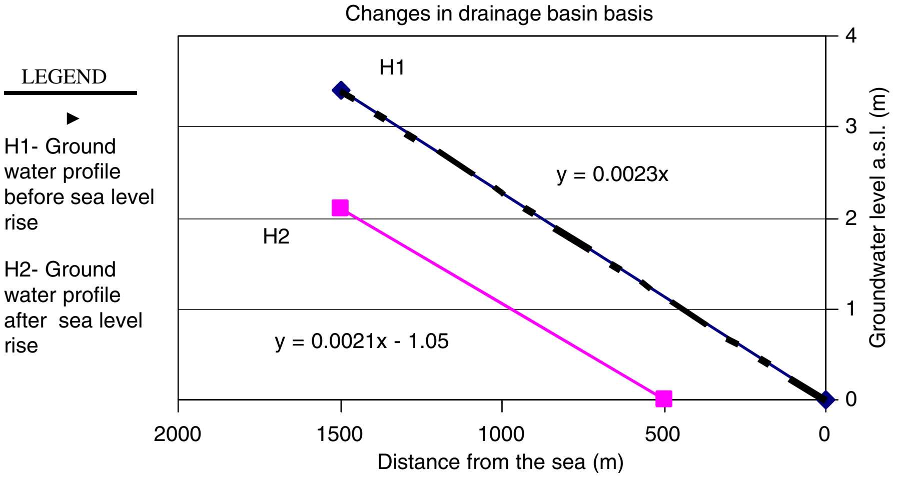

Fig. 7. Groundwater head profiles *H*1 and *H*2 of the two drainage basin bases.

both cases (Fig. 7). The results for profile *H*1 yield a volume of water of 28.7 MCM, and for profile *H*2, a volume of water of 24.9 MCM, the difference between the two profiles being 3.8 MCM (Table 3). Loss of groundwater due to changes in drainage basin basis and groundwater profiles is thus around 3.8 MCM/km of seashore.

4. Discussion

Estimation of permanent loss of storage capacity in Israel's Coastal aquifer for an SLR of 50 cm for 1 km of shoreline having an average topographic slope of 0.01 is given in column 6 of Table 2. The results indicate that the major component of this loss is due to a lateral movement of seawater into the aquifer of approximately 12.5 MCM/km of shoreline. This loss of permanent reserve could prove significantly greater for affected areas located in regions in which heavy pumpage has lead to the development of hydrological cones of depression, in such areas as Hadera, Ramat Gan, Tel Aviv, Holon, Nir 'Am, and the area between Ashdod and Erez Shiqma. In these areas, where water level drawdown has accompanied early warning signs of seawater intrusion, hundreds of millions of cubic meters of drinking water are in danger as a result of further seawater intrusion ([23]; Fig. 3).

The additional component of permanent reserve losses of storage capacity of around 3.8 MCM, focuses upon changes in drainage basin basis and groundwater profiles (from profile *H*1 to *H*2 in Fig. 7 and Table 3. This can be estimated for 1 km of seashore for a cross-section of the aquifer from the seashore to the aquifer's eastern limit, at a distance of around 10 km from the sea as regards the old drainage basin, and 9.5 km when related to the new drainage basin, as noted in Table 3.

When considering the sum of these estimated losses, total losses under conditions of an SLR of 50 cm reach approximately 16.3 MCM/km of seashore. These losses can be more critical when the drought seasons are more frequent, and recharge of the aquifer is less than the multi-annual average.

From the PRL estimate made earlier in this study it would appear that for a rate of SLR of 0.5 m, losses could result due to groundwater head decline as happens in a drought period. Having said that, in the case of drought, such losses could be renovated by recharge during subsequent rainy years or by imported water. By contrast, major losses due to significant lateral seawater intrusion into the aquifer, as well as to the change in drainage basin basis due to SLR cannot be easily rehabilitated. Such losses can be considered permanent and almost irreversible.

These losses can be enhanced or mitigated by other factors. In areas where the degree of consolidation of coastal lithology is low and the seashore is bounded by easily erodible rocks, progressive regression of the shoreline can be amplified by the process of intrusion of seawater into fresh aquifer water. However, areas of Israel's coast built of sandstone cemented by calcification, locally known as "kurkar" ridges, can give rise to steep topographic cliffs along the coastline. The degree of consolidation of cliff lithology at the water line leads to a very slow rate of erosion in such locations. It is more difficult for seawater to undermine these cliffs and advance inland, mitigating the coastal effect of rising sea levels.

Along the length of the coastline, the process of erosion due to SLR can cause shorelines to interface progressively with a variety of lithological components of the coastal aquifer's stratigraphy. As regards Israel's Coastal aquifer, two extreme alternatives may be possible. In one, erosion eats away the more permeable lithological layers, exposing more impervious lithological layers, impeding seawater intrusion into the aquifer, mitigating seawater intrusion (Fig. 8(1)). A second possibility, presented in Fig. 8(2), involves erosion of impervious material, exposing permeable lithological layers. In this case, the aquifer becomes more vulnerable and open to seawater intrusion.

Relatively rapid increase in SLR could result from global warming, leading to future climatic changes with more and stronger floods and storms. Such changes could amplify SLR over short- as well as long-term periods. Seawater could thus rapidly reach inland areas of big cities located in low relief areas, and destroy water resources and other natural coastal resources. This could enhance permanent reserve losses near the seashore in a relatively short time if sufficient measures are not previously taken to protect them. By way of example, this could occur in Israel in the Yarqon stream which flows through Tel Aviv

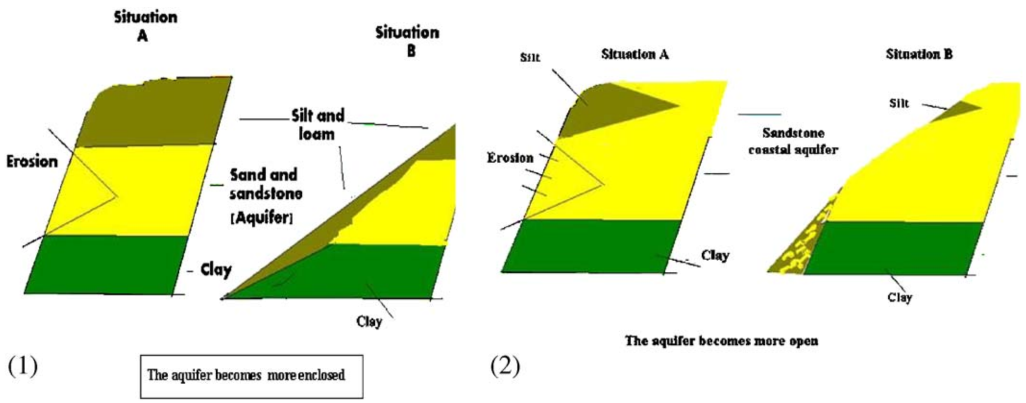

Fig. 8. Changes in lithology of the western Coastal aquifer border with more impervious material: (1) deposits, (2) removal.

(Fig. 4), but also in other deltaic and estuarine stream areas along the Israeli Coastal plain and similar areas in the world, increasing PRL.

Groundwater permanent reserve loss could be affected by extreme events in which a sudden and high amplitude rise of sea level hits continental and islands coasts. An example of this would be tsunamis, the apocalyptic consequences of which occurred in the Indian ocean at the end of 2004. Although not of the intensity of this tsunami, similar events can and have occurred in coastal areas of the Mediterranean Sea, along the coasts of the Greek islands, Lebanon, Egypt, Sicily, and Italy [24]. Such events on a smaller scale than that of a tsunami could occur again along the Mediterranean coast. Both continuous and sudden SLR could significantly impact fresh water resources of coastal aquifers while having additional ancillary effects on shoreline of Israel's coasts in particular and on Mediterranean and other seas and oceans coasts in general.

It ought to be noted that PRL can be considered as water resources virtually completely lost and very difficult to be replaced. It is practically impossible to reverse the process of seawater intrusion. Mitigating factors could overcome the adverse effects due to rising sea level. Realistic preparations must be made to limit seawater intrusion. Long-term water resources planning must therefore take the potential effects which might result from SLR into consideration at the earliest stage.

5. Conclusions and recommendations

The key conclusions and recommendations of this study relate to Israel's Coastal Plain, but could also be applicable to other coastlines around the world. These are:

- High-resolution shoreline mapping (contour mapping of at least 1 m accuracy within a km of the seashore) should be undertaken to delineate critical areas and paths where SLR may lead to significant advance further inland. As regards Israel's Coastal aquifer, such mapping should focus on all coastal areas having gentle topographic slope, such as the deltaic areas as this indicated in Fig. 4. Added emphasis should be placed upon those areas which are foci of significant groundwater pumpage, as well as areas having steep slopes but unstable cliffs, where a rise in sea level could engender lithological changes in the coast.
- SLR must be more accurately measured, and in critical areas, additional well-functioning observation wells should be emplaced along the coast. "Red-lines" of sea levels as well as critical fresh groundwater levels near the seashore ought to be delineated.
- Further preventive engineering measures and facilities ought to be deployed, especially along coasts having gentle slopes, taking into consideration not only erosion but also rate of sedimentation, to mitigate seawater intrusion into the aquifer and prevent hydrological and ecological disaster.
- Efforts ought to be made to prevent further alteration of the water storage basin and significant drops in the amount of available fresh groundwater resources along the coast. In areas where reserves of fresh water stand to be depleted as a result of SLR, alternative fresh water recharge by seawater desalinization and other facilities ought to form part of the long-term sustainable management planning for water resources.
- More sophisticated models ought to be developed to estimate the PRL due to SLR with improved accuracy. This could be a mass balance model that considers both natural and

artificial parameters, volume of water and sediment, global-warming factors, their trends, and their effects on SLR. Such a model ought to include the possible occurrence of severe changes owing to increases in storms and droughts during this period. The ultimate aim of such a model would be to foresee and draw attention to possible losses that might be expected between now and at least the middle of the 21st century.
- Specific efforts must be made to develop early warning signals of risk by use of models whose indices highlight coastal vulnerability to SLR, considering such parameters as coastal landforms, topography, proximity to groundwater resources, wave heights, etc. Such a model has been developed by Gornic [1] for US coasts.
- In order to operationally execute and consolidate these recommendations, the plethora of governmental and private offices currently involved ought to be merged into a single agency. In Israel, as in other areas in the world, this should include personnel from the governmental ministries of Infrastructure, Health, Environmental Quality, Economics, as well as the multitude of engineering, scientific, and economic academic institutes.

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