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Hydro-economic assessment of the potential of PV-RO desalinated seawater supply in the Mediterranean region

Modelling concept and analysis of water transport costs

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Introduction

Seawater desalination, although a traditional source of water in arid and water-scarce regions, is receiving attention worldwide due to the growing concern on dwindling traditional water resources. Desalination entails significant energy consumption, which may be unsustainable when the latter is provided by fossil fuels. However, renewable energy sources may make desalination more attractive. Until now, desalination has been regarded as a local source of freshwater for coastal areas or islands, but the mapping of regions suitable to be supplied with desalinated seawater has been seldom addressed systematically. Caldera et al., 2016, present a global scale analysis based on a simplified representation of water demand and energy requirements for desalinated water production and transport, suggesting that desalinated seawater could be supplied in water-stressed regions of the world by 2030, using renewable energy only, at a cost between 0.59 and 2.81 Euro/m^3. While their analysis provides general indications at global scale, the specificity of regions arising from topography, the distribution of population and land use may warrant a more detailed inspection. Appraising the potential of renewable energy seawater desalination as a water resource requires quantifying its costs of production (construction, operation and maintenance of desalination plants), as well as the costs of transporting desalinated water from the coastal production sites to potential users inland.

In this contribution, we describe the cost elements concurring to the total cost of desalinated seawater, and we quantify the component of costs associated to water transport from a coastal production site to the final users inland. We limit our analysis to the case of using renewable energy, and specifically photovoltaic (PV) energy, to feed plants based on reverse osmosis (RO) technology, currently representing a common choice by desalination engineers. We develop our cost analysis assuming PV to contribute 100% of energy used in both production and transport of desalinated water. Finally, we outline the envisaged steps towards a prioritization of investments in desalination in the Mediterranean.

Modelling the cost of desalinated seawater

The cost of one cubic meter of water **<u>at a point</u>** is given by:

$$LCoW = C_{transport} + C_{treatment} + C_{pumping} + C_{water\_storage} + C_{energy\_storage} \quad \text{Equation 1}$$

Where

$C_{transport}$ = levelized cost of transport of water to the user

$C_{treatment}$ = levelized cost of desalinated water at the plant gate

$C_{pumping}$ = levelized cost of the pumping stations to transport water from the plant to the users

$C_{water\_storage}$ = levelized cost of reservoirs required to store water

$C_{energy\_storage}$ = levelized cost of batteries required to store energy on a daily basis.

The cost of transport is computed taking into account the entity of the pipeline required to deploy water at a point as well as the operation and maintenance (O&M) and energy costs. We compute the total levelized cost of water to be deployed at any point of the study region, assuming that water is taken from the nearest suitable coastal location. Costs of transport reflect the distance and elevation difference between a point of deployment and the nearest source area. All other costs are constant for all points within the area served by a single source of water (area of influence). In practice, distances from source areas are computed as raster maps through an appropriate cost-distance operation, and the areas of influence are the corresponding nearest-neighbour allocation maps (see e.g. Pistocchi, 2014).

The costs of treatment depend on the size and operation parameters of the desalination plant, as well as on the characteristics of seawater. The costs of the pumping stations can be parameterized on the basis of the power of pumps to be installed (OECD, 2004). The costs of energy and water storage depend on the required capacity. In this contribution, we focus only on the costs of transport, meant as the costs associated to building and operating pipelines that convey water from a source area to a generic location (x,y) where there is water demand.

The investment cost depends on the diameter of the pipeline required to reach a generic point (x,y) from the source of desalinated water. In practical terms, we compute for each point the equivalent pipeline that would allow conveying the required water discharge to feed the total demand that can be reached through the point. To this end, we first of all define a maximum distance L_{max} from the source of desalinated water, at which this water can be deployed. Subsequently, we trace the trajectory connecting each point to the water source. For a given point, we have a single shortest trajectory **γ(x,y)** that connects the point to the corresponding source area. However, at each point we may have more than one trajectory connecting other points within distance L_{max} to the same source. We define the "catchment area" A(x,y) as the set of points having the same source area of point (x,y), and whose trajectories connecting to the source pass through point (x,y). A(x,y) represents the set of demand locations requiring a pipeline to pass through point (x,y).

The discharge to convey up to point (x,y) is calculated as the sum of water discharge required at the point, Q(x,y), plus the sum of demand at points in A(x,y):

$$F(x,y) = Q(x,y) + \int_{\mathrm{A(x,y)}} Q(p,q)dp\,dq$$

Equation 2

where Q(p,q) (m3/day) is water demand at the generic position (p.q) within A(x,y). The area integral in Equation 2 is computed in practice through a "flow accumulation" operation on the cost-distance surface raster map (see e.g. Pistocchi, 2014). Water demand is assumed to correspond to 0.15 m3/day for each inhabitant present at a given location. The diameter of the pipeline (m) required to convey $F(x,y)$ is computed using the Hazen-Williams formula as:

$$D(x,y) = \left(\frac{10.675\ \left(\frac{F(x,y)}{C}\right)^{1.852}}{J} \right)^{\frac{1}{4.8704}}$$

Equation 3

where J is the friction loss rate and C is a friction coefficient. We assume C=120 (-), valid for steel pipes, and J=0.005 (-). Under these assumptions, with F(x,y) in m3/day, Equation 3 can be written as $D(x,y) = 0.0104\ F(x,y)^{0.3803}$.

The expenditure for one meter of pipeline with diameter D(x,y) is given in €/m by:

$$E(x,y) = \begin{cases} 0.088433\ \mathrm{D(x,y)}^{1.29} + 65.8\ if\ \mathrm{D(x,y)} \leq 0.8\ m \\ 0.0040115\ \mathrm{D(x,y)}^{1.785} + 68.1\ if\ \mathrm{D(x,y)} > 0.8\ m \end{cases}$$

Equation 4

as from the FEASIBLE model (OECD, 2004)[1]. The total expenditure for a pipeline (€/m^3 of conveyed water) conveying the discharge F(x,y) to the generic point is then:

$$E_{pipeline}(x,y) = \int_{\gamma(x,y)} \frac{E(\sigma)}{365\,F(\sigma)} d\sigma \qquad \text{Equation 5}$$

where E(σ) is the unit expenditure at the generic position, along the trajectory **γ(x,y)**, defined by the curvilinear abscissa σ. The expenditure for an investment can be converted into an equivalent annual cost by the "present value of annuity" factor:

$$pva(r,n) = \frac{1-\left(\frac{1}{1+r}\right)^n}{r} \qquad \text{Equation 6}$$

where r is the annual interest rate and n is the number of years of useful life (or depreciation period) of the investment. The levelized investment cost of the pipeline (€/m3) is:

$$C_{pipeline}(x,y) = \frac{E_{pipeline}(x,y)}{pva(0.05,50)} \qquad \text{Equation 7}$$

The energy required to convey a cubic meter of desalinated water to the generic point (x,y) is computed in kWh/m^3 as:

$$\Psi(\mathrm{x,y}) = \frac{9810\left(Z_{max}(x,y) + J\int_{\gamma(x,y)} d\sigma\right) 2.78\ x\ 10^{-7}}{\eta} \qquad \text{Equation 8}$$

where η is the efficiency of pumping, and the line integral $\int_{\gamma(x,y)} d\sigma$ represents the geometric length of the trajectory and is computed through a "flow length" operation using the flow directions computed using the map of the distance from the nearest source area as a topographic surface (Pistocchi, 2014). In this exercise, we assume η=0.75. Finally the total cost of transport (€/m^3 of conveyed water) is computed as:

$$C_{transport}(x,y) = C_{pipeline}(x,y) + \psi\,\Psi(\mathrm{x,y}) + \omega E_{pipeline}(x,y) \qquad \text{Equation 9}$$

where ψ is the cost of energy (€/kWh), and ω is the percentage of the investment cost required annually for ordinary operation and maintenance. We set this parameter to a default of 0.02 (2%).

Identification of source areas

We computed the total levelized cost of water to be deployed at any point of the study region, assuming that water is taken from the nearest suitable coastal location. As such, the analysis grounds on the identification of suitable coastal locations for water desalination. A location is identified as suitable when the following criteria are met:

- Terrain slope is less than 10% (approx. 6°)[2]

[1] The functions are provided by OECD (2004) in US$/m. In 2004, the exchange rate of € against US $ was about 0.83. However, given the indicative value of the functions and the relative stability of the prices, we assume a unit exchange rate. This applies to all expenditure functions from the FEASIBLE model when values are given in US$.

- Does not include urban and protected areas or inaccessible areas such as forests, wetlands, waterbodies[3]
- It is within one kilometre distance from the coastline
- Location area is greater than 10 hectares (10 pixels).

Based on the above criteria, a total of 5927 areas are identified (Figure 1 and Table 1). These cover a surface of about 156,000 km2, with extents usually below 50 ha each, but in some cases with significantly larger extents (Figure 2), indicating that a sufficient amount of coastal areas can be considered for the development of desalination throughout the region.

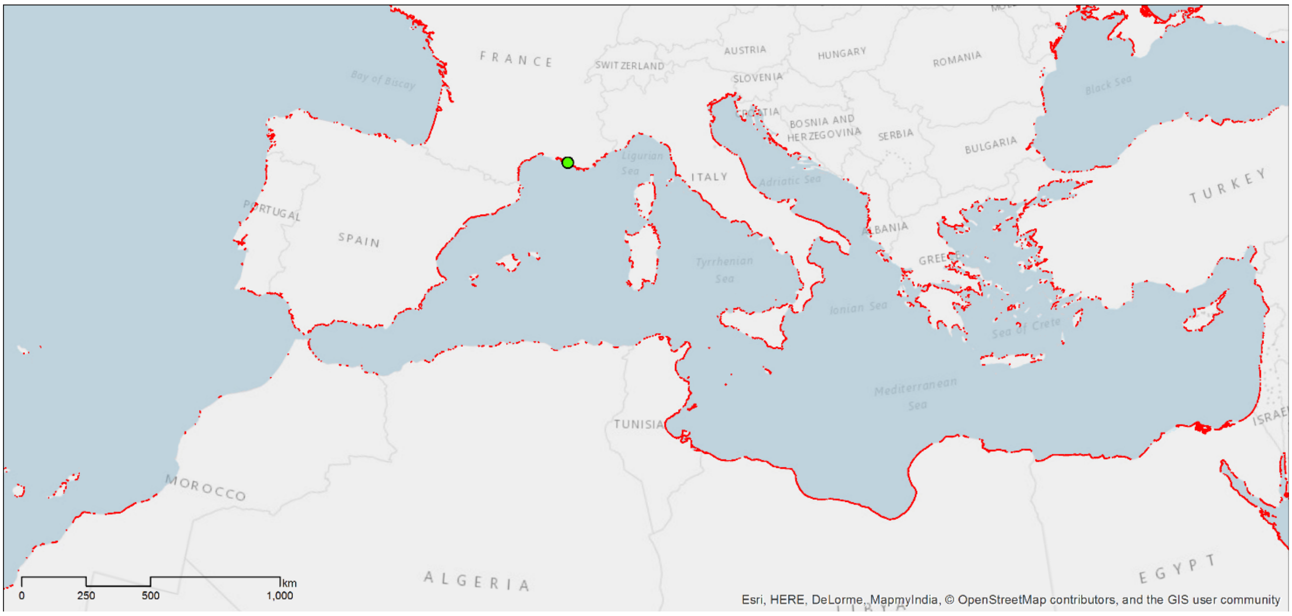
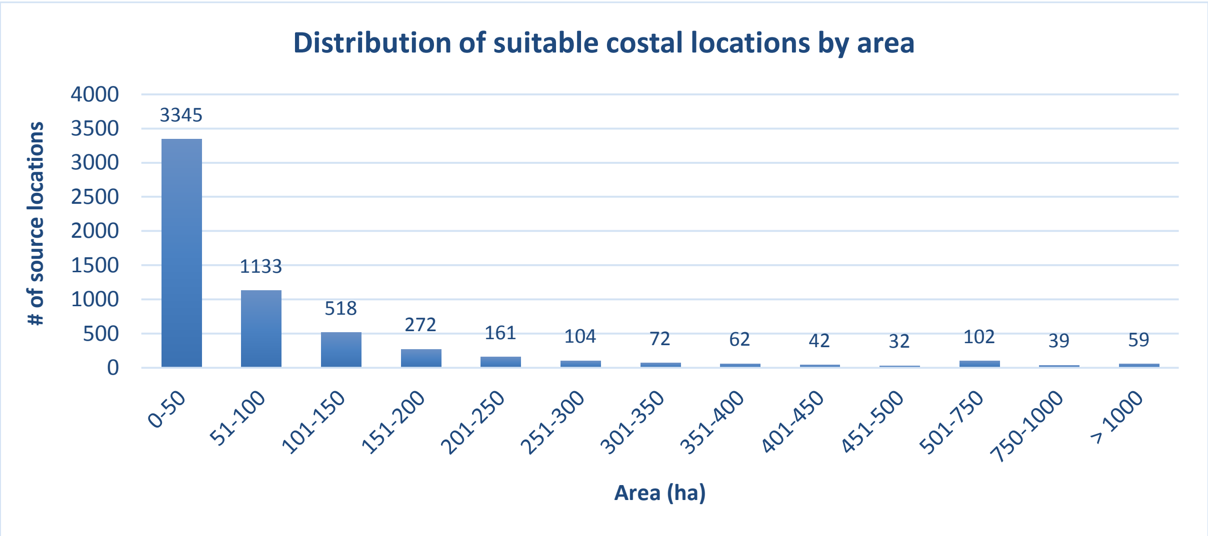


Figure 1 - Study region and distribution of suitable costal locations (in red)



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[2] Derived from NASA's Shuttle Radar Topography Mission (SRTM) at 90 meters spatial resolution, https://www2.jpl.nasa.gov/srtm/

[3] Land use information derived from the CORINE Land Cover (CLC 2012) dataset for EU and ESA Climate Change Initiative Land cover (CCI2015) for not EU region, at 100m and 300m spatial resolution respectively. Protected areas information derived from Natura2000 and the International Union for Conservation of Nature (IUNC) databases.

Figure 2 – frequency distribution of the extent of suitable areas in the study region

Territory or country	N. of suitable sites	Average Area (ha)
Albania	56	71
Algeria	92	41
Bulgaria	38	73
Canarias	82	47
Croatia	122	66
Cyprus	102	99
Egypt	617	155
France	613	85
Georgia	53	59
Gibraltar	3	28
Greece	635	82
Israel	43	60
Italy	810	97
Jordan	8	35
Lebanon	36	45
Libya	274	187
Madeira	4	17
Malta	13	57
Montenegro	15	41
Morocco	162	118
Palestinian Territory	11	104
Portugal	126	61
Romania	24	60
Russia	91	85
Saudi Arabia	91	260
Slovenia	5	63
Spain	525	68
Syria	29	89
Tunisia	239	157
Turkey	481	82
Ukraine	527	150

Table 1 – suitable areas identified for the siting of desalination plants in each country of the study region

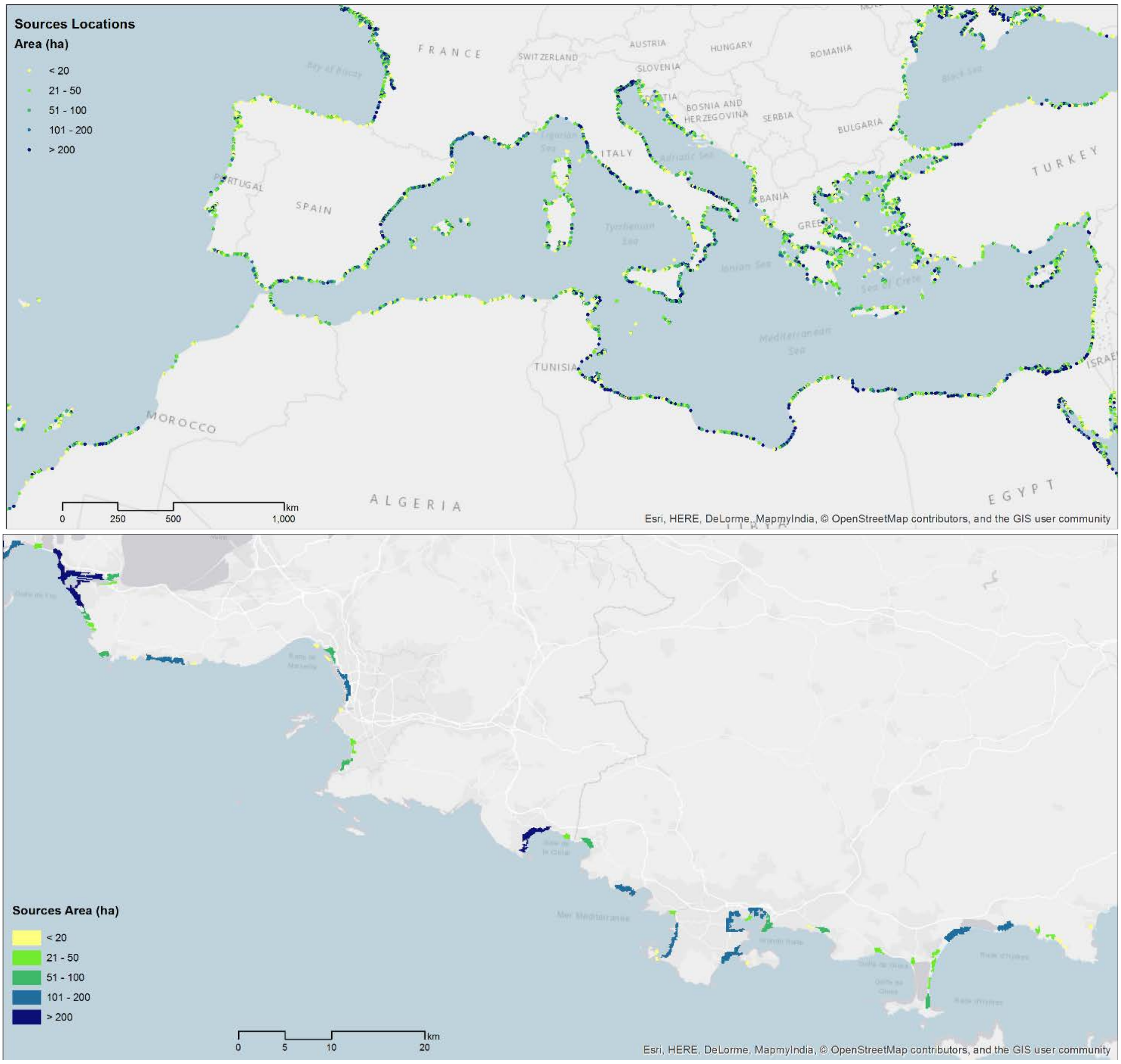


Figure 3 Map of suitable costal locations by area (above) and example detail of the Marseille area, France (below)

Calculation of shortest-path trajectories of water supply

The path distance also enables the definition of the area of influence of each source area, i.e. the region having a given source area as the nearest neighbour. The map of the path distance to the nearest source defines the shortest trajectory from each point to the nearest source and, consequently, the trajectories from all the points at longer distance from the source that pass through each inland point. We conventionally denote these trajectories as “upstream” of each point.

The suitable coastal locations identified in the previous step are used as sources to compute a suitable distance metric inland using the path distance algorithm from the ESRI software[4]. The “path distance” of an inland point from the nearest source is computed as the least cumulative cost distance over a cost surface, i.e. a surface whose values represent the degree of impedance to travel on a scale 1 to 5. The cost surface was generated with the following criteria:

[4] See: https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/path-distance.htm

- Waterbodies other than rivers, and protected areas are classified as inaccessible areas, except for corridors of 100 meters buffer each side of any transportation axis crossing them[5];
- Maximum impedance weight of 5 assigned to rivers[6], in order to reflect the significantly higher costs entailed by construction of crossings;
- Weight *(S)* of the slope gradient calculated with the following logistic function (Figure 4):

$$S = \frac{L}{1 + e^{-k(x - x_0)}}$$

Where $L = 3$, $k = 0.1$, and $x_0 = 60$

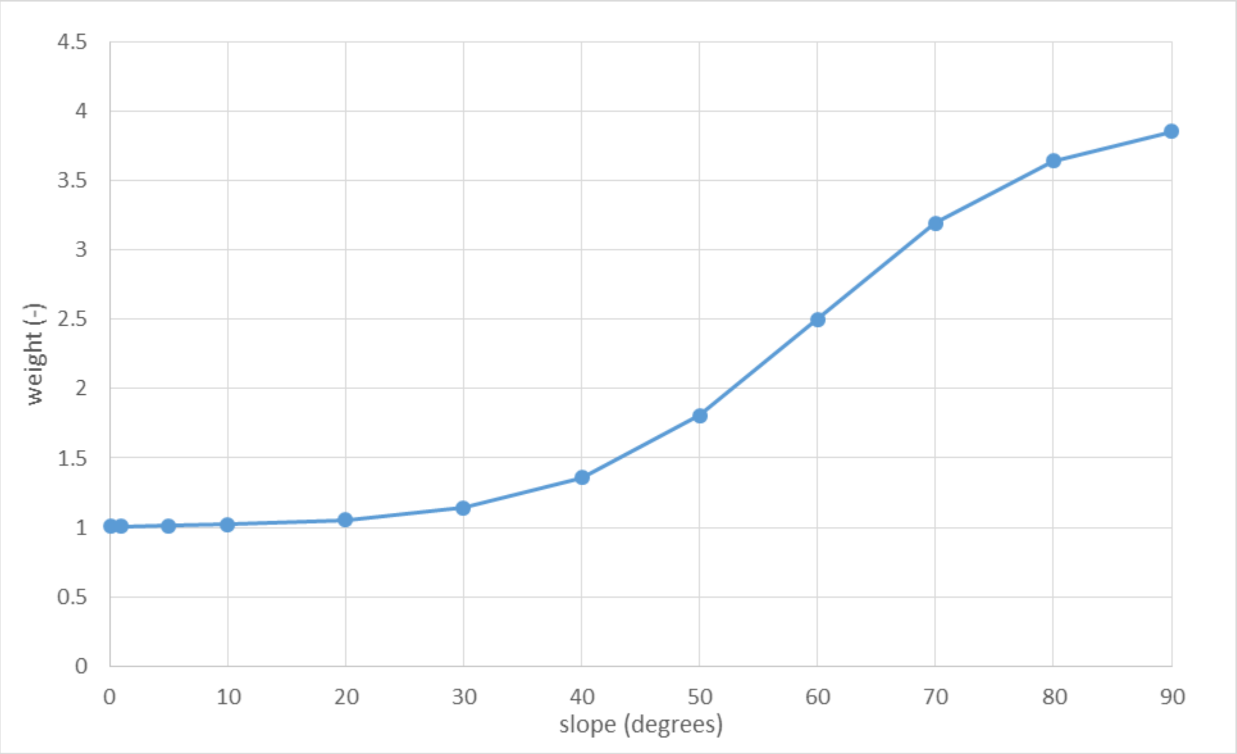


Figure 4 – weights assigned to terrain slope in the path-distance calculation

The map of the path distance to the nearest source defines the shortest trajectory from each point of the study area to the nearest source. The path distance toolset from ESRI also enables the definition of the area of influence of each source area, i.e. the region having a given source area as the nearest neighbour. The cost distance raster map can be used as a topographic surface on which flow directions can be computed. These can be used to compute flow accumulations of water demand, as discussed in Pistocchi, 2014.

Figure 5 and Figure 6 show the computed distance and the corresponding allocation to source areas for the study region.

[5] Transportation data derived from European Regional Map (ERM V91) for EU and Open Street Map for non-EU region

[6] Rivers data derived from CCM2 dataset for EU and Hydromed dataset for non-EU region

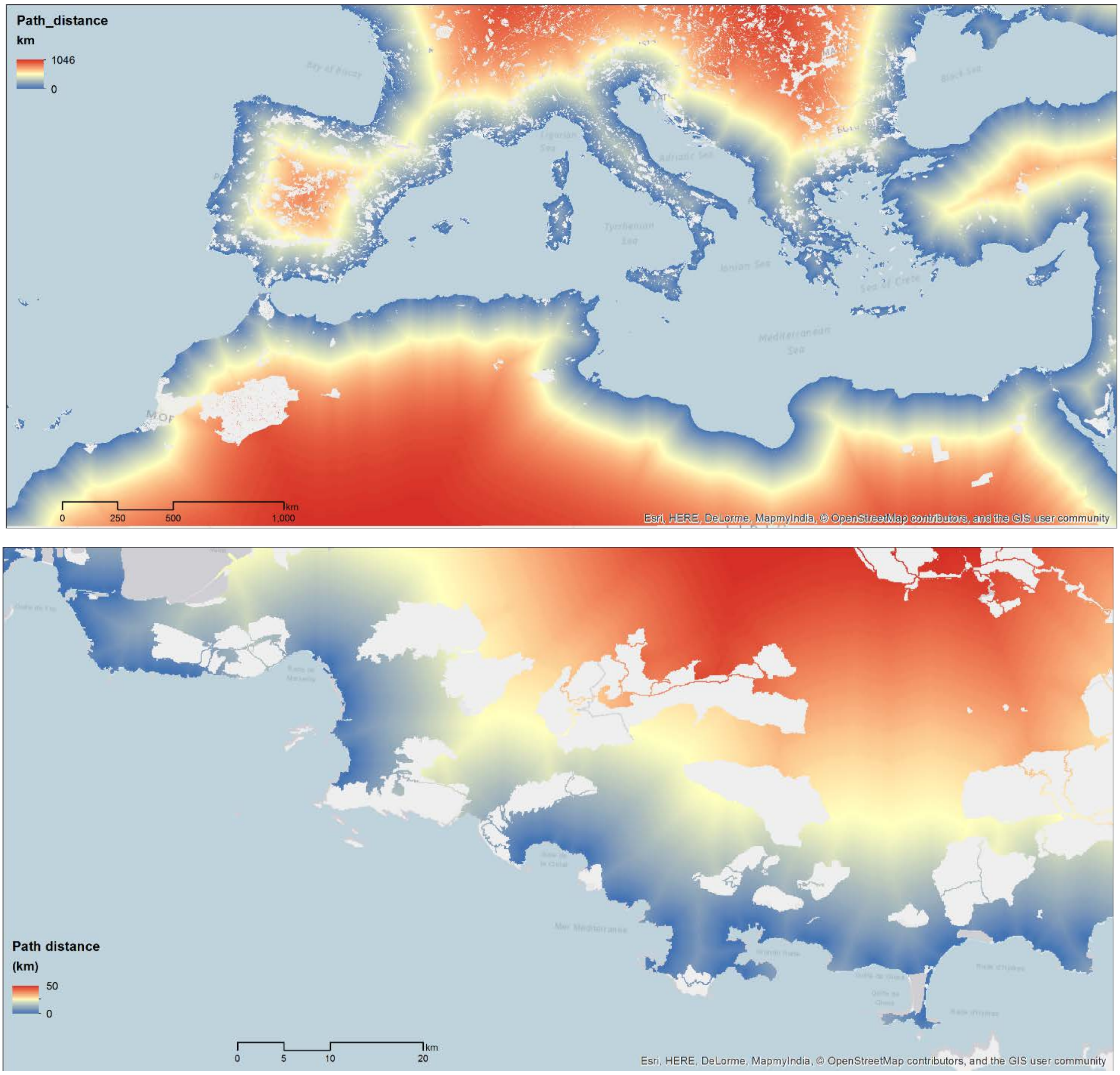


Figure 5 - Map of the path distance from the nearest source location (above) and example detail of the Marseille area, France (below)

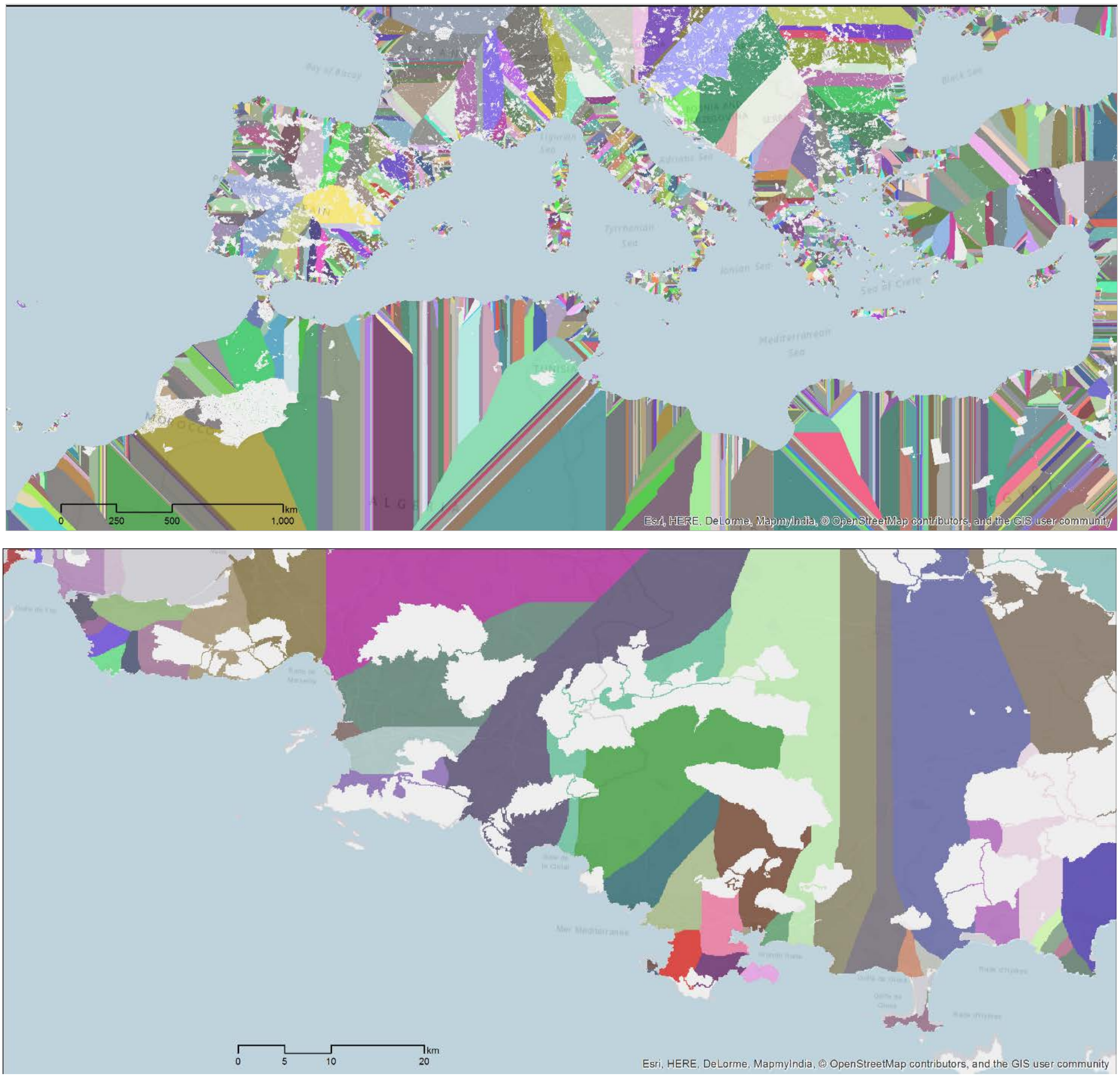


Figure 6 - Map of the study area segmented by the areas of influence of source costal locations (above) and example detail of the Marseille area, France (below)

Hydraulic sizing of pipelines

The sizing of the pipeline is based on the accumulated water demand from inland to the coast, along the downstream cost trajectories. Water demand is assumed 150 l/day per inhabitant, therefore in each point of the study area the local water demand Q is calculated from population count from the LANDSCAN dataset[7] multiplied by 0.15 (m^3/inhab/day), as shown in Figure 7. Then for each point the accumulated water demand F is computed using the flow accumulation algorithm from ESRI[8] (Figure 8).

Finally in each point the diameter of the potential pipeline conveying the required water discharge is computed through Equation 3 above (Figure 9).

[7] LS2013 http://web.ornl.gov/sci/landscan/index.shtml (Since the LandScan datasets has 1km spatial resolution it was downscaled to 100 meter spatial resolution prior to perform the calculations).

[8] https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/flow-accumulation.htm

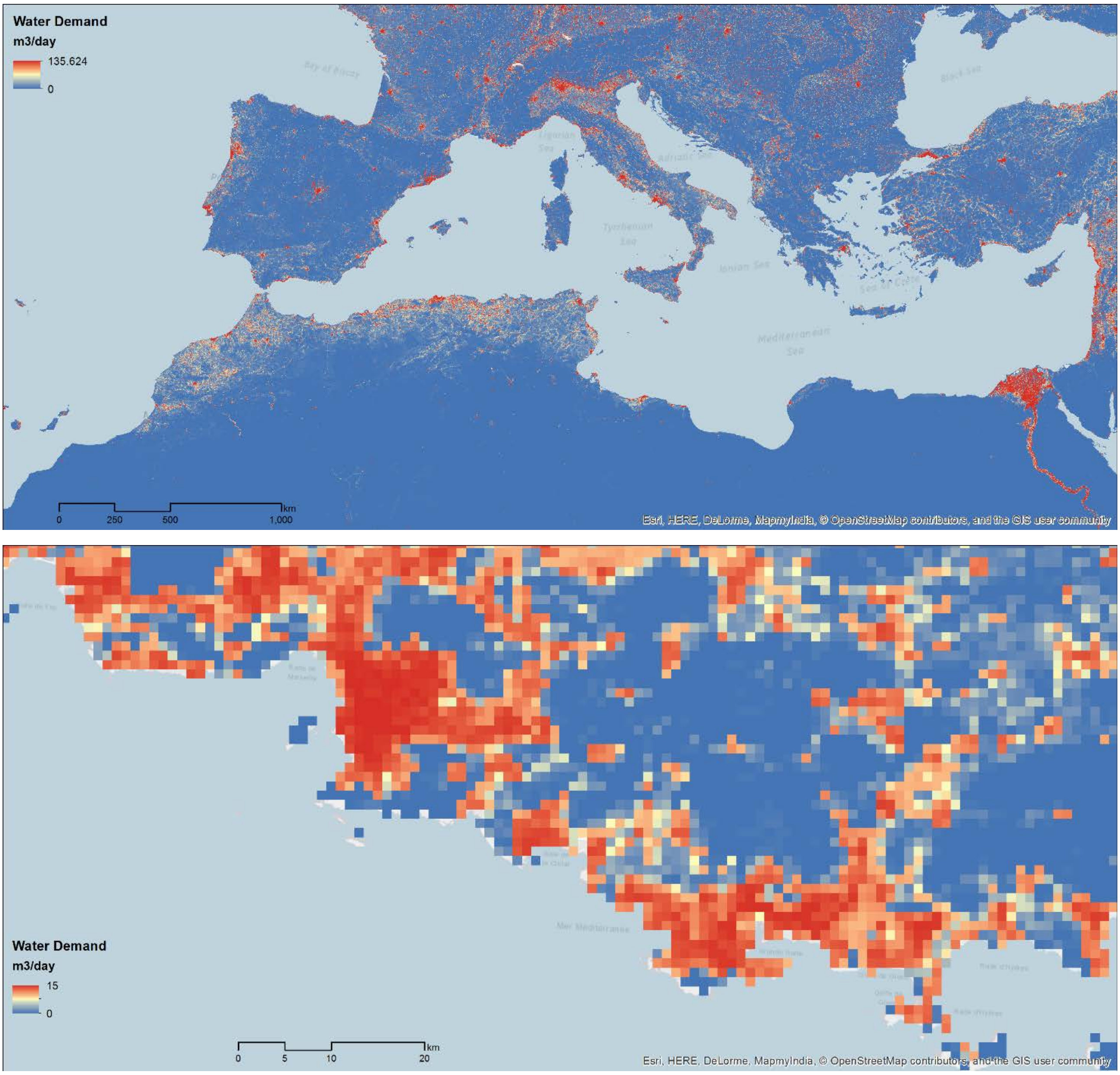


Figure 7 - Water demand distribution Q(x,y), derived from population data (above) and example detail of the Marseille area, France (below). Source: LandScan2013

The diameter can be used to compute the unit cost of the pipeline, using Equation 4 and Equation 5. It should be noted that Equation 4 does not account for singularities, such as river crossings, which may cause a significant local increase of unit costs. In this exercise, we consider distances up to a maximum (L_{max}) of 200 km from source areas.

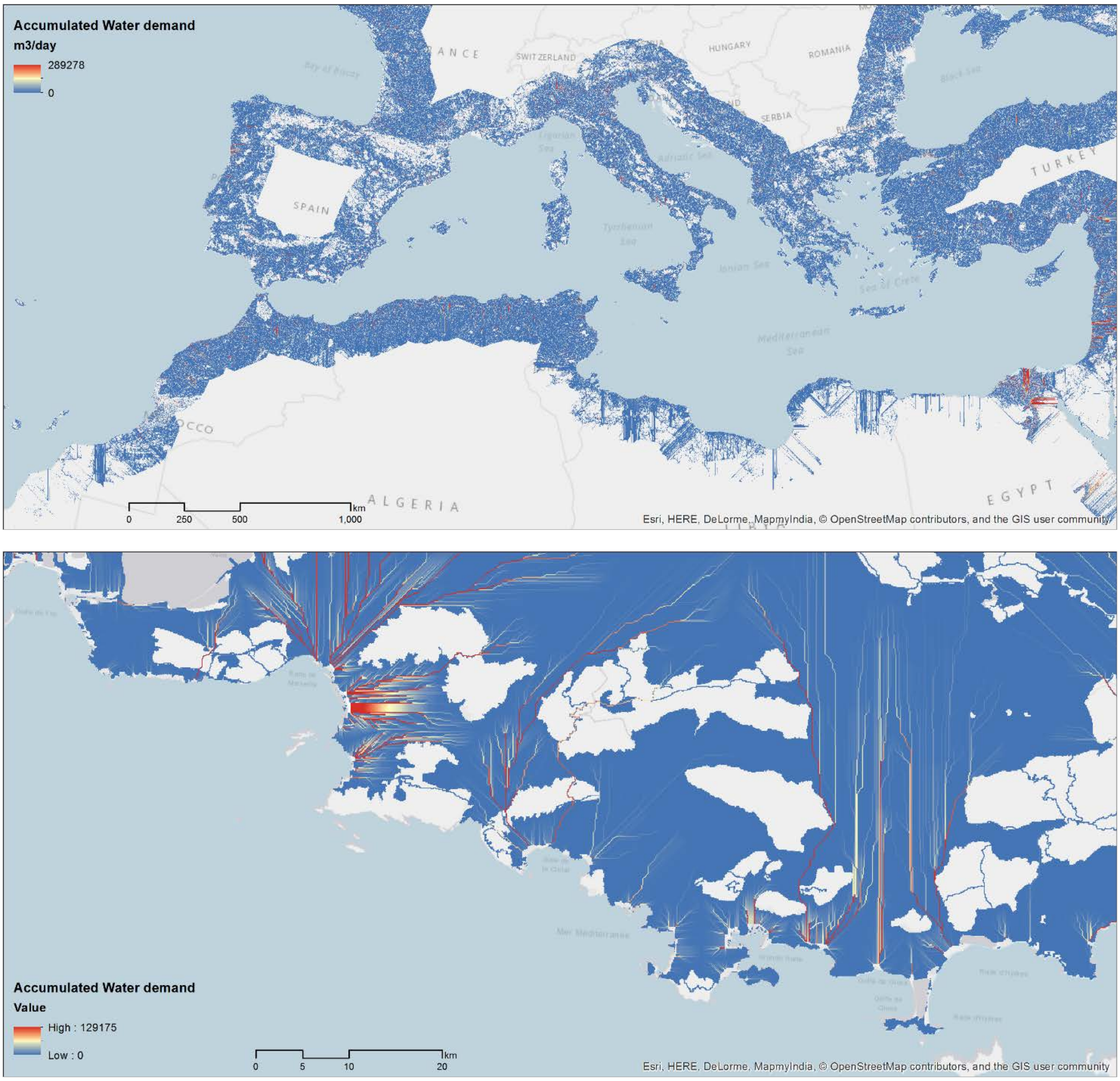


Figure 8 - Accumulated water demand *F(x,y)* considering a maximum distance inland of 200 kilometres (detail). High water volumes on the left correspond to the city of Marseille.

Calculation of the maximum pumping height

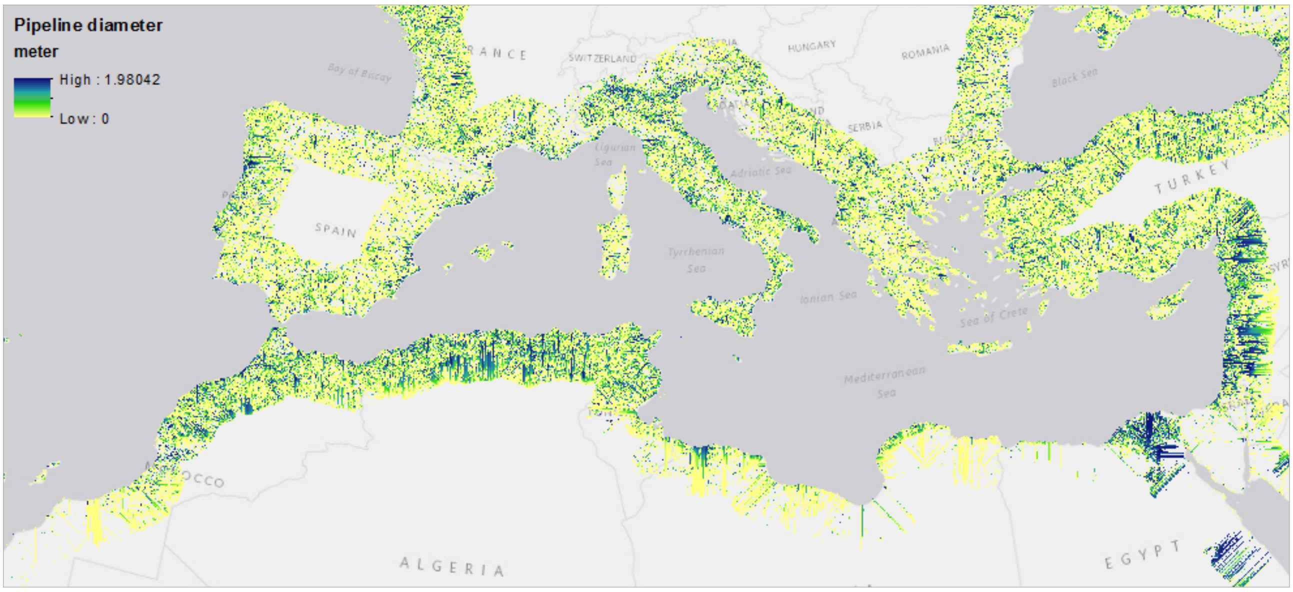
In order to compute the maximum topographic height along each trajectory from a source area to all points in its area of influence (Z_{max}), we used the TauDEM© algorithm “maximumUpslope”, which evaluates the maximum upslope value of an input elevation grid along flow directions[9].

In order to compute the elevation of a generic point x,y upstream of the nearest source location, we inverted the directions of the downstream cost trajectories previously calculated and thus obtained upstream cost trajectories[10]. Since the algorithm is meant for hydrological modelling, the computation of the maximum upslope value fails whenever two or more cost trajectories towards the source area converge (in which case, the reversed upstream trajectory splits); in these cases, the computation of the

[9]See http://hydrology.usu.edu/taudem/taudem5/help53/D8ExtremeUpslopeValue.html

[10] In practice, to avoid nodata gaps, the upstream cost trajectories were calculated using the flow direction tool from ESRI and the negative of the path distance surface as input surface raster.

maximum upslope restarts from the local elevation value for one of the branches in which the trajectory splits.



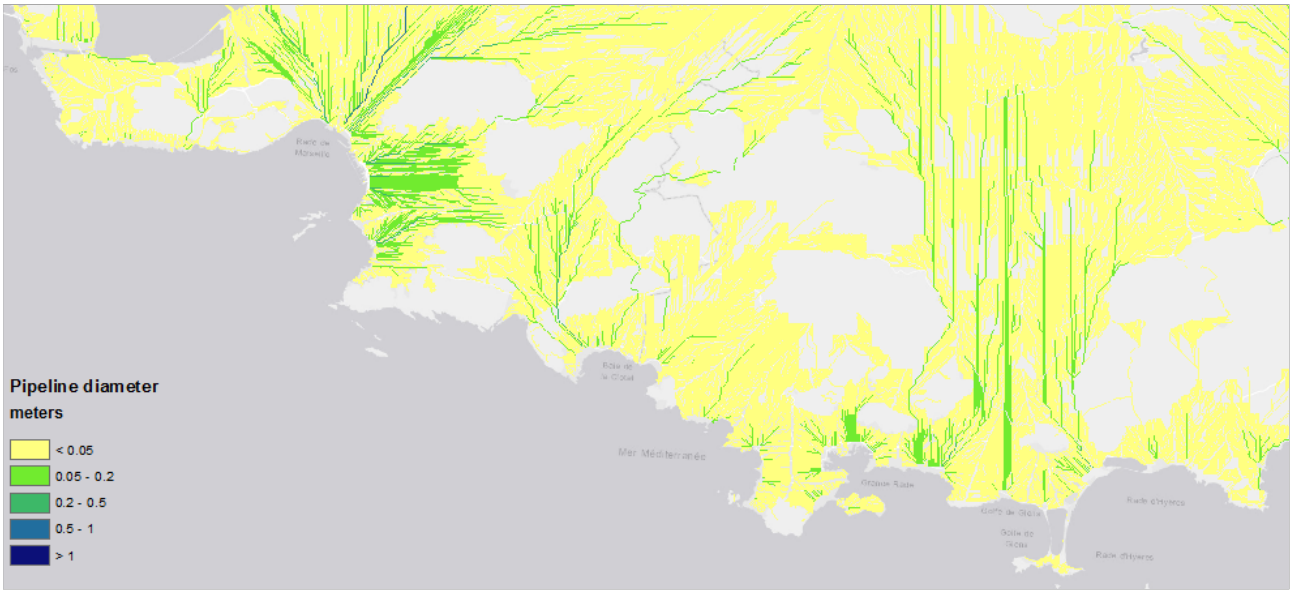


Figure 9 - Estimated pipeline diameter considering a maximum distance inland of 200 kilometres. Above: study area; below: example detail (Marseille area).

In order to correct this effect, it was necessary to iterate the calculation through a dedicated algorithm programmed in Python (see Annex I), that iteratively replaces the elevation at cells where trajectories split (identified as the cells for which the flow accumulation equals zero) with the local mean of the maximum upslope elevation of the neighbouring cells. Figure 10 illustrates how the algorithm operates in practice.

In this way it was possible to compute the maximum topographic height Z_{max} for all points in the study region (Figure 11).

It should be stressed that, in many circumstances, it may be convenient to excavate tunnels instead of overcoming obstacles along a pipeline track. These aspects need to be evaluated at a design stage which is clearly beyond the scope of this analysis, therefore the results obtained here are to be regarded as statistically representative but not as indications for local pipeline track planning.

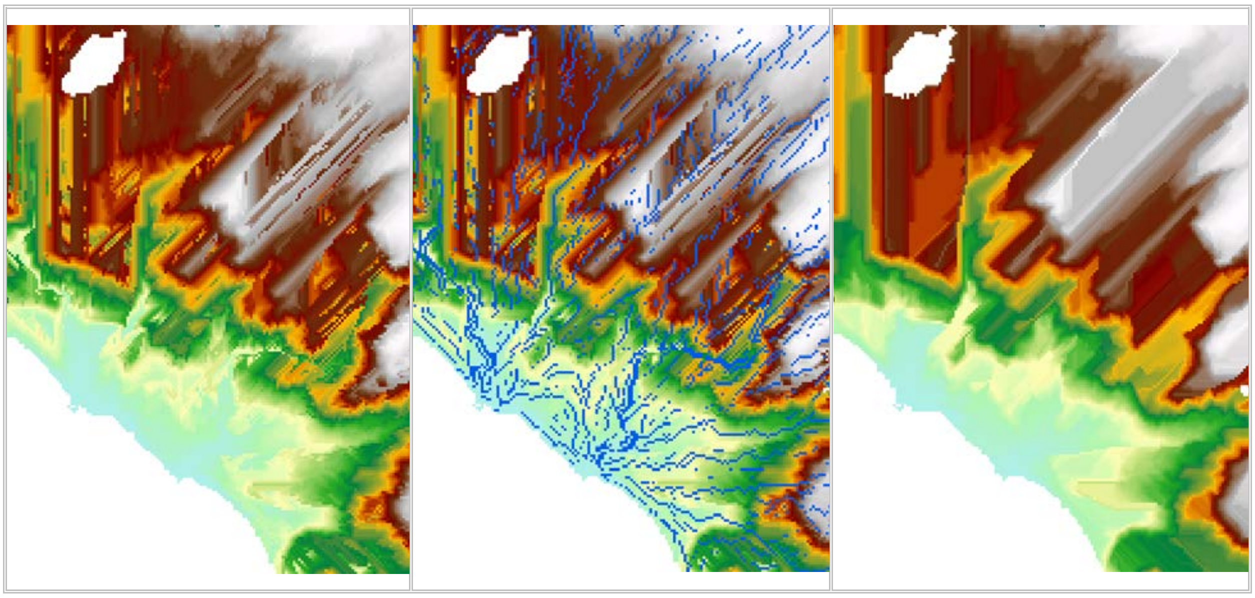


Figure 10 - Maximum upslope procedure: a) before iterations; b) in blue cells where Z_{max} does not propagate correctly; c) final result after iterations.

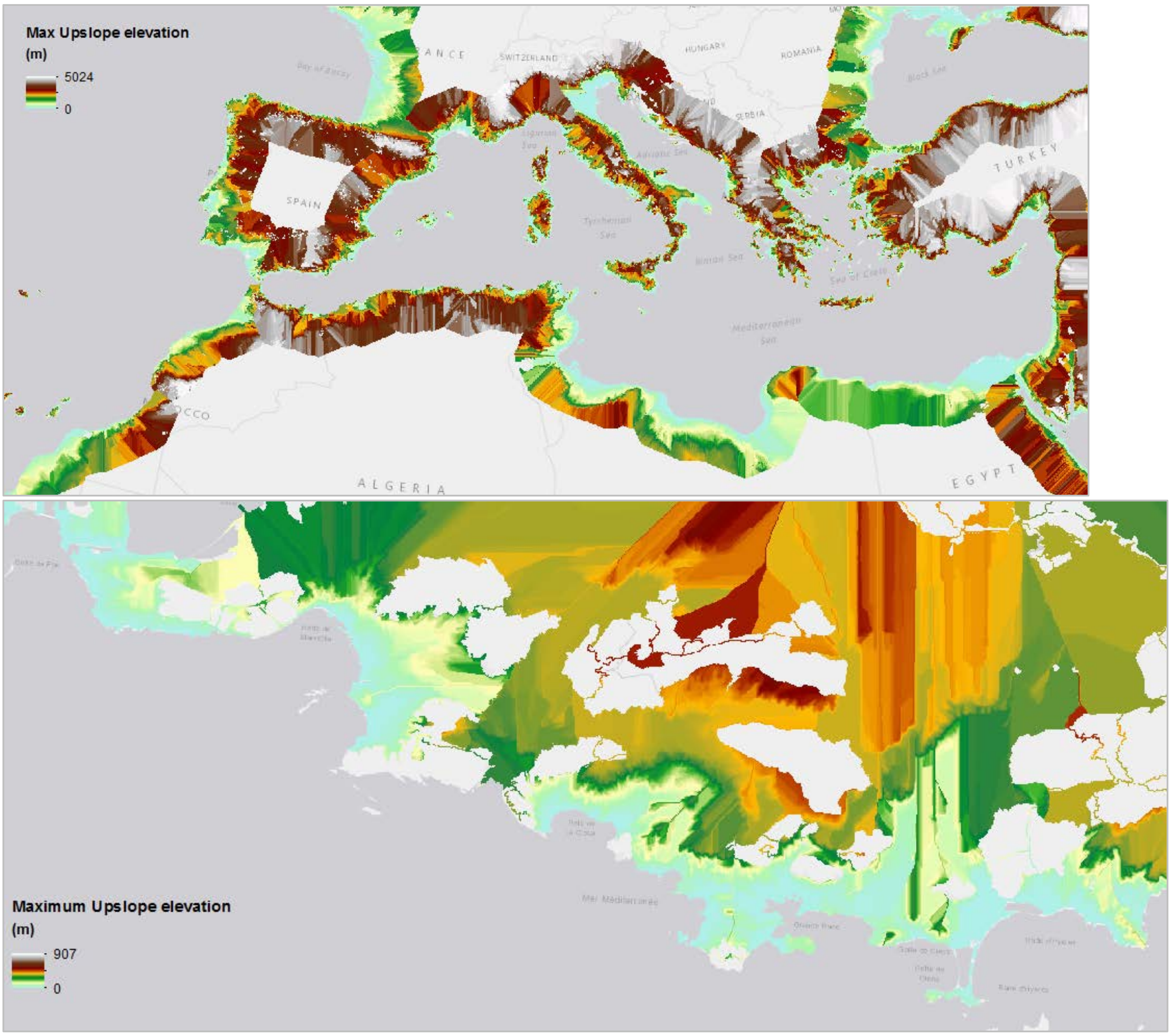


Figure 11 - Maximum upslope elevation from source locations along upstream trajectories, for a maximum distance inland of 200 km (above) and detail, Marseille region (below)

Cost of PV energy

Solar radiation data used to calculate the potential PV energy production have been supplied from the CM SAF Collaboration (www.cmsaf.eu), using the SARAH solar radiation data set (Müller et al., 2012, Müller et al.,2015). The hourly solar radiation data values have been combined with models to estimate the PV output power as a function of solar irradiance, temperature and wind speed (Huld and Gracia Amillo, 2015). The resulting geospatial map contains an estimate of the annual average PV energy production for a PV system with the following properties:

- Crystalline silicon modules
- Modules are mounted equator-facing at the local optimum angle that maximizes the annual PV energy production.
- Estimated system losses: 10% (losses in inverters, cables etc.)

Using the resulting map of annual PV energy output, the cost of PV electricity was then calculated using the following assumptions:

- All the energy that can be produced will be used (no curtailment)
- Cost of system: 1000euro/kWpeak
- lifetime: 20 years
- interest rate: 5%/year
- maintenance: 2% of initial cost per year (20euro/kWpeak/year)
- no battery storage
- The cost is apportioned between paying back the initial cost (50%), interest payments (30%), and maintenance of the system (20%)

Figure 12 shows the map of costs evaluated for the whole of the study region. From the PVGIS dataset, the average cost of PV energy is calculated for each suitable costal location as the zonal average within the source area, and associated to the source's area of influence in order to assign to each point the PV costs of the nearest source (Figure 13).

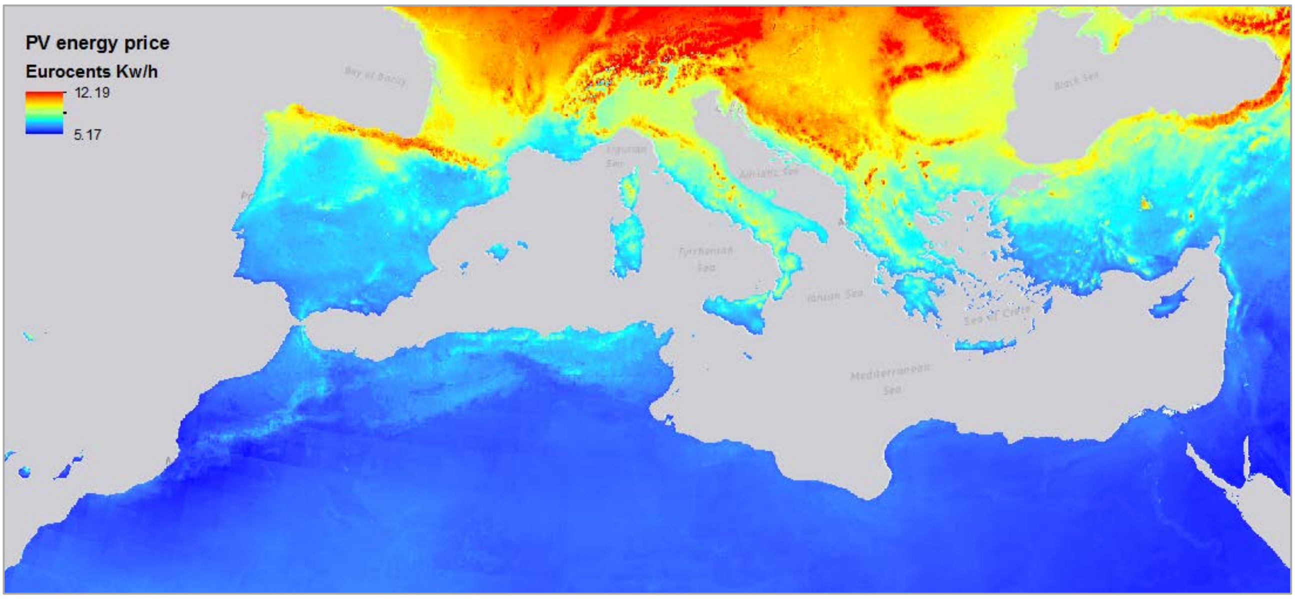


Figure 12 - Costs of photovoltaic energy in the study region (source: PVGIS)

Figure 13 - Average PV energy costs at costal locations

Mapping transport costs

Based on the above information, it is possible to compute the cost of investment in pipelines (Equation 7), the energy requirement for pumping to overcome the maximum height and friction losses (Equation 8), and the total transport cost (Equation 9). These are shown in Figure 14, Figure 15 and Figure 16 respectively. Annex II summarizes the GIS processing used to generate the maps.

The maps allow appreciating the distribution of costs and energy requirements to supply desalinated seawater to the population living within 200 km from the coasts of the study region. The latter is about 280 million persons. Figure 17 shows the distribution of energy requirements and total transport costs to supply such population with desalinated seawater. A significant share (more than a quarter of the total population) can be reached with an energy requirement below 1 kWh/m3, and about a half of the population can be reached with a total transport cost below 1 Euro/m3.

Way forward: mapping opportunities for desalinated seawater production

The transport cost and energy requirement for the supply of desalinated seawater is essential to appraise the feasibility of conveying water from the plant to the users. However, it is equally important to appraise the feasibility of desalinated seawater production. The latter depends on the possibility to reach out demand, on the economic costs of seawater desalination, storage and transport, and on the ecological sensitivity of the sites potentially useful for desalination (Figure 18). The analysis outlined above covers one of these criteria, while future work will be devoted to characterizing the other criteria defining the opportunity of PV/RO seawater desalination. Along with the possibility to reach demand at a cost and energy requirement below a threshold, another factor driving the opportunity of seawater desalination is the occurrence of droughts or water stress.

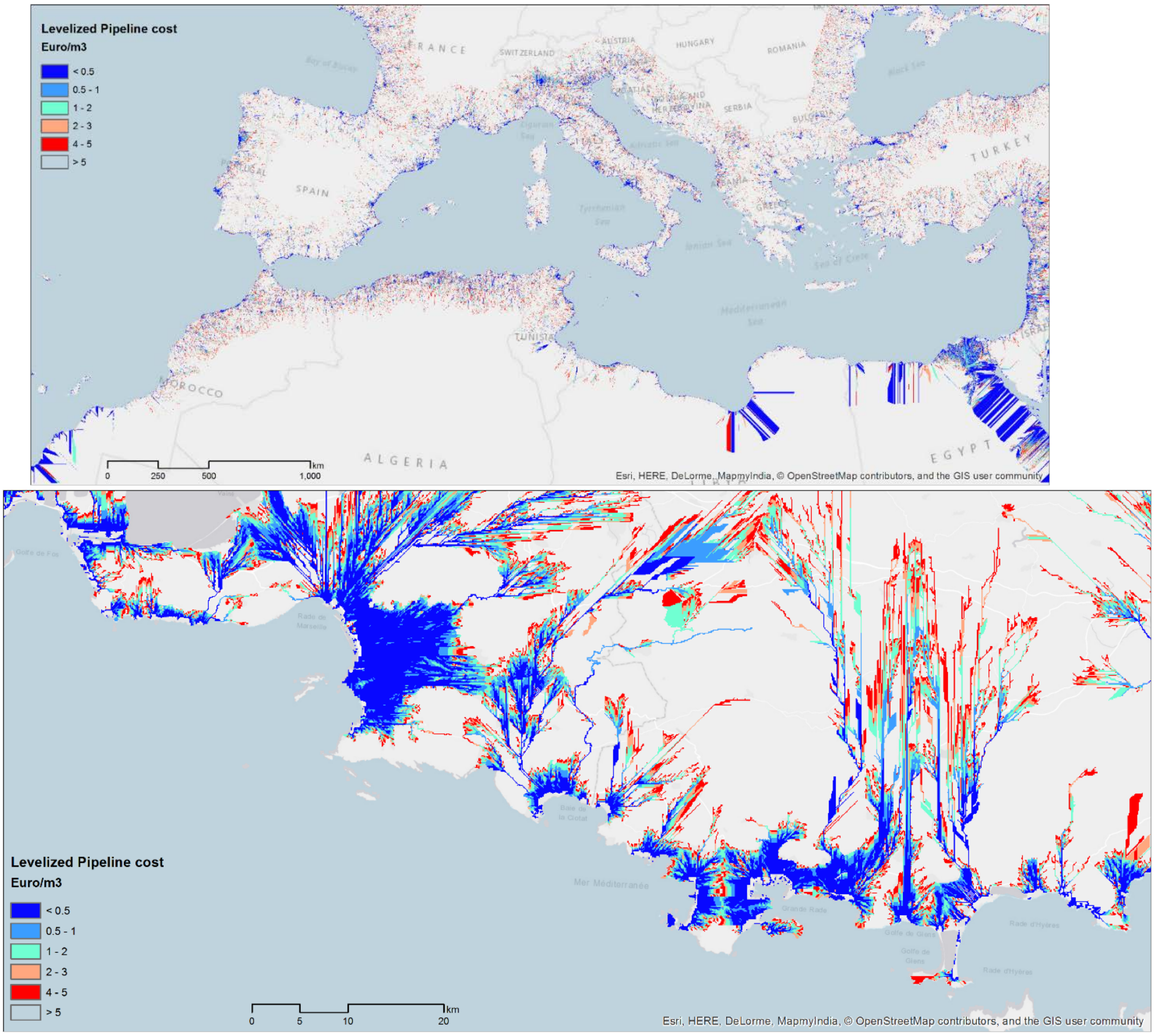
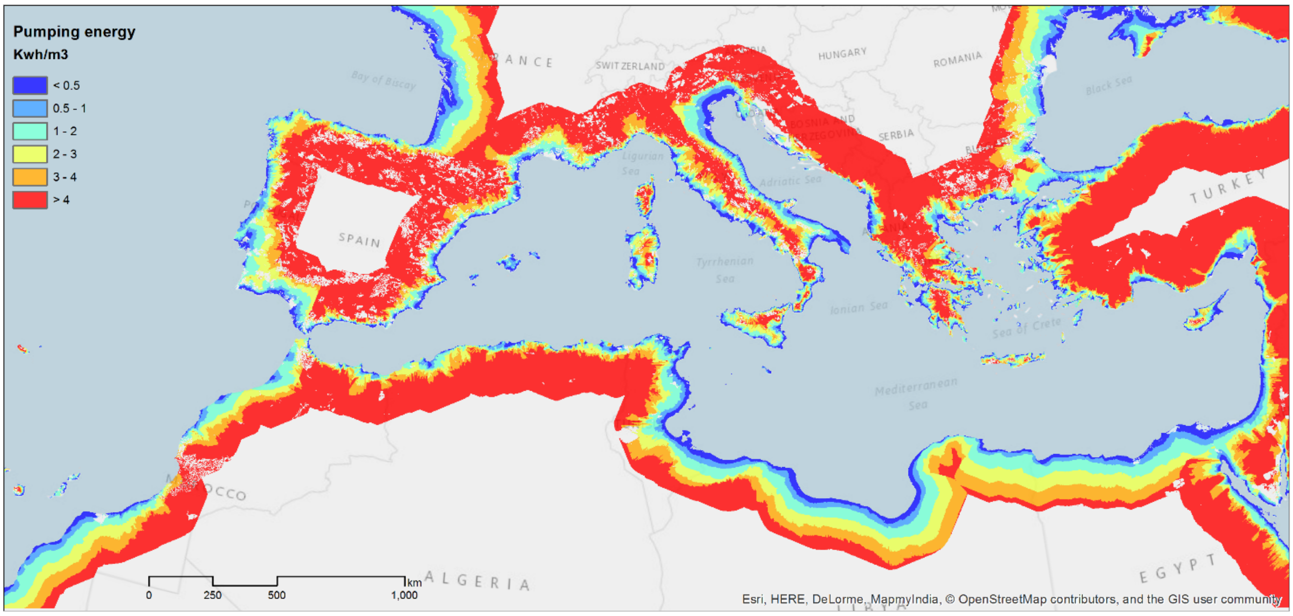


Figure 14 Levelized investment costs in €/m^3 of water conveyed by the pipeline, for a maximum distance inland of 200 km (Above: whole region; below: detail, Marseille region).



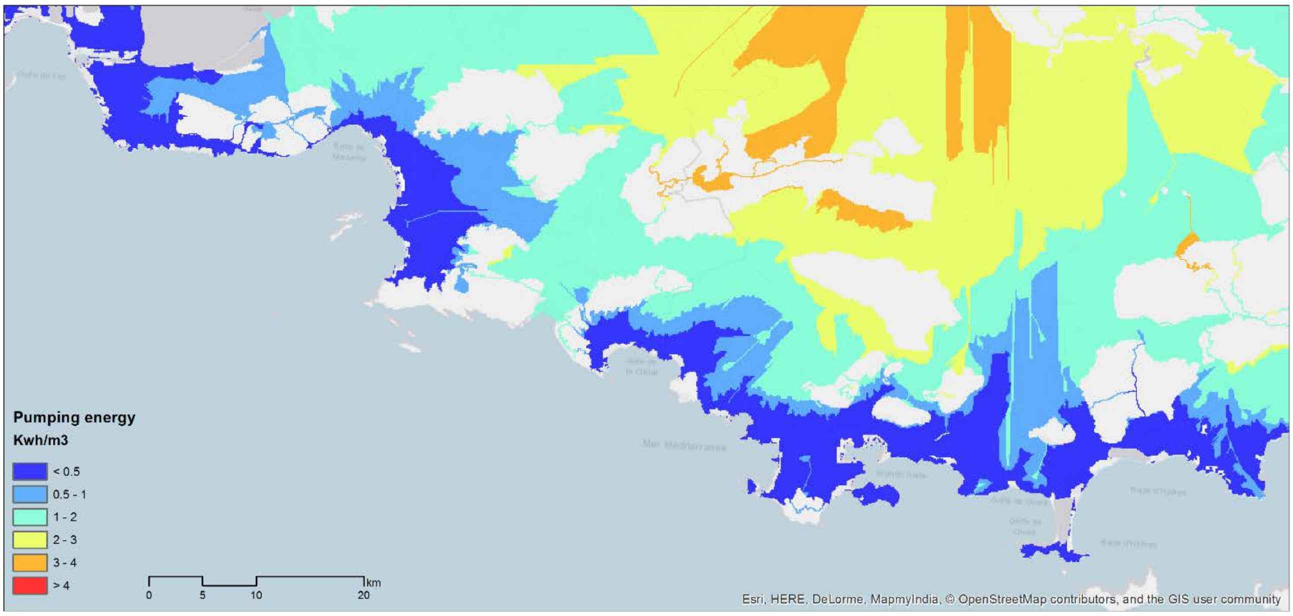


Figure 15 Map of pumping energy required to transport and distributed a cubic meter of desalinated water considering a maximum distance inland of 200 kilometres (Above: whole region; below: detail, Marseille region).

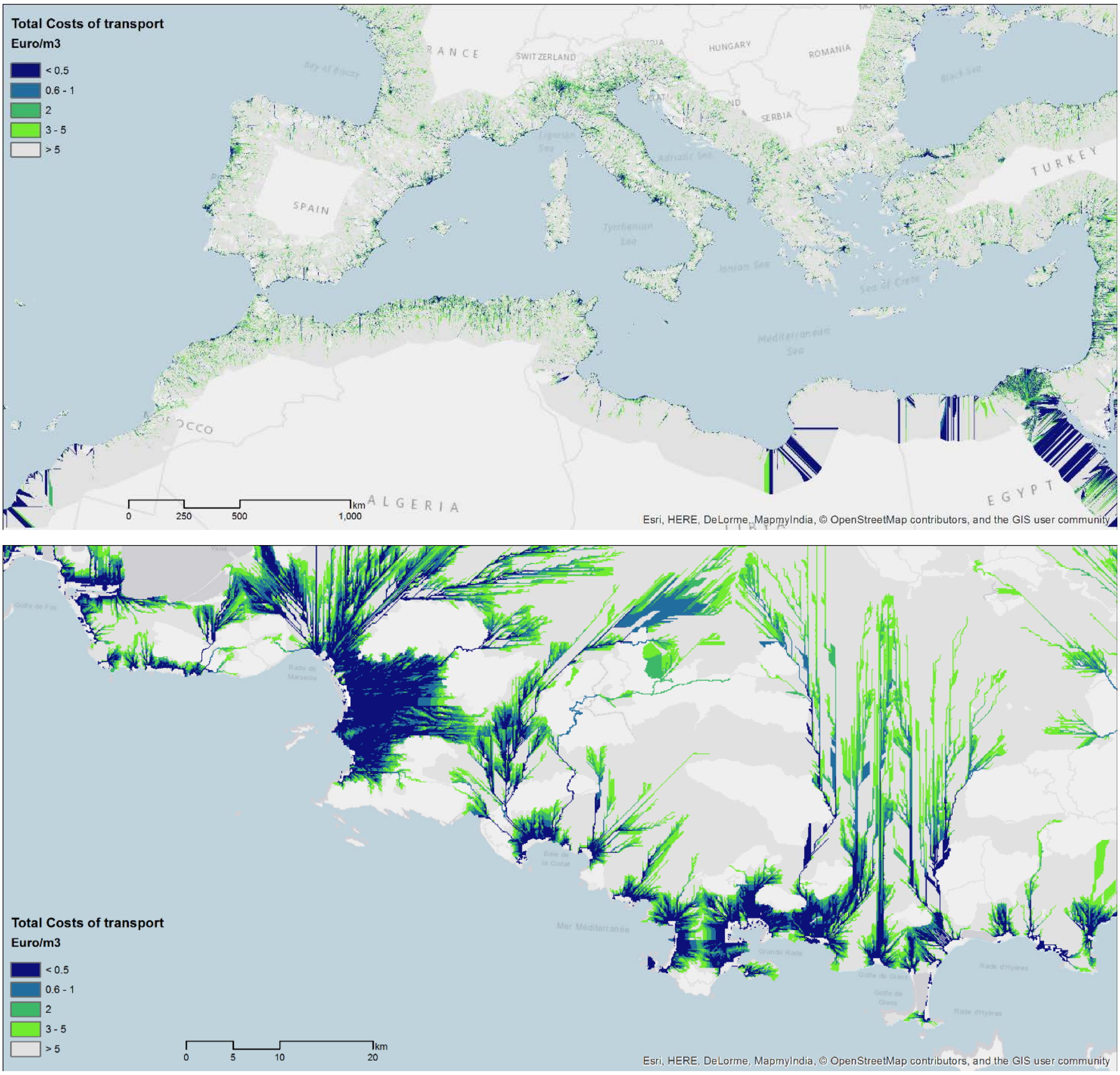


Figure 16 - Total costs of transport for cubic meter of desalinated water, including O&M, for a maximum distance inland of 200 km, for the whole study region (above) and detail, Marseille region (below)

The costs of production depend on the characteristics of seawater (*in primis*, salinity and temperature), as well as on the capacity of the plant. Salinity and temperature determine the pressure required in the RO process. They can be estimated as a first approximation on the basis of available data (Figure 19 and Figure 20).

The capacity of the plant depends on the expected production volume. The volume of water (m^3) that should be produced annually by the plant at a given source area can be computed as:

$$V = 365 \int_A \mathrm{Q(x,y)} B(x,y) dx\, dy \qquad \textit{Equation 10}$$

Where A is the area of influence of the source area, and B(x,y) is the Boolean condition stating whether the demand at point (x,y) should be satisfied. One possibility to specify B(x,y) is the Boolean statement B(x,y) = "$C_{transport}(x,y) \leq X$ ", where X is a transport cost threshold beyond which the cost of water transport is considered prohibitively high. Total energy demand for the transport of water inland (TE, kWh) is similarly computed as:

$$TE = 365 \int_A Q(x, y)\Psi(x, y)B(x, y)dx\,dy \qquad \text{Equation 11}$$

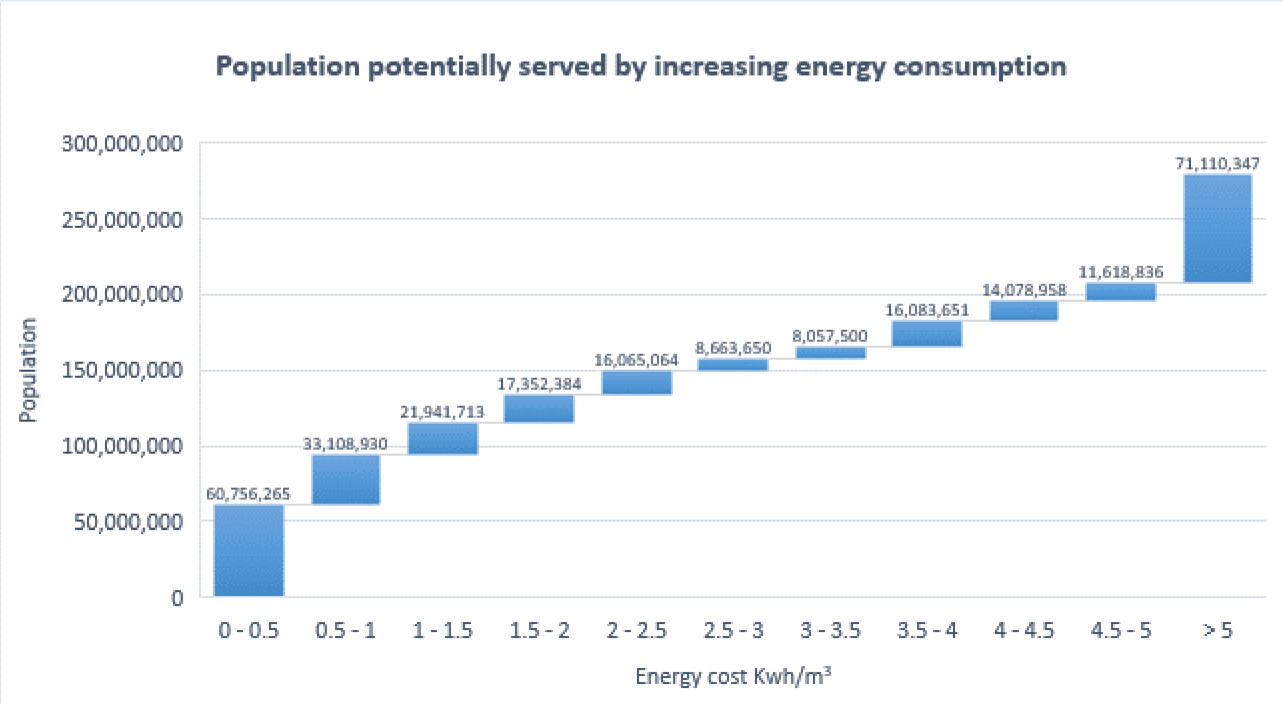
On the basis of the RO pressure and production volume, as well as on the basis of the total energy required for transport to the final users, it is possible to design the required PV plant capacity, hence the investment in energy production. Energy production and, consequently, water production will follow a temporal scheduling that depends on the availability of solar energy and will be in general staggered with respect to water demand, with a consequent need to store water. The variability of energy production will also call for some form of electricity storage. On the basis of the time patterns of solar energy availability, it is possible to compute the electricity and water storage requirements following procedures as outlined in Annex III.

It is important to observe that energy and water can, to some extent, be stored simultaneously by exploiting the elevation around a potential desalination site. By pumping water directly into a reservoir at elevation Z, it is possible to store energy in excess while securing a pressure head Z that reduces subsequent pressure (hence energy) demand for the RO process. In this regard, the maximum available elevation in the proximity of the potential desalination sites is a topographic factor of relative advantage: sites with higher elevations nearby will be favored over sites with lower elevations (Figure 21).

Finally, the ecological impacts of desalination are associated to local factors (e.g. entrapment of fish in the water intake works), to the disposal of brine, and membrane cleaning treatments. Mitigation measures should be implemented to reduce undesirable effects. Marine ecosystems that are particularly sensitive to brine are those with presence of *Posidonia oceanica* and other seagrass (Figure 22). *Posidonia oceanica* is classed as a priority habitat type by Directive 92/43/CEE; it covers vast areas between the subsurface and 35 m depth (Gacia et al., 2007) and plays an important ecological effect across the Mediterranean (Bouderesque, 2004); it shelters a high biodiversity of organisms, contributing to improve water quality (Gacia et al., 2007) and regulating biogeochemical fluxes along the coast (Romero et al., 1994). In fact, all Mediterranean Member States have used *Posidonia oceanica* as indicator to establish the ecological status of their water bodies in accordance to the Water Framework Directive (2000/60/EC). Many authors recommend to avoid the design and construction of brine discharges in areas containing these ecosystems. In the event of impossibility to fulfill of this recommendation, mitigation measures should be applied considering the volume of the effluent, the depth, and ranges of the meadows and hydrodynamics of the system (Sanchez-Lizaso et al., 2008).

In addition, sea floor topography and marine currents may be important in determining the dilution of the brine plume.

In the next phase of the work, appropriate indicators for all these factors will be computed for each of the identified potential sites for PV/RO seawater desalination.



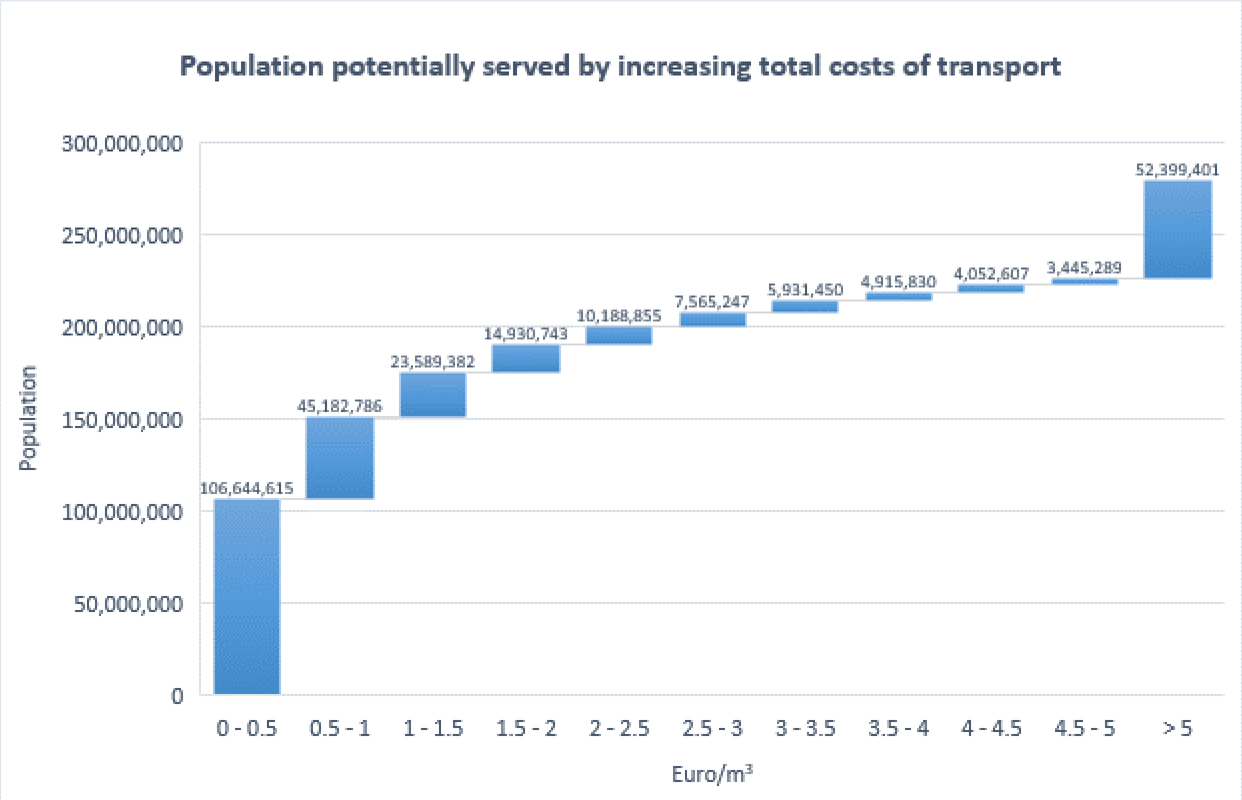


Figure 17 – distribution of population by energy requirements for transport (above) and total transport costs (below)

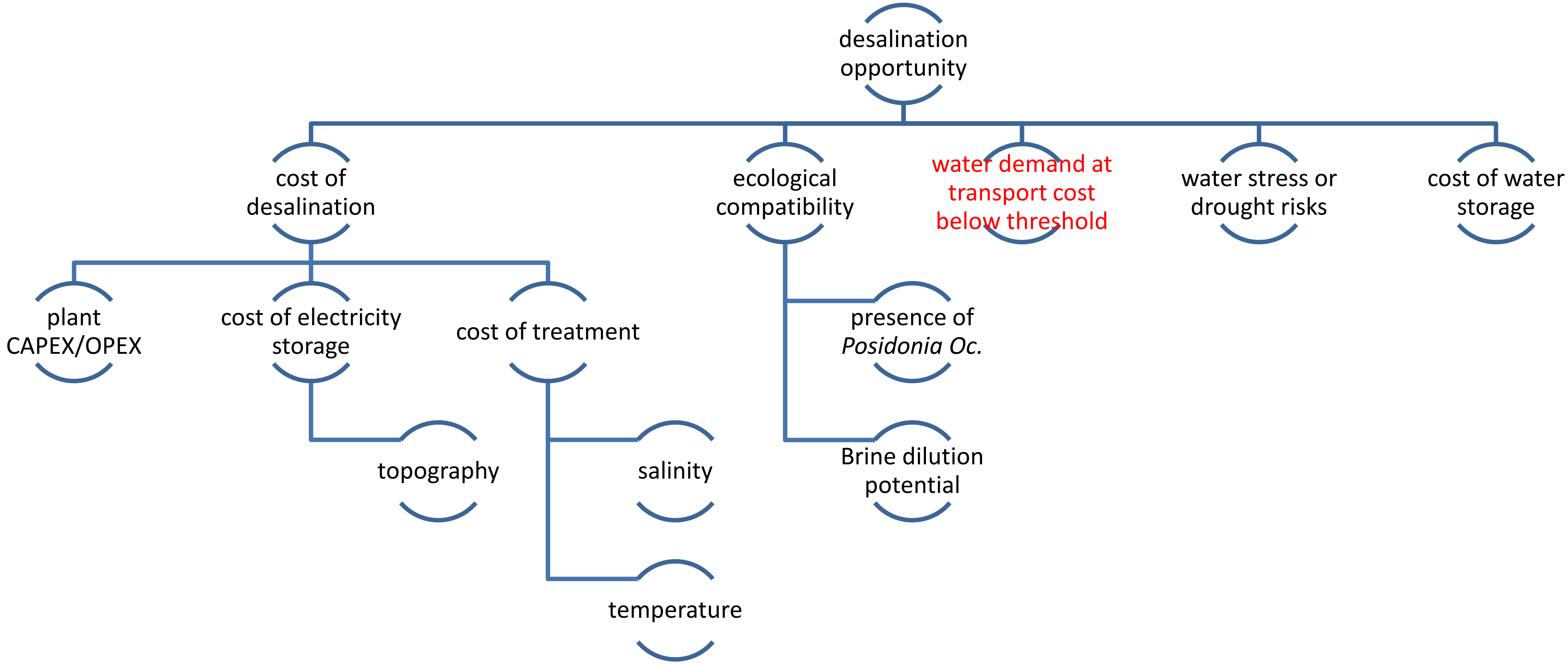


Figure 18 – overview of the desalination opportunity mapping exercise. The analysis presented in this contribution corresponds to the component marked in red. CAPEX = capital expenditure; OPEX = operation expenditure.

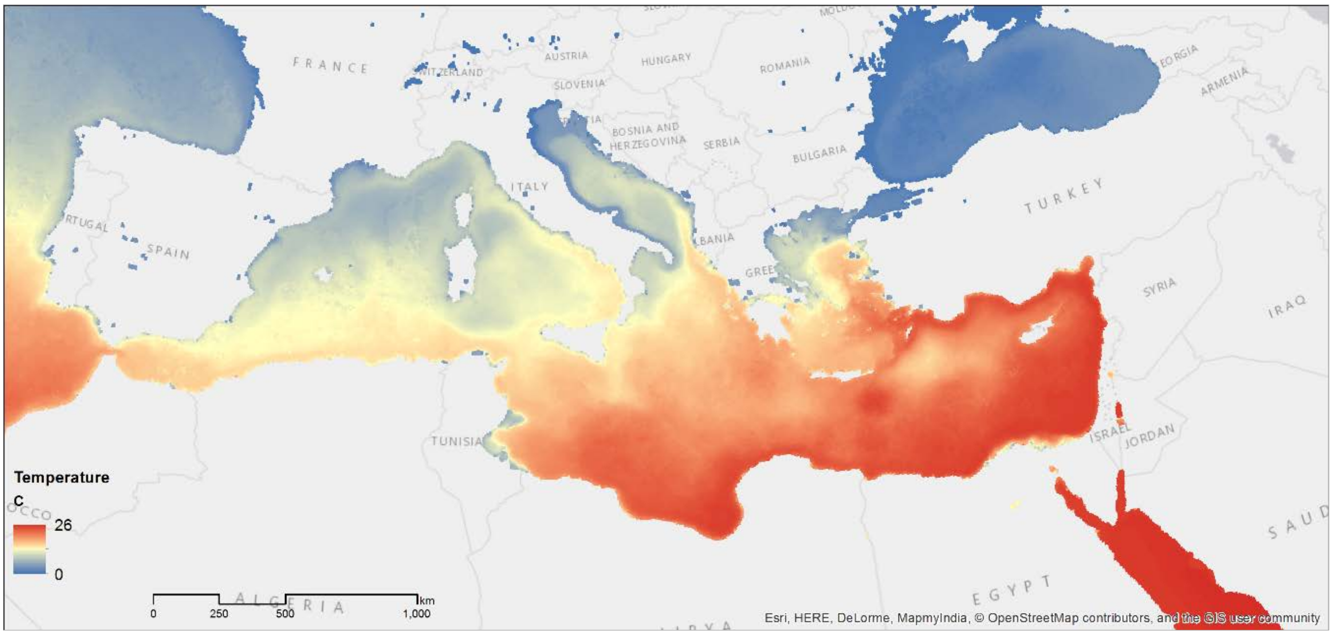


Figure 19 Mediterranean Sea temperature (Source EMIS)

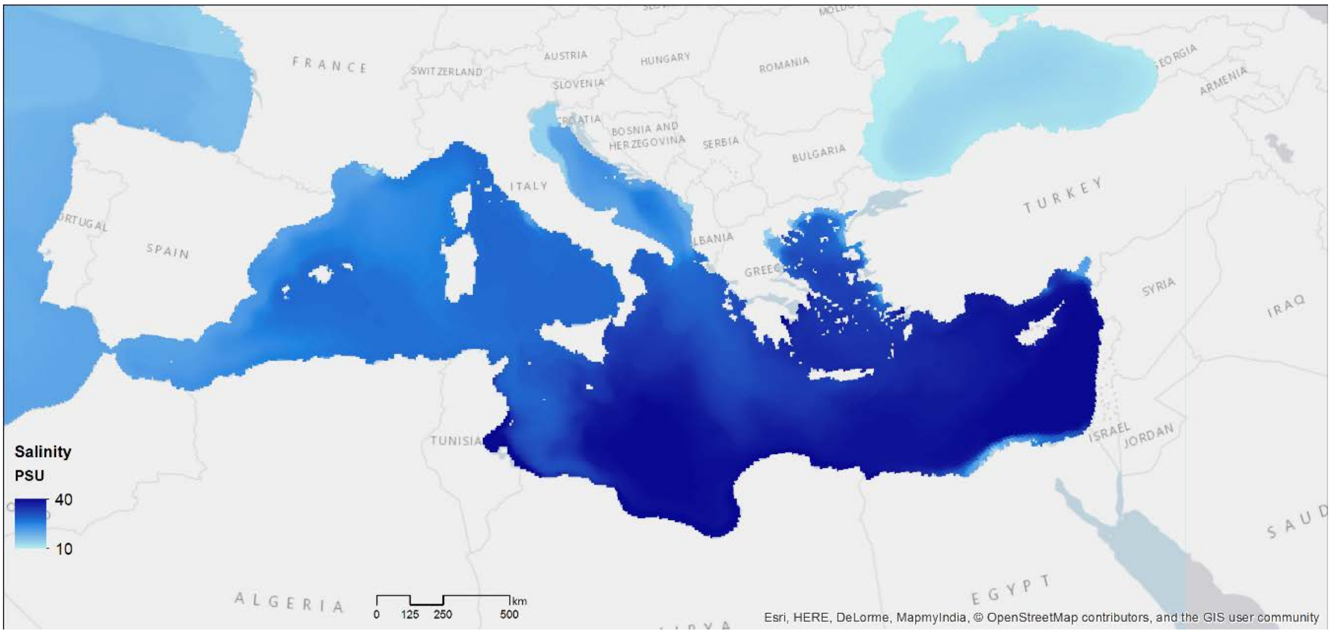


Figure 20 Mediterranean Sea salinity (Source EMIS)

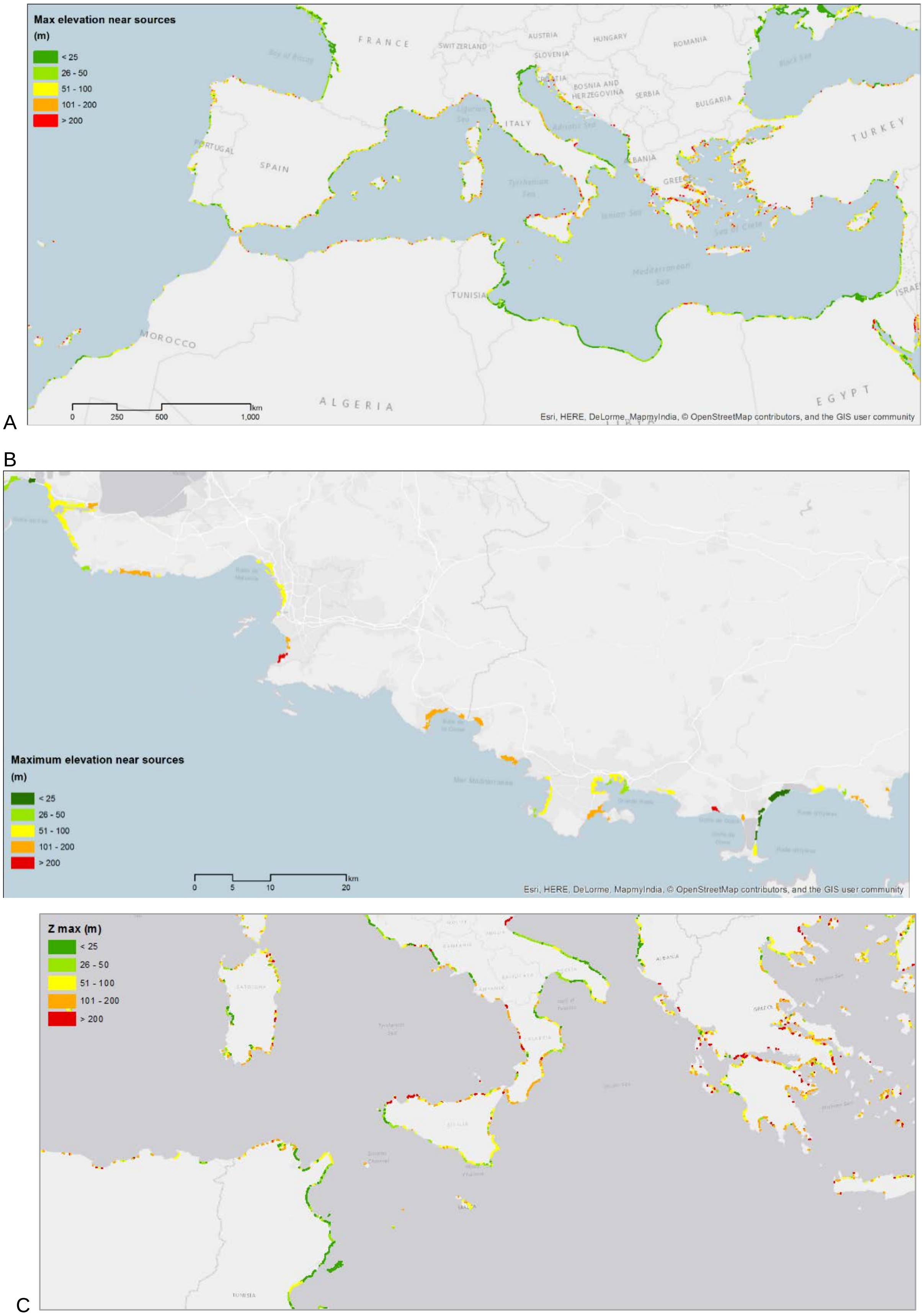


Figure 21 Map of maximum elevation 1 km nearby the source costal locations (A: overview; B,C: details on the Marseille area, France, and around Southern Italy and Greece)

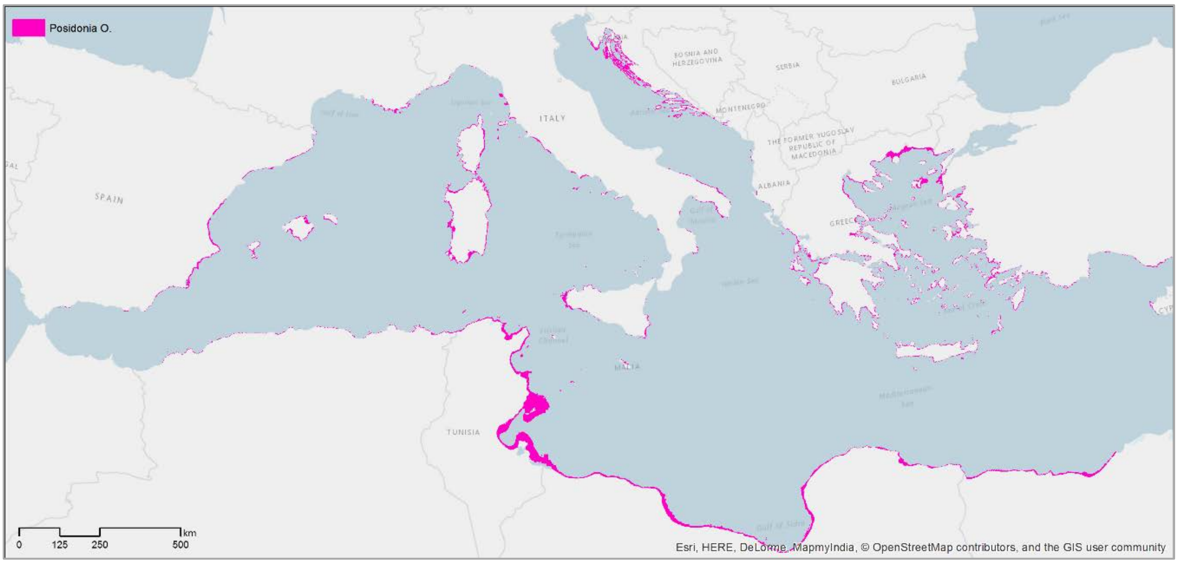


Figure 22 Occurrence of *Posidonia Oceanica.* (Source: Ocean Data Viewer UNEP-WCMC)

Conclusions

This report presents the general modelling concepts and the results of an exercise in mapping the costs of transport of desalinated water from coastal production sites towards users within 200 km of the coastline. It is shown that desalinated seawater can be deployed to more than a half of the population in this part of the Mediterranean at a cost below 1 Euro/m3. This cost makes desalination a source of water that can be considered competitive with emergency solutions (such as transport with tanks), and even with marginal resources such as deep fossil groundwater, in areas with severe water stress or during periods of droughts. As important as water transport, the costs and ecological impacts of desalination are key to decision making and will be addressed in the next phase of the work.

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Annex I – Python script for the calculation of maximum obstacle elevation along trajectories

```
# Name:           ZmaxLoop
# Purpose:         Compute maximum upslope elevation using TauDem tool D8ExtremeUpslope. The script
                  iterate a user defined number of times (range values. Given a flow direction
                  dataset (flowDir), at each iteration cells in the substvals map (i.e. cells with
                  flow accumulation equal zero) are substituted with the mean Z value of the
                  neighboring cells
#
# Author:         doratch
# Created:        28/03/2017
# Licence:        ESRI (arcpy)
# Requirements:   Spatial Analyst Extension
# -------------------------------------------------------------------------------------------
# Import system modules
import …
# Import Local variables:
WS = r"D:\WORKSPACE\DESAL\Analysis\Zmax\ZmaxLoop\output"
origDem = r"D:\WORKSPACE\DESAL\Data\WS\topography\srtm.tif"
flowDir = r"D:\WORKSPACE\DESAL\Analysis\Zmax\ZmaxLoop\input\flowdir.tif"
substval = r"D:\WORKSPACE\DESAL\Analysis\ZmaxTest\ZmaxLoop\input\map_substvals.tif"
inDem = arcpy.Raster(r'D:\WORKSPACE\DESAL\Analysis\Zmax\ZmaxLoop\output\Zmaxup0.tif')
# Setting workspace
import …
# Check out the ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")
# Load required toolboxes
arcpy.ImportToolbox("C:/dev/TauDEM/TauDEM5Arc/TauDEM Tools.tbx", "td")
# ===========================================================================
start_time = datetime.datetime.now()
print "Start Time:", str(start_time)
try:
    for i in range (1,501):
        print "start iteration " + str(i)
        print "start computing new dem..."
        newDem = Con((Raster(substval) == 1),
                 FocalStatistics(inDem, NbrRectangle(3, 3, "CELL"), "MEAN"), origDem)
        newDem.save(os.path.join(WS, 'newDem' + str(i) + '.tif'))
        newDem = (os.path.join(WS, 'newDem' + str(i) + '.tif'))

        print "start computingsrc Z max..."
        maxup = (os.path.join(WS, 'Zmaxup' + str(i) + '.tif'))
        arcpy.td.D8ExtremeUpslope(flowDir, newDem, "", False, "", "8", maxup)
        inDem = (os.path.join(WS, 'Zmaxup' + str(i) + '.tif'))
```

Annex II –GIS processing notes

Parameter	Tool/Function Description	Function Inputs	Function Output
PIPELINE COSTS			
Path distance **(pD)**	Pipeline cost weighted length (m) to reach a generic point x,y (path distance algorithm)	Cost surface, sources	downstream cost directions (costDIR), pD, influence area
Cost Energy zones	The cost of energy in the area of influence	Cost surface, ψ_i	ENRG_cost_ alloc_eucent
Length **(L)**	Pipeline length (m) to reach a generic point x,y (Flow length algorithm)	downstream cost directions (costDIR)	L
Discharge **(Q)**	Water demand (m3/day) at generic point x, y computed as function of population, where ***Q = Pop * 0.15***	Population data (LANDSCAN2013 _scaled)	Q
Cumulated discharge **(F)**	Cumulated water demand (m3/day) along the least cost trajectory (Flow accumulation algorithm) (Equation 2)	downstream cost directions (costDIR), Q	F
Diameter **(D)**	Pipeline diameter at each generic point x, y as function of F, where (Equation 3): ***D= Power (F, 0.3803) * 0.0104***	F	D
E_m **(Em)**	Expenditure (€/m) for one meter of pipeline with diameter D, where (Equation 4): ***Con("D_50"<= 0.8, Power(("D_50" * 1000),1.29) * 0.088433 + 65.8, Power(("D_50" * 1000),1.785) * 0.0040115 + 68.1)***	D	Em
E_{unit} **(Eunit)**	The unit expenditure (€/m/m3) for a pipeline conveying the discharge F(x,y) to the generic point x, y, where: $E_{unit} = E_m / F * 365$ OR $E_{unit} = \frac{E(\sigma)d\sigma}{365 F}$	Em, F	Eunit
E_{pipe} **(Epipe)**	The cumulated total expenditure (€/m/m3) for a pipeline conveying the discharge F(x,y) to the generic point x, y, where: E_{pipe} = FL (Eunit) OR $E_{pipe} = \int_{\gamma(x,y)} \frac{E(\sigma)d\sigma}{365 F}$	Eunit, downstream cost directions (costDIR)	Epipe

LC_{pipe} **(LCpipe)**	The levelized investment cost of the pipeline (€/m3) as (Equation 6): LCpipe = Epipe/pva OR $LC_{pipe} = \frac{E_{pipeline}(x,y)}{pva(0.05,50)}$	Epipe, pva	LCpipe
ENERGY COSTS			
L_{fric} **(fricL)**	Energy Friction loss computed as function of L, where: ***Lfric = 0.005 * L*** OR $L_{fric} = J \int_{\gamma(x,y)} d\sigma$	L	fricL
EN_{geodet} **(Zmax)**	Energy pumping needs as maximum elevation gap between source and destination	SRTM, flowDir, substvals	Zmaxup
ENRG	The energy required to transport and distribute a cubic meter of desalinated water to the generic point x,y computed as (Equation 7): ***ENRG = (9810 * ("Zmaxup_200.tif" + "fricL.tif") * (2.78E-7)) / 0.75***	Zmaxup, fricL	ENRG
LEVELIZED COST OF TRANSPORT			
C_{tran} (Ctran)	The total cost to transport a cubic meter of desalinated water to the generic point x,y computed as (Equation 8): ***Ctran = LCpipe + ("ENRG_cost_ alloc_eucent " * ENRG) + 0.02 * Epipe***	LCpipe, ENRG, Epipe, ENRG_cost_eucent	Ctran

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