SAND DUNE FIXATION: A SOLAR-POWERED SAHARA SEAWATER PIPELINE MACROPROJECT

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ABSTRACT

The paper proposes macro-engineering using tactical technologies that stabilize and vegetate barren near-coast sand dune fields with seawater. Seawater that would otherwise, as commonly postulated, increase the Earth–ocean volume. Anthropogenic saturation of the ground with pumped seawater should fix widespread active sand dune fields in deserts (such as the westernmost Sahara). Seawater extraction from the ocean, and its deposition on dune sand, is made via solar-powered pipeline. Stabilisation of one major erg in Mauritania is evaluated as a case study. The financial cost of the macroproject is estimated as a few billion US$—less than about 0.1 per cent of the USA’s 2007 gross domestic product. The initial investment may be between 0.6 and 1.1 billions US$. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: sand dune fixation; erg; seawater agriculture; Mauritania

INTRODUCTION

Large active sand dune fields are found, generally, in Earth’s desert regions—‘hot deserts’ cover ~14.2 per cent of Earth’s land (Peel et al., 2007). Some ergologists suspect that ‘global desertification’ (a persistent decline of ecosystems’ benefits for humans—loss of utility or potential utility—in already dry regions) is occurring and will increase as the 21st century unfolds (Yizhyaq et al., 2007). ‘Drylands cover about 41 per cent of Earth’s land surface and are home to more than 38 per cent of the total global population of 6.5 billion’ (Reynolds et al., 2007). Here, however, we focus only on certain active sand dune fields located in the northern Africa coastal nation of Mauritania (World Factbook, 2007) where few people live and work today (Niang et al., 2008).

Mauritania’s sand dune fields are well-developed depositional landforms of increasingly better known accumulation history (Lancaster et al., 2002; Martinez and Psuty, 2008). They contain a large volume of wind-blown sediment and are situated at three major depositional physiographic sites: (1) Akchar; (2) Aouker and (3) Majabat al Koubra, the farthest inland (Figure 1). The active sand dune fields of Mauritania exist in a region that receives <150 mm of precipitation per year. According to psammology, dune sand is an inert ‘soil’ without any positive characteristics for flora due to its coarse particles and big pore spaces that do not retain water for plant growth, the high permeability and leaching that removes plant nutrient elements, and the wind erodibility of sand. Wind erosion is the main land degradation process since plant nutrient particles are removed by saltation (Goudie, 2008); eroded mineral components increase sand dune instability (Yair and Verrecchia, 2002).

Aeolian movement of surface sand grains and other dry granular media can be reduced or stopped by the application of chemical stabilisers such as ‘Nano Clay’ (Desert Control, 2007) or ‘Biochar’ (Lehmann, 2007), installation of fences to trap windblown sand grains, and planted vegetation to prevent sand grain deflation. The
present-day and future movement of sand dunes, ground surface erosion of drought-reduced lakes (White and Mattingly, 2006) and accumulation of mineral dust clouds, including halite and other salts, challenge macro-engineering practice as well as seriously affect the lives and life styles of people downwind from major active and inactive dune fields (Thomas et al., 2005). So far, macro-engineering has only a few field-tested techniques to geographically fix contemporaneous migratory sand dunes: (1) remove the sand mechanically; (2) disperse the sand by mechanical reshaping and (3) immobilise the sand dunes with planted vegetation (Duran and Herrmann, 2006), fences, trenches, additives and other means. Such macroprojects, of course, involve nature’s further domestication by humans (Kareiva et al., 2007). Landscape rehabilitation is based on ecological planning and design that comprehensively examines degradational event processes caused by climate alterations and biodiversity changes; every landscape rehabilitation undertaking must be judged in the context of its unique geographical, economic, temporal, cultural and directly relevant environmental context.

Bodele depression (Engelstaedter and Washington, 2007) in Chad is Earth’s largest single source of atmospheric mineral dust; Mauritania’s eastern drylands and desert is Africa’s second largest source of mineral dust. The mineral dust clouds emanating from northern Africa, triggered when near-surface boundary layer wind speeds are $>10$ m s$^{-1}$, quickly change the Earth’s albedo and can strongly suppress eastern North Atlantic Ocean hurricane formation (Evan et al., 2006). In other words, the Sahara’s uncontrolled or mitigated mineral dust storms do have major consequences for humans (Goudie and Middleton, 2001). If mineral dust clouds were eliminated technologically, then northern Africa might become a well-vegetated region. Vegetated regions have greater dust deposition as a consequence of the filtering effect of the aerial plant parts (reduction of drag forces). Deposition of mineral particles by any natural or unnatural process also contributes to stabilisation of sand dunes. Summarising, we propose to foster plant growth—both wild and cultivated species—on the sandy dunal surfaces of Mauritania,

Figure 1. The major ergs of the Sahara. 1, Grand Erg Occidental; 2, Grand Erg Oriental; 3, Ubari; 4, Murzuk; 5, Calanscio; 6, Great Sand Sea; 7, Selima; 8, Fachi-Bilma and Ténéré; 9, Majabat al Koubra; 10, Aouker; 11, Akchar; 12, Iguidi; 13, Chech. Adapted from Figure 4 of Ba et al. (2001).
and eventually Chad and Libya, by the land’s intensive irrigation with pumped seawater. The seawater withdrawal from the world’s ocean would also serve to induce a (measurable but modest) lowering of global sea level to prevent a worldwide ‘rising sea level crisis’ as suggested by James E. Hansen and many other experts.

THE ACTIVE SAND DUNE FIELD MACRO-PROBLEM

Under natural circumstances, a tenfold reduction in aeolian sand migration can be induced by a mere 3 per cent moisture increase and the deposition of sea-spray halite particles on subaerial seashore dune sand increases the angle of repose of coastal sand dunes (Jackson and Nordstrom, 1998). Injection water seepage effects on the lee-side slope of sand dunes generally acts to reduce the angle of repose while water suction acts generally to increase the angle of repose (Lu and Chiew, 2007). Nowadays, it is well known that sand saturated with hypersaline solutions does retain more moisture than sand saturated with moderately and slightly hypersaline solutions.

Sand moves by creep, saltation and aerial suspension. Seawater regularly sprinkled onto the surface of mobile sand dunes would deposit minerals in the space between granular materials, especially after the freshwater is evaporated during the daytime (Table I). In the future, one could imagine that this surface-deposited particulate material may be harvested from the topmost crust of artificially stabilised sand dunes by specialised commercial-scale mineral harvesting machines. (Modified for desert use and equipped with wider tyres, Caterpillar 657E Wheel Tractor Scrapers might suffice.) After evaporation, the mineral-rich layer and/or encrustation will contain many useful materials and its mining could obviate some current ‘polluting’ mine excavation and processing operations (Wang et al., 2007). Re-irrigation with imported seawater would simply restock the mining region and continue the effort towards sand dune immobilisation. The irrigation potential for Mauratania using renewable freshwater resources is considered negligible (FAO, 1997); sand dune seawater sprays, immitating nature’s strand sea spray, are a new form of irrigation but for the single purpose of mining seawater elements (Walker et al., 2006). In a sense, one could mine an artificial ‘ore’ emplaced during a very short period of time. Instead of industrialised ‘solar ponds’, people in Mauritania would be harvesting valuable minerals from ‘solar dunes’.

STABILISATION OF SAND DUNES IN MAURITANIA

Mauritania is mostly desert—it is constantly hot, dry and dusty and mostly barren, with flat western Sahara plains [elevation extremes: lowest place is Sebkhet Te-n-Dghamcha (~5 m), highest place is Kediet Ijill (915 m)] and a vast encroaching sand dune field that now threatens to inundate the nation’s post-1960 capital of Nouakchott (18°07’ North Lat. by 15°05’ W Long.). The 10 000 ha urban region, with a population of >700 000, is situated on a reddish-coloured sand dune field (Chenal and Kaufmann, 2007). The average solar insolation level for Nouakchott is approximately 6.55 kWh m\(^{-2}\) day\(^{-1}\).
Mauritania’s human population of ~3-1 millions is distributed very discontiguously over an area of 1.03 million km²; most persons are concentrated in the near-sea level capital, a seaport since 1987, in the seaport of Nouadhdibou and along the Senegal River in the southern part of Mauritania. Nouakchott may, in the near-term future, have some of its below sea level strand region submerged by adjacent ocean water influx owing to significant post-construction erosion south of the new deepwater harbour jetty (Elmoustapha et al., 2007). Mauritania’s territory includes approximately 25 per cent of the Senegal River basin (~75 500 km²). Mauritania and Senegal are the only two countries in northern Africa with all their agricultural production located within drylands. Freshwater is so valuable a commodity to those nations sharing the Senegal River’s surface runoff that only ~3 per cent of the river’s outflow ever reaches the North Atlantic Ocean. Constructed in the Senegal River delta by 1986, the Diama Dam blocks tidal or storm surge seawater intrusions upriver. Less than 50 000 ha of Mauritania’s land is irrigated with freshwater. Of a total annual production of 191 million kWh, only 14 per cent of Mauritania’s electricity production derives from hydropower while 86 per cent is manufactured from fossil fuel combustion.

Mauritania is seriously affected by sand dune migration. For instance, desert sands invaded the ancient city of Chinguetti and homes on the edge of the settlement were abandoned (see Figure 2 of Berger (2006)). This is a rather common present-day situation (Figure 2).

THE SOLAR-POWERED SAHARA SEAWATER PIPELINE (SSSP)

Flexible solar power assemblies include a flexible photovoltaic device attached to a flexible thermal solar collector (Hamakawa, 2005; Kurokawa et al., 2007; Leon et al., 2007). Our macroproject invokes a seawater pipeline-integrated photovoltaic flexible solar power module or membrane that will not ever—or, at least, for a period of tens of years—debond under very harsh desert conditions of sunshine and windblown particle abrasion. The pliable photovoltaic coating will need to cover part of the upper hemisphere of the (steel, plastic, concrete or other material) pipe, which is the basic support structure for the proposed electricity-generation system.

We noticed the map in Figure 1 of Sakurai and Sakurai (1992) devoted to irrigation of arid zones really seemed, fortuitously, to resemble northern Africa and, in particular, Mauritania. The identity of shape can be compared with Schluter (2006). The Sakurai’s placement of the inland artificial lake seems even to represent Mauritania’s world-famous 38 km-wide ‘Richat Structure’ (21°04’ N Lat. by 11°22’ W Long.), with a central depth elevation of 400 m and surrounding walls nearly 100 m higher. The Richat Structure exposes a flat-lying limestone in the Maur Adrar Desert (Matton et al., 2005). The Richat Structure sits at an elevation of nearly 600 m, yet the centre part of the crater-shaped geomorphologic feature is ~400 m above present-day sea level. For maximum use as a seawater pool, it may be necessary to build a small dam on the Richat Structure’s southwestern edge.
Roger H. Charlier, during 1991, suggested a route for a freshwater-carrying steel or concrete pipeline starting from the seaport of Nouakchott, which currently depends entirely on a single inadequate groundwater resource, and heading eastward into the Sahara, finally changing direction to meet Libya (Charlier, 1991) (Figure 3).

We propose to utilise (in part) the same route for the SSSP—that is from the Capital Nouakchott to Tidjikdya (18°27' N Lat. by −11°27' W Long.) the distance is ~ 486 km while we would build a seawater conveying pipeline section leaving Tidjikdya and ending near Ouadane (20°51' N Lat. by 11°37' W Long.), a distance of ~ 265 km. Such a routing would allow use of the Richat Structure as a pooled seawater resource base from which other agricultural and industrial activities may be carried out in accord with the Sakurai’s patented suggestions. Whether the Sakurai’s knew it or not, this facility will not contaminate the fresh groundwater held in the ‘Continental Terminal’ formation first discovered in 1931 (Kogbe and Dubois, 1980). Therefore, construction and operation of the SSSP will not require the authoritative allocation of values in global society with respect to either freshwater or seawater (international hydropolitics).

Deserts seem likely to become prominent landscape features in the near-term future. Of course, if there is a revolutionary technical improvement in solar photovoltaic cell technology, then less land would have to be dedicated to electricity generation (Schaller et al., 2006; Mahowald, 2007).
In the proposed solar-powered Sahara seawater pipe case, we assume the use of reinforced concrete or steel pipes/tubes. The presumed big hydraulic pipeline (with a large tube diameter) is expensive but such a tube has the advantage of decreasing greatly the pressure loss and increases significantly the efficiency. The SSSP pipes/tubes may have high interior pressure so they must be composed of steel or something even stronger—perhaps from some 21st century-invented composite fibre material. The absence of metals would, of course, mean the absence of rusting and, perhaps, reduced interior fouling. Such composed material has higher maximum stress (up to 600 kg mm$^{-2}$, steel has only $\sim$120 kg mm$^{-2}$) and low specific-density ($\sim$1800 kg mm$^{-3}$, steel is $\sim$7900 kg mm$^{-3}$). Due to expected manufacturing efficiencies, it may be, or become, cheaper quite soon during the 21st century. In other words, no particular materials or techniques will need to be specially developed for the SSSP because we simply orchestrate the extant panoply of macro-engineering’s techniques, weaving them around particular geographical and social conditions, to create a twin-goal macroproject which, in its numerous ramifications, raises a somewhat grand vision.

**CASE STUDY**

*Dune Stabilisation Macroproject*

As an example, here we quantify the stabilisation of the dunes on erg Akchar, which is one of the three major ergs of Mauritania (see Figure 1) (Ba et al., 2001). The erg surface is about $S_{\text{erg}} = 300 \times 300 = 9 \times 10^4$ km$^2$ = 9 x 10$^6$ ha. The distance from the ocean to the middle of erg Akchar is approximated to $L_{\text{duct}} = 150$ km, which is also the design value of the duct length accepted here. To estimate the mean altitude of the erg's dunes we used topographic data for the geographic zone 18–22°N latitude and 15–10°W longitude. We used digitised data downloaded from the Global Topography project (Smith and Sandwell, 1997) (Figure 4). The mean altitude of the erg we obtained by numerically processing the topography data is $H_{\text{erg}} = 279$ m.

The total volume of seawater $Q_{\text{sw}}$ necessary to stabilise the erg’s sand dunes is given by

$$Q_{\text{sw}} = S_{\text{erg}} q_1$$

where $q_1$ is the amount of water necessary to stabilise a unit erg surface. Here, we accept $q_1 \equiv 0.5$ m$^3$ water m$^{-2}$ dune surface. Now we assume the dune stabilisation macroproject will be completed in $N$ years. A uniform (in time) seawater flow rate $q_{\text{sw}}$ is assumed. Then, in the volumic flow rate in cubic metre per second is

$$q_{\text{sw}} = \frac{Q_{\text{sw}}}{365 \times N \times 24 \times 3600}$$

Figure 4. Geographical location and topography of erg Akchar.
SAND DUNE FIXATION

The speed $w_{sw}$ of seawater in the duct of diameter $D_{duct}$ is given by

$$w_{sw} = \frac{4q_{sw}}{\pi D_{duct}^2}$$

(3)

The power $P_{pump}$ required to move the seawater in the duct is obtained from

$$P_{pump} = g\rho_{sw}q_{sw}H/\eta_p$$

(4)

In Equation (4), $g = 9.78 \text{ m s}^{-2}$ is gravitational acceleration, $\rho_{sw} = 1030 \text{ kg m}^{-3}$ is seawater’s mass density, $H$ is the hydraulic head and $\eta_p \approx 0.75$ is the efficiency of the pump. The hydraulic head is obtained by summing the mean height of the erg with the lost pressure height $\Delta H$ due to friction

$$H = H_{erg} + \Delta H$$

(5)

Only linear pressure losses are considered next and

$$\Delta H = \lambda \frac{L_{duct} w_{sw}^2}{D_{duct} 2g}$$

(6)

where $\lambda$ is the linear pressure loss coefficient given by

$$\lambda = \begin{cases} \frac{1}{\sqrt{100\text{Re}}} & \text{for Re } < 10^5 \\ 0.0032 + \frac{0.211}{\text{Re}^{0.237}} & \text{for Re } > 10^5 \end{cases}$$

(7)

where the Reynolds number is defined by

$$\text{Re} = \frac{w_{sw}D_{duct}}{v_{sw}}$$

(8)

where $v_{sw}$ is the kinematic viscosity of seawater. The constant value $v_{sw} = 13 \cdot 10^{-4}/\rho_{sw}$ is adopted in this study. The energy consumed with pumping $E_{pump,year}$ is obtained (in J year$^{-1}$) from

$$E_{pump,year} = 365 \cdot 24 \cdot 3600 \cdot P_{pump}$$

(9)

The average daily solar global irradiation on a horizontal plane ground surface in Nema (Mauritania) is $G_{day} = 26 \cdot 46 \text{ MJ m}^{-2} \text{ day}^{-1}$ (Badescu, 2006). The yearly solar global irradiation $G_{year}$ is of course

$$G_{year} = 365G_{day}$$

(10)

The energy provided per unit surface area by PV cells during a year, $E_{PV,year,1}$ is given by

$$E_{PV,year,1} = G_{year}\eta_{PV}$$

(11)

where $\eta_{PV}$ is PV cell efficiency (yearly average). In our computations, we have used a rather high (optimised) value $\eta_{PV} = 0.15$ which applies for Nema (Badescu, 2006). The energy provided by the whole PV cells surface during a year, $E_{PV,year}$ is obtained from

$$E_{PV,year} = E_{PV,year,1}D_{duct}L_{duct}$$

(12)
The energy consumed per year with pumping, $E_{\text{pump,year}}$, is provided in part by the PV cells. The remaining part, $E_{\text{classic,year}}$, should be provided from classical energy sources. One has

$$E_{\text{classic,year}} = E_{\text{pump,year}} - E_{\text{PV,year}}$$  \hspace{1cm} (13)

To evaluate the financial magnitude of the Akchar erg dune stabilisation macroproject we have to estimate the cost of the duct, of the PV cells and of pumps enabling seawater movement, respectively. The cost $c_{\text{duct}}$ of the duct is given by

$$c_{\text{duct}} = c_{\text{duct,1}} L_{\text{duct}}$$  \hspace{1cm} (14)

where $c_{\text{duct,1}}$ is the cost of a unit length of duct. Similarly, the cost of installing the duct, $c_{\text{inst,duct}}$ is given by

$$c_{\text{inst,duct}} = c_{\text{inst,duct,1}} L_{\text{duct}}$$  \hspace{1cm} (15)

where $c_{\text{inst,duct,1}}$ is the cost of installing a standard unit length of duct. The unitary costs depend of course on various factors, such as the duct diameter $D_{\text{duct}}$ as well as the material of the duct. Table II shows the input values used in this work.

The cost of the pumping installation, $c_{\text{pump}}$, is obtained from

$$c_{\text{pump}} = P_{\text{pump}} c_{\text{pump,1}}$$  \hspace{1cm} (16)

where $c_{\text{pump,1}}$ is the cost of pump of unit power. Table III shows statistically average values for $c_{\text{pump,1}}$, as a function of pumping device quality. The gold-plated cost in Table III is for a custom-built installation. The inexpensive cost is for an off-the-shelf, commercially mass-produced fluid pump. The maintenance cost per year for the pumping system, $c_{\text{pump,maint}}$ is

$$c_{\text{pump,maint}} = f_{\text{pump,maint}} c_{\text{pump}}$$  \hspace{1cm} (17)

where $f_{\text{pump,maint}}$ is a given fraction. Here $f_{\text{pump,maint}} = 0.01$ has been adopted.

### Table II. Approximately cost of the duct and its installation over ground

<table>
<thead>
<tr>
<th>Diameter of duct, $D_{\text{duct}}$ (m)</th>
<th>Cost of steel duct, US $ \text{m}^{-1}$</th>
<th>Cost of plastic duct, US $ \text{m}^{-1}$</th>
<th>Cost of fabric duct, US $ \text{m}^{-1}$</th>
<th>Cost of installation (steel, plastic), US $ \text{m}^{-1}$</th>
<th>Cost of installation US $ \text{m}^{-1}$ (fabric)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>19</td>
<td>9</td>
<td>4</td>
<td>900</td>
<td>100</td>
</tr>
<tr>
<td>0.5</td>
<td>45</td>
<td>21</td>
<td>10</td>
<td>1500</td>
<td>400</td>
</tr>
<tr>
<td>1</td>
<td>380</td>
<td>200</td>
<td>90</td>
<td>2000</td>
<td>600</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
<td>300</td>
<td>140</td>
<td>2700</td>
<td>800</td>
</tr>
<tr>
<td>3</td>
<td>1100</td>
<td>600</td>
<td>290</td>
<td>3500</td>
<td>1000</td>
</tr>
<tr>
<td>5</td>
<td>2300</td>
<td>1200</td>
<td>510</td>
<td>4000</td>
<td>1300</td>
</tr>
<tr>
<td>10</td>
<td>5100</td>
<td>2400</td>
<td>990</td>
<td>5000</td>
<td>1800</td>
</tr>
</tbody>
</table>

Note: Thickness of steel duct wall is about 1 per cent of diameter, thickness of plastic duct wall is about 10 per cent of diameter. Fabric ducts are inflatable and flexible from high strong artificial fibre.

### Table III. Cost of a pump of unit power $c_{\text{pump,1}}$ (adapted from Axion (2007))

<table>
<thead>
<tr>
<th>Pump quality</th>
<th>Cost (US $ W^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting corners</td>
<td>2</td>
</tr>
<tr>
<td>Inexpensive</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>8</td>
</tr>
<tr>
<td>Expensive</td>
<td>16</td>
</tr>
<tr>
<td>Gold plated</td>
<td>32</td>
</tr>
</tbody>
</table>
The cost $c_{PV}$ of the PV cells is obtained from the product of the cost of a unit surface PV cell, $c_{PV,1}$ and the total surface covered by PV cells

$$c_{PV} = c_{PV,1} L_{duct} D_{duct}$$  \hfill (18)

Using the estimate for future PV Cells technology, the cost per square metre of flexible PV cells sheeting is $c_{PV,1} \cong 100 \text{US$ m}^{-2}$ (Liu et al., 2007). The maintenance cost per year for PV cells, $c_{PV,maint}$ is

$$c_{PV,maint} = f_{PV,maint} c_{PV}$$  \hfill (19)

where $f_{PV,maint}$ is a given fraction. Here $f_{PV,maint} = 0.01$ has been adopted.

The cost of the classical energy consumed during a year, $c_{classic,year}$, is given by

$$c_{classic} = E_{classic,year} c_{classic,year,1}$$  \hfill (20)

where $c_{classic,year,1}$ is the cost of a classical energy unit. Here electricity is considered and $c_{classic,year,1} \cong 0.1 \text{US$ kWh}^{-1}$ (Pelletheat, 2007). The cost of classical energy during $N$ years, $c_{classic}$, is obtained from

$$c_{classic} = N c_{classic,year}$$  \hfill (21)

The initial investment cost $c_{invest,stab}$ for duct, PV cells and pumping installation, is given by

$$c_{invest,stab} = c_{pump} + c_{PV} + c_{duct} + c_{inst,duct}$$  \hfill (22)

The maintenance cost $c_{maint,stab}$ for $N$ years of the PV cells and pumping installation is

$$c_{maint,stab} = N (c_{pump,maint} + c_{PV,maint})$$  \hfill (23)

The total costs, $c_{tot,stab}$, after $N$ years of the dune stabilisation project, is

$$c_{tot,stab} = c_{invest,stab} + c_{maint,stab} + c_{classic}$$  \hfill (24)

Seawater Agriculture Macropject

It is estimated $\sim 10$ per cent of Earth’s land is already affected by salt deposition. Of $\sim 5000$ food and fibre crops that are cultured by humans, only a few can survive with water that contains $> 0.5$ per cent salt, and most suffer serious yield reductions at $\sim 0.1$ per cent salt. Still, the use of saline waters and even seawater for halophytic crop cultivation is an attractive option for farmers in some dryland regions (Lieth and Mochtchenko, 2004). The world’s first commercial food to be grown entirely on poor soil irrigated by seawater is Salicornia bigelovii (Glenn et al., 1997). The increasing salinisation of inland waters (Williams, 2001), and the calls for ‘reversing the flow of water and nutrients from the ocean to the land’ (Hodges et al., 1993), combined with the prospects for progressive genomic manipulation of photosynthetic plants, means that saline water will soon have a greater value to humans than it has had in the recent historic past. Cropping of vast additional segments of the Sahara (Glenn et al., 1998), or the Sahara’s near-term future coverage by a Sahara Tent Greenbelt (Cathcart and Badescu, 2004), might curtail or even terminate the natural suppression of North Atlantic Ocean tropical cyclones.

In an attempt to recover part of the costs of the erg Akchar dune stabilisation macropject, an additional project has been considered. After the dune stabilisation macropject is completed, the duct and all existing infrastructure may be used for seawater agriculture. Seawater irrigation does not require special farming equipment. The large existing test farms have used either flood irrigation of large basins or moving seawater. Seawater agriculture needs approximately 35 per cent more irrigation fluid volume when grown using seawater than conventional crops grown using freshwater. Generally, there are no insurmountable macro-engineering problems associated to commercial seawater agriculture.
Computation of the crop surface that may be irrigated per second, $S_{\text{irrig, sec}}$, is made by

$$S_{\text{irrig, sec}} = \frac{q_{\text{sw}}}{S_{\text{irrig, 1}}}$$  \hspace{1cm} (25)

where $S_{\text{irrig, 1}}$ is the surface of crops that may be irrigated with 1 m$^3$ of seawater. The cycle of the irrigation procedure is denoted by $t_{\text{irrig}}$. Then, the total irrigated surface $S_{\text{irrig}}$ is given by

$$S_{\text{irrig}} = t_{\text{irrig}} S_{\text{irrig, sec}}$$  \hspace{1cm} (26)

Input values were suggested from the project Ras al-Zawr where $S. \text{bigelovii}$ is cultivated (SaudiAramCo, 2007). There, computer-controlled pivot-irrigation arms—one for each 50 ha circle—sprayed seawater pulled in by three diesel pumps at a rate greater than 28 m$^3$ min$^{-1}$. It took six and one half hours for the arms to complete a single circuit. From these data, one finds that $S_{\text{irrig, sec}} = 0 \cdot 763$ m$^2$ land m$^{-3}$ water and $t_{\text{irrig}} = 23400$ s.

The cost of the irrigation installation $c_{\text{irrig}}$ is of course proportional with the irrigated surface

$$c_{\text{irrig}} = S_{\text{irrig}} c_{\text{irrig, 1}}$$  \hspace{1cm} (27)

where $c_{\text{irrig, 1}}$ is the cost of irrigating a unit surface of cultivated crops. Depending on the crops, $c_{\text{irrig, 1}}$ ranges from 500 to 5000 US$ ha$^{-1}$ (Farm Management, 2007). Here, we accept 1875 US$ ha$^{-1}$ which yields $c_{\text{irrig, 1}} = 0 \cdot 185$US$/m^2$. The maintenance cost per year for the irrigation installation, $c_{\text{irrig, maint, 1}}$ is

$$c_{\text{irrig, maint, 1}} = f_{\text{irrig, maint}} c_{\text{irrig}}$$  \hspace{1cm} (28)

where $f_{\text{irrig, maint}}$ is a given fraction. Here, $f_{\text{irrig, maint}} = 0 \cdot 05$ has been adopted. The maintenance cost $c_{\text{irrig, maint}}$ for $N_1$ years of the irrigation installation is

$$c_{\text{irrig, maint}} = N_1 c_{\text{irrig, maint, 1}}$$  \hspace{1cm} (29)

The cost associated to the irrigation installation, $c_{\text{tot, irrig}}$, after $N_1$ years of operation is

$$c_{\text{tot, irrig}} = c_{\text{irrig}} + c_{\text{irrig, maint}}$$  \hspace{1cm} (30)

The economic gain per year from the crops irrigated with seawater, $g_{\text{irrig, year}}$, is given by

$$g_{\text{irrig, year}} = S_{\text{irrig}} g_{\text{irrig, 1}}$$  \hspace{1cm} (31)

where $g_{\text{irrig, 1}}$ is the economic gain per unit surface of cultivated crops per year. The economic gain after $N_1$ years from the cultivated crops, $g_{\text{irrig}}$ is given by

$$g_{\text{irrig}} = N_1 g_{\text{irrig, 1}}$$  \hspace{1cm} (32)

During 6 years of field trials in Mexico, $S. \text{bigelovii}$ produced an average annual crop of 1.7 kg m$^{-2}$ of total biomass and 0.2 kg m$^{-2}$ of oilseed (Imaz et al., 1998). It is expected that the benefits from the cultivated $S. \text{bigelovii}$ consists of food products like cooking oil and ‘sea asparagus’, a gourmet food delicacy that sells in Europe for US $ 20 per pound (0.4536 kg) (Global Warming, 2007). In calculations we considered as possible products to sell, oil (0.75 US $ kg$^{-1}$) and sea asparagus (40 US $ kg$^{-1}$). In the two cases, $g_{\text{irrig, 1}}$ is evaluated to about 0.15 US $ m^{-2}$ and 8 US $ m^{-2}$, respectively.

The economic profit $p_{\text{irrig}}$ of the irrigation system after $N_1$ years is given by

$$p_{\text{irrig}} = g_{\text{irrig}} - c_{\text{tot, irrig}}$$  \hspace{1cm} (33)
The total cost, $c_{t\text{ot}}$, of the erg Akchar dune stabilisation macroproject and dune irrigation macroproject, after $N + N_1$ years of operation, is obtained from

$$c_{t\text{ot}} = c_{t\text{ot},\text{stab}} + c_{t\text{ot},\text{irrig}}$$ (34)

**Results**

Generally, the energy consumed with pumping the seawater in the duct is decreased by increasing the number of years $N$ chosen to finish the Akchar erg stabilisation macroproject. When $N$ is of the order of 10 or 20 years, the macroproject is intensively consuming energy and money. Here, we show results for $N = 50$ years (Figure 5). An inexpensive pump in Table III has been considered. The seawater speed in the duct $w_{svw}$ and the pumping power $P_{\text{pump}}$ become reasonably small only at duct diameters $D_{\text{duct}}$ larger than 3 m (Figure 5a). Thus, it is obvious that at smaller duct diameters, the surface covered by PV cells is rather small and most of the energy required to move the water is provided from classical energy sources (Figure 5b). However, for diameters larger than 7 m the energy provided by the PV cells becomes comparable with that from classical fuels. When $D_{\text{duct}}$ is larger than 9 m, the PV cells become the main energy supplier.

The duct cost $c_{\text{duct}}$ increases by increasing the duct diameter $D_{\text{duct}}$, as expected (Figure 6a). Obviously, $c_{\text{duct}}$ depends on the duct material, with composed fabric the least costly solution. The same feature exhibits the expense of installing the duct, $c_{\text{inst,\text{duct}}}$, but in this case the dependence on duct diameter $D_{\text{duct}}$ is weaker than the dependence of $c_{\text{duct}}$ on $D_{\text{duct}}$. The cost of the pumps comprising the pumping installation $c_{\text{pump}}$ decreases by increasing $D_{\text{duct}}$, as well the cost of the energy for pumping provided by using classical fuels, $c_{\text{classic}}$ (Figure 6b). However, both $c_{\text{pump}}$ and $c_{\text{classic}}$ have a rather weak dependence on duct diameter for $D_{\text{duct}} > 6$ m. The cost of pumps is of the order of millions US $ while the cost of the energy consumed for seawater pumping during 50 years is of the order of

![Figure 5](image.png)

Figure 5. (a) Seawater speed $w_{svw}$ and pumping power $P_{\text{pump}}$ and (b) various energies (the energy consumed during a year with pumping, $E_{\text{pump, year}}$, the energy provided by PV cells and from classical fuels, $E_{\text{PV, year}}$ and $E_{\text{classic, year}}$, respectively) as a function of duct diameter $D_{\text{duct}}$.

Computations performed for $N = 50$ years.
thousands of millions US $. The initial investment cost $c_{\text{inv,stab}}$ depends on the material used to manufacture the duct, with composed fabric the least expensive solution (Figure 6c). Whatever the duct material, $c_{\text{inv,stab}}$ has a minimum that is about 4 m for steel and plastic ducts and about 4.5 m for composed fabric ducting. The minimum initial investment in the erg Akchar sand dune stabilisation macroproject is about 1100 millions US $ in the case of pipes composed of steel and plastic and about 600 millions US $ in the case of ducts fabricated with composed fabric.

The seawater irrigation macroproject associated to the Mauritanian erg stabilisation macroproject was studied next. The results are shown in Figure 7, which refers to a duct diameter of 4.5 m, associated to minimisation of the initial investments in the stabilisation macroproject in case of fabric ducts (see Figure 6c). The irrigated surface $S_{\text{irrig}}$ decreases by increasing the number of years $N$ to complete dune stabilisation (Figure 7a). This is easily understood: increasing $N$ decreases the seawater mass flow rate used by the dune stabilisation macroproject. For all computations $S_{\text{irrig}}$ ranges between 1 and 4 ha, and for $N = 50$ years (the case treated in Figures 5 and 6) the irrigated surface is about 1.5 ha. The cost of irrigation system $c_{\text{irrig}}$ and the cost of irrigation and its maintenance for $N = 20$ years, $c_{\text{tot,irrig}}$, decrease by increasing the number of years $N$ (Figure 7b). These costs are of the order of thousands US $, well below the investment costs associated to the dune stabilisation macroprojects (see Figure 7b). The economic gain $g_{\text{irrig}}$ from the crops irrigated with seawater is shown in Figure 7c for two different products. This economic gain decreases by increasing $N$, as expected. In the case of cooking oil, $g_{\text{irrig}}$ is less than 0.1 million US $ but the economic gain is of the order of a few millions US $ in case of sea asparagus. In practice $g_{\text{irrig}}$ will probably fall within the range of these extreme values.

The economic gain provided by induced seawater agriculture may be increased by increasing the seawater speed $w_{\text{sw}}$ in the duct after the dune stabilisation macroproject is completed. This ensures a larger seawater mass flow rate and, consequently, a larger land surface may be irrigated. However, there is a limited provision for increasing $w_{\text{sw}}$, due to the fact that the friction losses increase with the square power of $w_{\text{sw}}$. Doubling $w_{\text{sw}}$ is probably an upper
bound and this is associated to doubling the irrigated ground surface $S_{\text{irrig}}$. (Friction loss may be reduced markedly by coating the inside of the pipe with a low-cost carbon nanotube fabric liner or plastic.) This means the economic profit might be doubled in respect to the values presented in Figure 7c. However, even in these most optimistic situations, the economic gain associated to the seawater irrigation macroproject goes far to compensate the costs associated to the dune stabilisation macroproject. Therefore, the decision about practical implementation of the dune field stabilisation macroproject should be taken without considering (immediate) economic reasons. Even so, an eco-audit must follow-up any implementation of these nested macroprojects that have previously been fully vetted in a structured environmental management system evaluation done by dry land degradation experts (Barrow, 2006).

Finally, note that the computations reported here are very rough and, in practice, the costs of the macroproject may be significantly larger.

**EFFECTS ON GLOBAL SEA LEVEL RISE**

*Circa* 3900 BC—about 1100 years after global sea level stabilised following the Last Glacial Maximum—civilisation commenced with the human use of newly abundant coastal margin resources; *circa* 2300 BC, urban governments commenced construction of monumental infrastructures (Day *et al*., 2007). Contemporaneous destabilisation of global sea level impacts urban governments and infrastructures on present-day coastal margins (Ericson *et al*., 2006). For example some major cities—places such as Lagos, Karachi, Mumbai, Kolkata, Bangkok, Jakarta, Manila and Shanghai—presently find their fresh groundwater reservoirs being contaminated by saltwater intrusions that may be further aggravated by a postulated greater, yet unproved, future global sea level rise. ‘Global Warming’ appears to be a real existential risk, but its impact during the 21st Century and beyond could plausibly
range from nil to negligible to severe. Computer models of future atmospheric realities are still extremely simplistic as compared to the actual phenomenon of Earth’s air (Tyrell et al., 2007).

Worldwide, since \(~10.5\) per cent of the world’s population reside on land that is \(<100\) km from the shoreline at elevations \(<10\) m above sea level (\(\sim 2.2\) per cent of all land), the international and intranational legal implications of coastal zone adjustments instigated by the alleged impending global sea level rise are profound (Caron, 1990). Hydrogeology may have a central role to play in a macroproject solving any prospective future global sea level rise because that profession already has a burgeoning role in the underground sequestration (injection and storage) of aerial CO\(_2\) gas in deep saline aquifers (Celia, 2002). For example during this century, BP PLC operates an isolated natural-gas processing plant in the Sahara near In Salah (27°12’ N Lat. by 2°28’ E Long.), Algeria (Ball, 2005).

The SSSP macroproject here proposed involves a massive anthropogenic redistribution of Spaceship Earth’s seawater cargo. Whatever the cause of a future global sea level rise, whether it is ‘global warming’ or some other phenomenon or aggregation of phenomena, James E. Hansen defines a substantial global sea level rise to mean ‘a total sea level rise of at least 2 m, because that would be sufficient to flood large portions of Bangladesh, the Nile Delta, Florida and many island nations, causing forced migration of tens to hundreds of millions of people’ (Hansen, 2005). More than 20 years ago, Walter Stephenson Newman (1895–1978) and Rhodes Whitmore Fairbridge (1914–2006) speculated that humans could, using macro-engineering tactical technologies, manage any future global sea level rise by ‘. . . diverting sea water into continental depressions’ filled to present-day global sea level (Newman and Fairbridge, 1986). By our estimation, the Caspian Sea region could store \(\sim 13\) 000 km\(^3\), the Aral Sea region \(~1000\) km\(^3\), the Qattara Depression \(~3200\) km\(^3\), the Dead Sea \(~1260\) km\(^3\), Lake Eyre region \(~200\) km\(^3\) and the Salton Sea region \(~400\) km\(^3\) of seawater. Total global land depression storage capacity \(\sim 18\) 060 km\(^3\) and all of the seawater is stored in the open air, subject to solar evaporation. In other words, these seawater storehouses must be constantly replenished at some undetermined financial and energy cost. The area of the Earth’s ocean is \(\sim 3.62 \times 10^8\) km\(^2\). If the ocean rose by J. E. Hansen’s 2 m, the volume of that increase would be \(\sim 725\) 000 km\(^3\), meaning that removal of \(\sim 18\) 060 km\(^3\) is only \(\sim 2.5\) per cent of the volume that must be shifted to the Earth’s land from the ocean’s basin in order just to maintain present-day global sea level. Where can the remaining 97.5 per cent (\(\sim 705\) 940 km\(^3\)) be stored, withheld from our world’s ocean, for an indeterminate time period?

First, a maximum of 7200 km\(^3\) of freshwater, about 20 per cent of the Earth’s total annual river runoff is retained in artificial reservoirs created by anthropic dams (Oki and Kanae, 2006). Second, the total natural unused, unsaturated volume of pore space beneath the world’s land is huge—to a depth of \(\sim 2000\) m, if only unconsolidated sands, sandstones and carbonates are considered, \(\sim 25\) 000 000 km\(^3\) exists which might be filled artificially with seawater. ‘Sands retain most of their original porosity down to a depth of 1 km. Porosities of approximately 48 per cent at the surface show little change for the initial 100 m of burial, and then begin to decrease slightly with depth: to 45 per cent at 300 m and 37 per cent at 1 km’ (Hay and Leslie, 1990). The Kalahari sand sheet situated in southern Africa, with a 2.5 million ha area, is very probably the world’s largest continuous surface of loose sand. Water of any purity can be forced to accumulate rapidly in the unsaturated vadose zone (Anderson, 2007). Oilfield repressurisation with deliberately injected seawater has been used for many years to halt widespread land subsidence caused by oil and natural gas mining.

J. E. Hansen’s global climate warming scenario entails a global sea level rise, ‘. . . a process that will shift the interface between land and sea, resulting in the inland extension of maritime-related flooding and elevated soil salinities’ (Greaver and Sternberg, 2007).

The SSSP macroproject installation considered in this single tactical macro-engineering assessment can pump the volume \(V_{sw} = q_{sw} t\) of seawater, where \(t\) is time. For the duct considered in Figures 5 and 6, the volumetric flow rate is \(q_{sw} = 28 \cdot 5\) m\(^3\) s\(^{-1}\) and the amount of seawater extracted from our world’s ocean and deposited on Mauritania’s sand dune fields during a year is about 0.9 km\(^3\). This is a very small quantity if we compare with that associated to the 2 m global sea level rise expected by Hansen. However, the Intergovernmental Panel on Climate Change’s latest projection for future global sea level rise during the 21st Century is 18–59 cm. Therefore, any sand dune seawater saturation effort need only be adequate to compensate for each year’s potential global sea level rise. So, we conclude that the northern Africa SSSP macroproject may contribute to, but it is not a solution for, the future rise of global sea level.
SAND DUNE FIXATION

CONCLUSION

We have shown that an SSSP macroproject sited in Mauritania can be both economic and developmental, with extensive future applicability worldwide. The SSSP’s macro-engineering concept of extraction and long-term storage of excess seawater in city-threatening active coastal sand dune fields via simple and effective tactical technologies (artificially duplicating, in part, the Earth’s natural Hydrologic Cycle) is revolutionary.

The Sahara includes large expanses of sand dunes called ergs. These dunes are formed and constantly reshaped by the prevailing winds. Our SSSP macroproject is intended to foster development of region-wide soil moisture heterogeneity in Mauritania’s inland ergs for the purpose of stabilisation by irrigating the dunes with unadulterated seawater pumped from the nearby North Atlantic Ocean. Future irrigation seawater may be infused with slightly cleansed urban sewage that could fertilise irrigated field crops (Heinonen-Tanski et al., 2007).

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