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ORIGINAL PAPER

A sea surface height control dam at the Strait of Gibraltar

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Abstract Global sea-level rise is now seen as one of the most significant impacts of human-induced climate change and is expected to seriously affect most coastal areas in the next 10–100 years. However, for the coasts of the Mediterranean Sea and Black Sea, a dam on the Strait of Gibraltar would provide long-term protection for at least the next few millennia. The dam would be designed to initially cause a height difference between its two sides of about a metre and allow inflow of Atlantic water to balance net evaporation. In addition to coastal protection, benefits of the dam include providing a land link between Europe and Africa, and power generation. Negative effects include possible large-scale changes in Atlantic Ocean flow, and perhaps climate, a long-term rise in Mediterranean salinity with eventual impacts on fisheries, and the need for shipping to pass through locks both at Gibraltar and Suez. The Mediterranean salinity rise would be slow, causing serious effects only after several centuries. Mitigation, when needed, would require pumping out large volumes of Mediterranean deep water, over or through the dam. The dam would be a major project, requiring international agreements and resources. It will probably not be built soon, but rising sea levels will make a dam ever more necessary, and discussions need to start to quantify costs, benefits and impacts.

Keywords Climate change · Sea-level rise · Strait of Gibraltar · Mediterranean

1 Introduction

Global sea-level rise in the "industrial era" from 1880 to 1980 has been estimated at about 18 cm, or 1.8 mm/year (Douglas 1991). More recent estimates (e.g. Church and White 2006) suggest acceleration over this period to roughly match the 3 mm/year measured

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since 1993 by satellite altimetry (AVISO 2015; NOAA 2015; University of Colorado 2015). The present rise rate is therefore about 30 cm per century. Thirty centimetres may seem manageably small, but the number will grow, since it is driven by anthropogenic carbon emissions (IPCC5 2013). These continue at an increasing rate, in spite of mounting pressure to reduce them. Sea level is therefore expected to rise for many centuries and may also accelerate further as ice melts on Greenland and Antarctica (IPCC5 2013).

Thirty centimetres of sea-level rise may appear manageable on many coasts where the daily range of tides is about an order of magnitude larger. In areas where the tide range is small, such as the Mediterranean Sea and Black Sea, the impact of such a rise will be much more strongly felt (Hallegatte et al. 2013, noting especially Fig. 2). Also, on the longer term, the rise is expected to continue. Committed sea-level rise is estimated at 2.3 m/°C of global warming (Levermann et al. 2013). Since the world is struggling to limit the warming to 2 C, an eventual sea-level rise of at least 5 m must be expected over a period of several centuries.

The world therefore needs to plan for future defences against sea-level rise of several metres. A dam on the Strait of Gibraltar (Fig. 1) would provide long-term protection against sea-level rise to every coastline and coastal city on the Mediterranean Sea and Black Sea. Few other parts of the world have a similar option for protection without the need to pump large volumes of water.

The word "dam" suggests a wall of concrete holding back water with a height difference of many metres. Although the word is used here for brevity, this discussion is of a sea level rise barrage designed to stabilize sea level in the Mediterranean Sea and Black

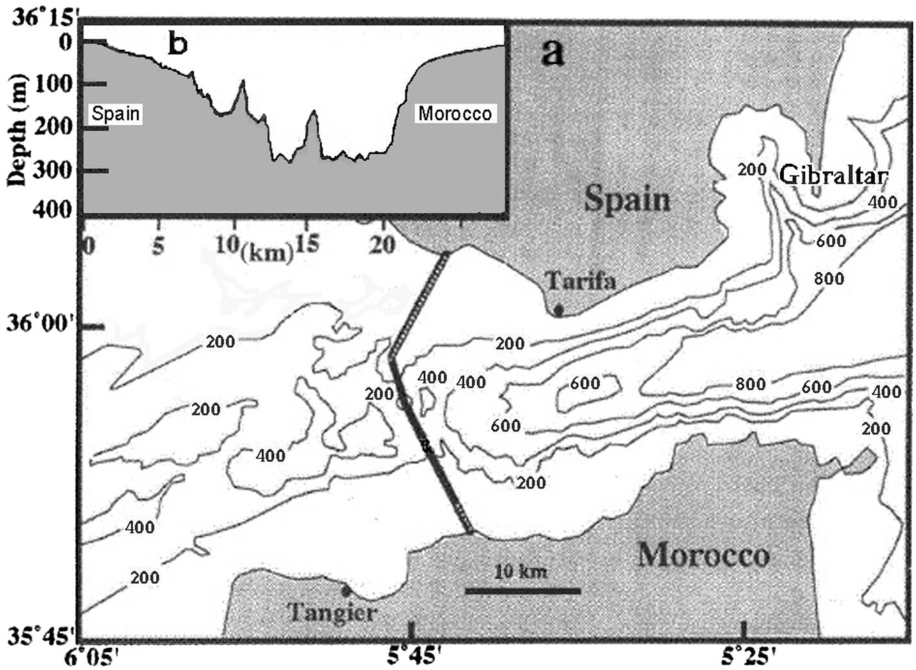

Fig. 1 **a** Map of the Strait of Gibraltar (redrafted from Johnson 1997) showing the position of the dam following the shallowest sill to the west of Gibraltar, with *inset* **b** the depth profile along the dam. At the narrowest section of the Strait, near Tarifa, depths are much larger

Sea, with a relatively minor sea-level difference between its two sides. The design would need to accommodate the fact that height differences could increase significantly in future years.

The idea of a dam in the present case was suggested by a recent report (UNESCO 2012) which concluded that, due to the connection of the Mediterranean to the global ocean through the Strait of Gibraltar, the MOSE project of movable barriers is inadequate to defend the city of Venice on the long term. The report states "the sea will eventually rise to a level where even continuous closures will not be able to protect the city from flooding. The question is not if this will happen, but only when." The conclusion that cities such as Venice are inevitably doomed can have severe implications for even short-term planning. However, the Gibraltar Dam is an alternative, which needs to be at least discussed.

Environmental impacts of the dam need to be carefully assessed. Blocking the deep outflow of salty water from the Mediterranean may affect the global thermohaline circulation enough to impact weather patterns and global climate. The salinity of water in the Mediterranean itself would rise. This rise would have to either be accepted, with serious future consequences for Mediterranean fisheries and water quality, or be mitigated through a major saltwater pumping project at the dam. Such pumping would restart the saltwater outflow. Without pumping, serious effects in the Mediterranean will occur only after several centuries, by which time sea level rise is expected to be a much more urgent problem.

The dam brings benefits beyond flood protection, primarily providing a land link between Spain and Africa. A tunnel under the Strait, proposed for this purpose (SECEGSA 2015; SNED 2015), would follow the same route as the dam, but preliminary drilling has shown problems with the complex geology, and the present design provides for only a single rail line. The dam would provide a safer link with much higher traffic volume. The dam also has potential for generation of electricity, for tourism, and for improved monitoring of Atlantic water inflow.

2 Natural blocking of the Strait of Gibraltar

Pliny the Elder in the first century AD recounted a popular story in his Natural History by which the Mediterranean Sea was created when the Atlantic Ocean gained admission through the Strait of Gibraltar. The idea that the Mediterranean was once dry land has been referred to by many writers since, with increasing evidence from geology, botany and evolutionary biology. It was finally confirmed by drilling missions of the Glomar Challenger in 1970 and 1975 (Hsu 1983). Plate tectonic movement is thought to have closed the Strait about 6 million year ago and most recently reopened it about 5.3 million years ago.

Under present climate conditions, the estimated Mediterranean freshwater deficit (excess of freshwater removed by evaporation, over input by rain and rivers) is about 50 cm/year (Mariotti et al. 2002), so that this is the rate at which Mediterranean Sea level will initially sink if the Strait is blocked and no inflow from the Atlantic is allowed. If this sinking continued, then this deficit would empty the Mediterranean in a few thousand years, depositing its salt in beds which are one of the modern signatures of the past blocking event (the Messinian Salinity Crisis). This event would have raised global sea levels by about 10 m.

The fact that Mediterranean sea level has been much lower than that at present is confirmed by erosion of deep canyons by many Mediterranean rivers, notably the Rhone and Nile, both near the present coast lines and in areas presently far from the sea (for example, the Nile River at Aswan). Canyons are also found in the present deep bed of the Mediterranean, showing that large areas must have dried completely. The evidence is discussed in more detail by Hsu (1983), and the Messinian Salinity Crisis is still a topic of active research.

3 Dam history

A Gibraltar Dam was most famously proposed for the German Atlantropa project of the 1930s (see for example Cathcart 2006, and references therein). This was designed to lower Mediterranean sea level by up to 200 m, provide new land and allow power generation from the resulting inflow at the Strait. Mediterranean Sea and Black Sea area totals about 0.8 % of global ocean area, so lowering the Mediterranean by an average of 150 m results in a global sea-level rise of about 1.2 m, since the evaporated water ends in the ocean. Proponents of Atlantropa did not explain how the world would cope with this rise, and the rise does not seem to be discussed in historical descriptions of the proposal.

The Atlantropa project aimed to provide 1930s Germany with new land, assuming a German-led, united Europe. However, a 200-m sea-level drop would cause a whole new set of problems in the Mediterranean, leaving present coasts high and dry. The Atlantropa proposal included plans to maintain Venice as a coastal city of waterways and lagoons using dams and to connect it to the lower and now-distant Mediterranean by way of a long canal. The present proposal would stabilize sea level, maintaining coast lines in their present position. The Atlantropa proposal included other dams, notably on the Bosporus to generate power from water flowing from the Black Sea. In the present case, no dam would be needed there, since Black Sea and Azov Sea levels would be stabilized along with the Mediterranean.

We note that in the absence of the Gibraltar Dam, the Black Sea does not have as easy an option for long-term protection by a dam at the Bosporus, since the level of a dammed Black Sea will tend to rise, and a large volume of outflowing water would need to be pumped over the dam to maintain a stable Black Sea level. A similar problem would arise for the Baltic. Here a dam would be relatively easy to construct, and many coastal cities could be protected from global sea-level rise if sufficient water were pumped out. However, in many more northern areas of the Baltic, land is still rising after the last ice age, and coasts need little protection.

Two other areas for which dams have also been proposed are the Red Sea and the Persian Gulf. In both cases, the dam would require more rock fill than at Gibraltar, and in both cases the proposals were made with the object of lowering the enclosed sea level by several tens of metres by evaporation and then generating electricity from water inflow through the dam. As with Atlantropa, these projects are unlikely to be popular since they involve a significant decrease in sea level of large bodies of water, with major impacts on many coastal communities and ecosystems. Other options for carbon-free power generation are available through wind, solar or nuclear generation. Nonetheless, building dams to protect against global sea-level rise might still be a good idea for these areas.

In a popular article in the Scientific American, Stommel (1958) presented the "entertaining fantasy" of controlling climate by building a Gibraltar Dam. The article was written at a time when climate change was seen as a possible human activity with the goal of improving the planet for human habitation. Stommel felt that the dam was feasible and that the resulting block of the deep, saltwater outflow from the Mediterranean might lead to a long-term climate change, but he was unable to say whether this would lead to warming or to cooling.

More recently, Johnson (1997) urged damming the Strait of Gibraltar to prevent what he saw as a coming ice age triggered by increased salt outflow due to building of the Aswan Dam on the Nile. There were protests about the publication of the article, since the chain of logic was unverified, and the claimed effects of Mediterranean saltwater outflow appeared exaggerated (Rahmstorf 1998). Johnson planned to limit the increase in Mediterranean salinity by leaving a gap in the barrage. The reduced water exchange through the Strait would then lead to a reduction in salt outflow for several centuries, but then to an equilibrium with higher Mediterranean salinity, and the same eventual salt outflow as before the dam was constructed.

Now that warming and a rising global sea level are seen as a continually increasing danger, there is a much clearer need for such a dam, and it is important to study the idea for one of the few places where a long-term, large-scale defence against sea-level rise is practical.

4 Flow control

At present, the net inward flow of water from the Atlantic at Gibraltar balances the water loss due to the excess of evaporation over river and rain inflow. This net flow amounts to about 1200 km^3/year, 40,000 m^3/s or 0.04 Sverdrups. The exchange flow is much larger. The present near-surface flow inwards is about 1 Sverdrup, (1,000,000 m^3/s), which is almost balanced by a deep, outward flow driven by the higher density of water in the Mediterranean compared with the Atlantic. A dam would block this deep outflow and cut the near-surface inflow from 1,000,000 to 40,000 m^3/s.

The dam could be designed to allow surface flow into the Mediterranean with an average 30-cm sea-level drop from present sea level. However, the dam will not be built in the next 10 years, and probably not in the next 50, by which time global sea level will have risen appreciably. For discussion here, an average 1-m drop across the dam is assumed from the Atlantic, down to the Mediterranean.

If the channel for water flow over the dam is designed to be 20 m deep, then the Froude number is equal to one at a flow rate of 14 m/s. The kinetic energy from the potential energy of water dropping 1 m implies movement at 4.4 m/s, so that the flow would be subcritical for this level difference. The channel width for the flow would therefore need to be a total of about 450 m, perhaps consisting of nine 50-m-wide channels. These flow channels could easily be bridged by a road or rail link and could be harnessed later for power generation when height differences are larger. Tides at Tangier just outside the Strait have a range of about 2 m peak to peak, while tides in the Mediterranean are much smaller. A mean height difference of 1 m would therefore increase to near 2 m at high tide (giving currents of about 7 m/s) and reduce to nothing at low. Such flows would allow passage for migration of whales and fish.

The average flow required to maintain a constant Mediterranean level is expected to vary interannually, and on the longer term as climate changes. A suitable flow control system needs to be designed, probably using gates that can be raised and lowered. Only the long-term average flow is important for maintaining sea level, so that a rapid response in flow control at the dam is not required. Any system for siphoning or pumping out deep salty water (see below) allows for additional control. The height control systems need to be secure enough to prevent disasters due to a breach in the dam. Additional reinforcements may need to be added as the water height difference across the dam increases.

5 Effects on deep Atlantic circulation

Oceanographic effects of the dam outside the Mediterranean need study. The deep outflow of salty water from the Mediterranean would be blocked unless deep Mediterranean water was artificially pumped into the Atlantic. Bryden and Kinder (1991) suggested that outflow through the Strait has "profound effects on the global thermohaline circulation" and recommended that it should be regularly monitored. In contrast, Rahmstorf (1998) stated that "the outflow of Mediterranean water has a small but noticeable effect on the circulation and climate of the North Atlantic," and suggested only minor impacts if this flow was stopped. The question needs more study. As global ocean and climate models become more sophisticated and of higher spatial resolution, the effects of the dam can be more precisely assessed. Global ocean models need to be run with and without the dam, so that the resulting impacts and their evolution with time can be studied.

6 Mediterranean salinity increase

Without control measures, Mediterranean salinity would tend to increase. The Mediterranean shows an excess of evaporation over the combination of precipitation and river flow, as noted above. Since only freshwater is removed, the main effect of replacing the 1200 km^3/year deficit with salty (37 psu, or parts per thousand) Atlantic water will be to increase average Mediterranean sea water salinity by about 0.01 psu per year (Mediterranean and Black Sea total volume is 4,250,000 km^3), or 1 psu every 100 years.

The increase in Mediterranean salinity will lead to an equivalent smaller reduction in global ocean salinities, as occurred in the Messinian Salinity Crisis. Total ocean volume is 1.34 billion km^3, so the Mediterranean contains 0.3 % of the total volume. A 1-psu rise in Mediterranean salinity will therefore result in a 0.003-psu drop in global salinity.

We need to understand and quantify the long-term effects of the salinity rise in the Mediterranean. If a 5-psu rise in Mediterranean salinity is acceptable, then we have 500 years before this value is reached, and time to plan responses. Any attempt to reduce the salinity rise by pumping at the dam requires a significant increase in flow rates through the dam, since the deep salty water pumped out will also need to be replaced with Atlantic surface water. As the deep water becomes saltier, less of it will need to be pumped out over or through the dam to balance the salt flux inwards, but the required flows are still large.

One can imagine a tunnel under the dam to allow some natural outflow of salty bottom water when the density difference becomes sufficient to drive this against the pressure due to the 1-m proposed head. Such a passive tunnel would need to be large and would need to be closed at first to allow the height difference across the dam to build. At 280 m depth, a Mediterranean average salinity of 41 psu would be enough to balance a 1-m height difference against Atlantic water at 37 psu. A salinity of 45 psu would provide a 1-m head to drive flow the other way at this depth. Greater height differences due to future sea-level rise would need higher Mediterranean salinity to drive outflow. Such a tunnel would probably be hard to service and maintain. Some form of siphon or pumping would seem to be an easier option.

Siphons would consist of large-diameter pipes, one to two kilometres long, linking deep water on the two sides of the dam and coming to near the surface at the top of the dam. Pressure differences would be the same as for the tunnel and could drive some outwards flow, but pumping would probably also be needed. Pumping would allow the pipes to be much shorter and could be largely powered by electricity generated at the dam itself. Supplemental solar power from the Sahara could also be used. We should have 500 years to work out the details, but it is clear that some increase in Mediterranean salinity will have to be accepted.

If left unchecked, the salinity will continue to rise at about 0.01 psu per year. High salinity has significant effects on fish at present levels, with major harm by about 50 psu. These effects need to be quantified. If the increase is allowed to continue, then in about 1000–2000 years we should expect much of the Mediterranean to be devoid of natural fish populations.

There is also concern that ventilation (oxygen inflow to deeper water) would be reduced by higher salinities. At present, oxygen is carried to deep waters when high-salinity surface water cools and sinks. The effect of future climate change on this process has been studied by Hermann et al. (2008). They concluded that increased stratification would reduce deep oxygenation. Inflow of Atlantic water at the surface over deeper, higher-salinity Mediterranean water might increase stratification, but this is unclear.

There is clear evidence from layers of "sapropels" (from the Greek, sapros pelos, or stinky mud) in Mediterranean sediments that deep oxygenation has been interrupted in the past, most recently 8000–10,000 years ago, making deep waters anoxic. These interruptions are ascribed to heavier rainfall, leading to lower-salinity surface water in the Mediterranean, which prevents high-oxygen surface water from mixing to the bottom (Rossignol-Strick et al. 1982; Ruddiman 2008). Numerical modelling is required to study the effect of the dam on deep water formation.

It has been suggested that the slow, but eventually significant, drawdown of global salinity by accumulation of salt in the Mediterranean might have a cooling effect on earth's climate through allowing sea ice to form more easily. This might be a distant, long-term benefit of the Gibraltar Dam, should it last that long, but this link is questioned.

7 Effects on shipping

Locks will be required at both Gibraltar and Suez where the present canal has none. This will increase transit times for shipping. Any slowdown, either at Suez or at Gibraltar, will reduce the competitive position of the Suez Canal with respect to the Panama Canal (and in the near future possibly also the proposed Canal in Nicaragua) for shipping between East Asia and Europe.

On the other hand, the locks on the Suez Canal would have the positive effect of blocking the influx of invasive species. This influx has increased significantly as the canal has been widened and deepened, removing the block previously provided by the Bitter Lakes (Galil 2009). Locks at Suez could be installed in both the south and north sections of the canal to allow the Bitter Lakes to return to the higher salinity that previously blocked species invasions.

For redundancy, Gibraltar locks would probably be constructed at both the Spanish and Moroccan coasts. They would need to handle today's traffic of 120–150 major vessels per day, plus smaller boats and any future traffic increase. Some of the traffic presently recorded through the Strait is of passengers and trade between Spain and Morocco (or Europe and Africa), which would be replaced by the land link afforded by the dam.

The locks would affect military traffic, but the impact would apply to all countries impartially, and it is not clear whether the net effect on global security is negative or positive. Nuclear submarines may still, at the present time, transit the Strait submerged as part of their "stealth" missions, and their passage would become known as they passed through the locks. Again, this may be a net benefit.

8 Cost of the dam

The Strait of Gibraltar is 14 km wide, but at this narrowest point the depth is over 600 m (Fig. 1). Such a depth requires a very large volume of rock fill, assuming the dam will be built by dumping loose rock. A more practical site for a dam is about 15 km further west, where the length is increased to about 25 km, but where maximum depth is reduced to 284 m (Bryden and Kinder 1991). The dam would still be a major project, but could use local rock transported only a relatively short distance on land and brought to the dam site by ships designed to drop the rock onto the dam as it grows underwater. The dam would not need to withstand a large head of water pressure, though as global sea level rises, and this would increase to a few metres of water in future centuries. The resulting loose rock structure might be slightly permeable at first, but could easily be filled with finer material and will tend to solidify naturally by marine fouling.

Cost estimates for a Gibraltar Strait dam do not seem to be available. Stommel (1958) noted that the dam would need "only about ten times the fill needed to build the Fort Peck Dam in Montana." Wikipedia (http://en.wikipedia.org/wiki/Fort_Peck_Dam) gives the amount of fill for that dam as 0.1 cubic km and the cost as $100 million in 1940. Stommel's factor 10 then gives 1 cubic km and a cost of $1 billion (in 1940 dollars) for Gibraltar. Inflation increases the cost by 25–50 times for construction today. Johnson (1997) shows a map of the dam site and estimates that it would require about 1.3 cubic km of rock material for an angle of repose (downward slope of the rock surface) of 30°, as commonly used for dams holding back reservoirs on land. If the sea bottom of the Strait was assumed to slope uniformly down to its 284 m maximum depth at the centre, and then uniformly back up to the other side, then it is simple to calculate volume for a dam length of 22.3 km (the equivalent length for a best fit of a triangle to the actual profile, as suggested by Bryden and Kinder, Fig. 3), angle of repose of 30°, 100 m width of the top of the dam and an added 10 m of height above sea level to protect against high tides and storm surges. This gives 1.23 cubic km, similar to Johnson's estimate.

Annual world coal production is about 2.5 cubic km (8 billion tons), for example, so the Gibraltar Dam is not beyond imagination. A reasonable guess for cost of mining, transporting and dumping bulk rock might be $10 per ton, giving a total cost of about $35 billion. Alternative cost estimates are available from open-pit mining. For example, the Chuquicamata copper mine in northern Chile has a pit 4.3 by 3 km across and 900 m deep, with a volume of about 3 cubic km, or twice what is required for the dam. This also gives a cost estimate, since from this pit thirty million tons of copper have been extracted, worth $60 billion at an average price of $1 per pound. This sum paid for excavation of twice the rock needed for the dam, plus crushing and processing, and all access and infrastructure costs for a remote site.

The dam would need to be designed to be stable in the event of at least moderate earthquakes. An angle of repose of 30° was proposed for a Gibraltar Dam by Johnson (1997). If smaller angles of repose are required to increase dam stability, then, using the above simplified calculation, the volume of rock increases to 1.45 cubic km at 25° and 1.78 cubic km at 20°. This increases the cost, but less than proportionately if construction infrastructure is already in place.

Based on these numbers, plus rough estimates for other required construction, the cost of the dam is on the order of $50 billion. Clearly, this number could be better defined with further study. Movement of large amounts of rock by special trucks, conveyor systems and ships can be made very efficient, which might reduce the total. The price could also be reduced substantially if the project were to fit with a government "make work" project, or linked to road and rail transport between Europe and Africa.

9 Benefits of the dam

Use of the dam to provide a land link between Europe and Africa could be a major, perhaps dominant benefit. The danger of illegal immigration over the dam is obvious but manageable. A rail link between Spain and Morocco has been proposed (http://en.wikipedia.org/wiki/Strait_of_Gibraltar_crossing; SECEGSA 2015; SNED 2015) but seems to be progressing very slowly, if at all. Last reported activity was in 2007, with a suggested completion date of 2025. The proposal takes the form of a deep rail tunnel, at present with a single track. A bridge option is also being considered. Local tectonic activity due to the Azores–Gibraltar transform fault is a severe problem, especially for the tunnel, but the dam would make a surface rail and road link possible. The dam would also cross this fault. This could be a severe problem for a solid concrete dam, but should be less significant for a loose rock structure.

The water height difference across the dam will be small at first, but the amount of electric power that could be generated at Gibraltar could still be significant, since the flow of water needed to stabilize sea level in the Mediterranean is large. Once the large volume of rock is in place to defend against present global sea level, only a relatively small increase is required to raise the height for future increases. The potential energy loss from 40,000 tons of water per second dropping 1 m is about 400 MW. If converted to electricity at 60 % efficiency, this could be worth $12,000/h at 5 c/kW h, or $100 million per year. This value would increase in future years as global sea level rises above the Mediterranean.

Several aspects of the dam would provide opportunities for tourism, including the locks, the spillways and the length of the dam itself on both the Atlantic and Mediterranean sides. The dam will also allow much more precise monitoring of Atlantic water inflow and hence of the water cycle of the Mediterranean basin.

10 Costs of other options

The alternative to the dam is to defend Mediterranean and Black Sea coastline locally. Costs can be high in some areas, as for the $7 billion already spent on the MOSE project for Venice. A local engineer, speaking in Western Canada of coastal defences needed today, estimated a cost of $5000 per metre of coastline for basic reinforcement. This would give $250 billion as the cost of defending the entire 50,000 km of Mediterranean coastline, which is an upper limit for the length that requires defending, but a lower limit for the long-term cost as sea level continues rising above 1 m. Also, rock walls of the type used in this work usually seriously reduce the beauty of coasts. The Gibraltar Dam has the clear advantage of maintaining the Mediterranean near or slightly below its present level, with all its natural beauty and present infrastructure intact.

Nicolls (2010), discussing estimates of potential damage and defence costs for sea-level rise, quotes estimates of $500 and $1000 billion for global defence against a 1-m sea-level rise. These numbers suggest costs of $700 and $1400/m for the total 356,000 km of global coastline, implying $70 and $140 billion for the Mediterranean Sea and Black Sea. A more recent assessment (Hinkel et al. 2014) suggests larger costs. Thus the dam is a viable option even with only a 1-m rise, and even without considering aesthetic advantages. Larger rises, implying proportionately higher costs, improve the viability of the dam. Full impact assessments are needed, with and without the dam.

11 Removing the dam

A common comment on the dam is the risk of it breaking. If Mediterranean sea level was significantly lower than the level of global ocean, then the dam would need to provide reliable protection, and any damage from storms, or slumping due to earthquakes or slow tectonic motion, would need to be repaired. In fact though, the main body of the dam might well prove to be extremely stable, and a more worrying question should be, “how easily can the dam be removed if its net benefit becomes, or is found to be, negative?”

This requires an economic as well as an engineering study. Once the dam is in place and a land link established, the expected growth in associated infrastructure and trade patterns would bring pressure to maintain the dam. Still, environmental damage might be found to dominate. Since we are discussing dismantling at a date far in the future, we should expect advanced technology, perhaps in the form of a fleet of autonomous underwater vehicles loading rock onto deep cargo slings which would be ferried for dumping in deeper water.

If removal of sea-level protection could be tolerated, then a free flow of surface water could be allowed by opening a relatively small break in the top of the dam. This would restore uninterrupted shipping and could be bridged to allow the land link to continue. If the lack of saline outflow from the Mediterranean was found to lead to a net negative effect on Atlantic circulation or weather patterns, then a larger break could be made, say down to a depth of about 200 m to allow deep water outflow, which could still be bridged. Such a break would restore the net flux of salt out of the Mediterranean to the value before dam construction, but would maintain a higher salinity in Mediterranean deep water. If the present-day salinity of Mediterranean deep water needed to be restored, then a greater volume of the dam would need to be removed. The studies of Farmer and Armi (1986), Garrett et al. (1990) and Bryden and Kinder (1991) show that the depth profile of the Strait determines the salinity exchange, and this profile would need to be more closely restored.

12 Discussion

At present, it seems quite possible that this project will join the list of ideas which are discussed, resisted, discarded and rediscussed as priorities change and new options are discovered. It may be seen as another example of human meddling with nature. However, meddling is ongoing though increasing global carbon emissions, and action is now needed to deal with the consequences. Developing countries are expanding both their economies and their energy consumptions, and emissions are therefore expected to grow, implying a sea-level rise at the high end of the range of future estimates.

Any drop in Mediterranean sea level implies a rise in the global average level. Since Mediterranean Sea and Black Sea together represent about 0.8 % of global ocean area, a drop of 1 m in Mediterranean sea level would result in an 8-mm rise in global sea level. This might be hard for non-Mediterranean nations to accept. They might also object to the 0.8 % extra rate of rise that they would experience with the dam in place and the Mediterranean level stabilized. This would seem a less reasonable objection, since any prevention of coastal flooding must cause some increase in sea-level elsewhere. If world opinion allows Mediterranean countries to defend themselves with a dam, but not to lower the level of the Mediterranean below its level at the time the dam is built, then there is a major incentive to build the dam soon.

The dam aims to defend coastlines, but affects a major body of water. In fact the Mediterranean has about 15 % of the world's coastline and only 0.8 % of its area. The large ratio of these numbers therefore indicates a high "coastline effectiveness".

13 Conclusions

Many major coastal cities now have plans for defence against rising sea levels. One can easily imagine the world of 2100 in which all coastlines are altered by heavy reinforcement, except in the Mediterranean Sea and Black Sea, where protection is provided by the Gibraltar Dam. Here the historic coastlines would be preserved intact, emphasizing this area's value as a heartland of human cultural heritage.

As sea levels continue to rise, the need for the dam will become more obvious. There is a high probability that the dam will be built within a 50-year time frame. Possible future existence of a dam has a significant effect on present long-term planning for Mediterranean and Black Sea coasts. Discussions and studies on the impacts need to be started now.

The dam could also provide a high-volume trade link between Europe and North Africa, which would help to balance the living standards between these two areas. This would reduce the flow of migrants out of North Africa and the present resulting death toll by drowning in the Mediterranean. Benefits through tourism, power generation and flow monitoring could also be significant.

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