Regional Macro-Model for Transboundary Water Resources Planning

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KEY FINDINGS

The macro model identifies optimal pathways and sizing of infrastructure to allocate freshwater from different potential locations suitable for seawater desalination at the Mediterranean and the Red Sea to demand areas in Palestine and Jordan.

The macro model is formulated as a non-linear optimization problem where the objective function minimizes the combined cost of sea water desalination, infrastructure and energy.

Energy is the key component of the combined cost and its minimization leads to the most cost-effective solutions.

MOTIVATION

Freshwater production and allocation are a key challenge of the SALAM Initiative in view of the substantial freshwater deficits that are expected in the coming decades [Future Freshwater Deficits in Palestine and Jordan, p. 18]. It is clear that massive seawater desalination will be needed in order to match these deficits, as in the region there are no additional renewable freshwater resources that can be exploited. The selected locations for seawater desalination, denoted hereafter as Production Points (PP), are: 1) North of the city of Netanya, Israel (PP-1), 2) Extension of the plant in Gaza, Palestine (PP-2), 3) North of Haifa bay, Israel (PP-3), 4) Aqaba, Jordan (PP-4), 5) Extension of the plant near the city of Ashdod and/or new plant at Ashdod, Israel (PP-5) and 6) Extension of the plant in the city of Hedera, Israel (PP-6). Water supplied from Haifa would transit through a tunnel and released into Lake Tiberias. The elevation difference between the Mediterranean Sea and Lake Tiberias could be used for hydropower. This is presented in [Large-Scale Hydropower Plant at Lake Tiberias in the Context of Transboundary Water Transfer, p. 50]. The model focuses on the optimal distribution of the desalinated water to the Connection Points, which were defined for each demand cluster [Water Conveyance System for Freshwater Deficit Coverage in Jordan and Palestine, p. 37]. The distribution of the allocated water with each cluster is beyond the scope of work of the project and not addressed. Numerous demand clusters will face substantial freshwater deficits. There is a need to determine the capacity of each production point and to outline the water transportation infrastructure in such a way that the freshwater deficit at each connection point for the selected time horizon is covered. For the present study, the planning horizon 2050 has been considered.

The objective is to determine the best solution in terms of cost for a specified planning horizon. Any other solution under consideration by the regional decision makers could be compared to the “cost minimal solution”. In other words, the Macro-Model provides the means to estimate the economic implications of the decision makers preferences, e.g. with regard to location and productions capacities of SWD-plants, on the water allocation pathways, associated energy requirements, total cost and specific water cost.

METHODOLOGY

The macro model is formulated as a Mixed Integer Non-Linear Programming (MINLP) problem. The aim is to find the cost-optimal way to supply the connection points from the production points (desalination plants). The optimization relies on the network outlined in [Water Conveyance System for Freshwater Deficit Coverage in Jordan and Palestine, p. 37], and therefore, on the connections between

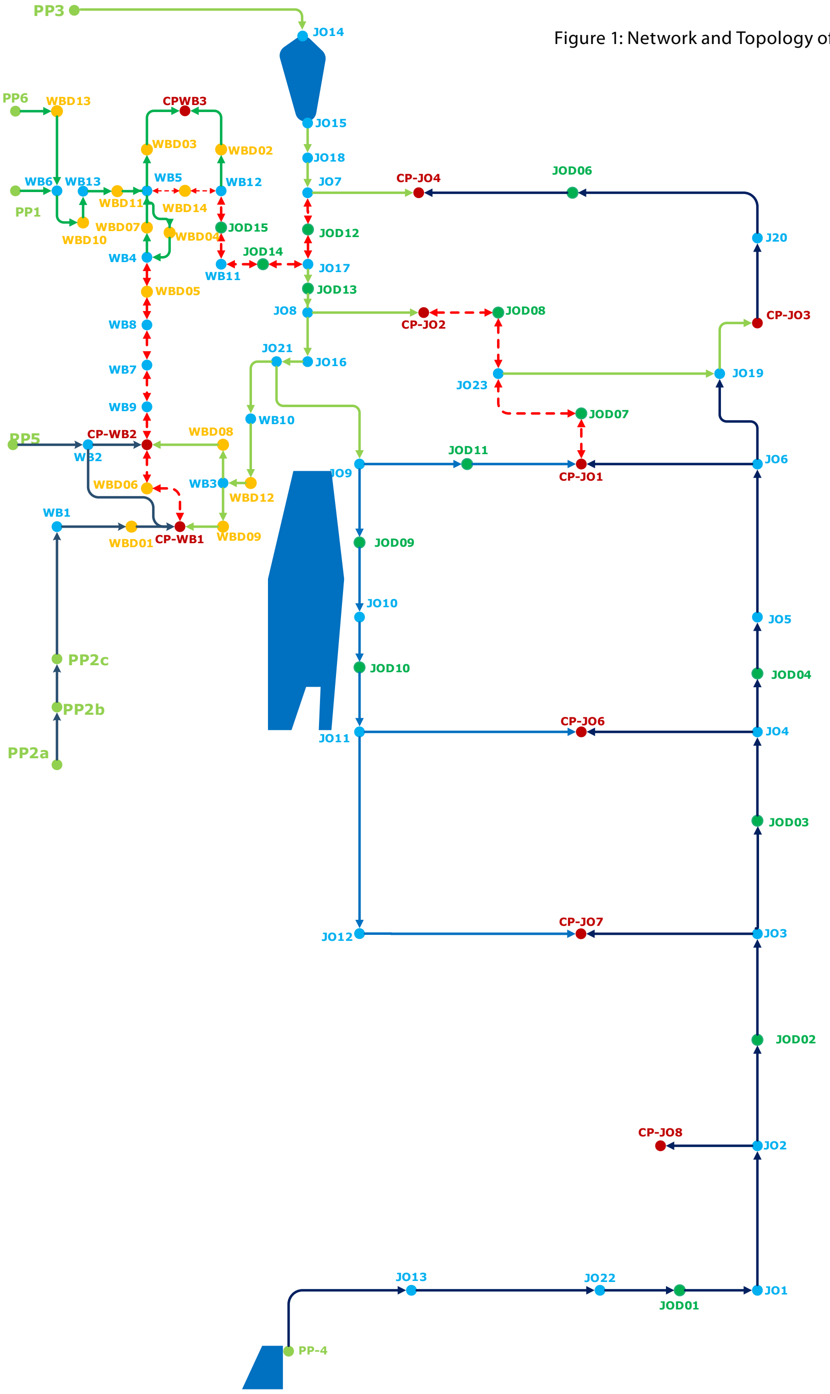

Figure 1: Network and Topology of the Macro-Model

potential production and demand areas [Water Production and Transfer Strategies, p. 22]. The complete network (Figure 1) is an overlay of all alternative water production and transfer strategies, comprising nodes and links. A node is a physical point at which mass must be conserved and also at which there could be a demand (a connection point is a node in the network). A link is a pipe connecting two nodes. The decision variables are: 1) The discharge along a link, between nodes *i* and *j*, Q_{ij} *(m^3/s)*; 2) The energy head needed to transfer water along a link , between nodes *i* and *j*, E_{ij} *(m)* and 3) The diameter of the pipe along the link, between nodes *i* and *j*, D_{ij} *(m)*.

The objective function is the sum of four terms: 1) cost of desalination; 2) cost of pipe installation and maintenance cost; 3) cost of power installation, its maintenance and energy cost for system operation; 4) the benefit from hydropower generated at Lake Tiberias via the transfer of water desalinated north of Haifa.

The starting network is presented in Figure 1. The pathways and the freshwater deficit values of each demand cluster in 2050 [Future Freshwater Deficits in Palestine and Jordan, p. 18] are inputs of the model. Constraints are set on the maximum desalination capacity of each plant. The AMPL community edition software was used for the coding of the optimization model (using the AMPL scripting language). The employed non-linear solver was the public domain open-source coin-or IPOPT.

NAME	SWD PLANT	CAPACITY (MIO. M³/A)	SHARE (%)
Netanya	PP-1	139.74	13.37
Gaza	PP-2	0.0	0.00
Haifa	PP-3	564.61	54.30
Aqaba	PP-4	154.14	14.75
Ashdod	PP-5	186.50	17.85
Hedera	PP-6	0.0	0.00

Table 1: Optimal Water Supply from the Desalination Plants (2050)

RESULTS & CONCLUSIONS

The results of the optimization for the time horizon 2050 are presented in terms of output from the desalination plants and discharges and diameters for the active links. The supply from the desalination plants is detailed in Table 1.

The routes identified by the optimization are presented in Figure 2. Haifa would supply central and northern Jordan. Aqaba would supply the south of Jordan. Netanya and Ashdod supply Northern and Southern West Bank respectively.

The optimum is dictated by the cost of the energy needed for transportation, as the desalination plants are neutral in the sense that they bear relatively similar costs. Haifa is by far the preferred desalination spot (54% of the total supply). The main advantage of Haifa compared to Aqaba is the shorter distances to demand centers in North and Central Jordan. The benefits generated by the hydropower plant at Lake Tiberias further lower the specific water cost. The optimization clearly identifies desalination in the Mediterranean coast as the preferred source of freshwater. Water production at Aqaba is hampered by the costs of energy required for the transportation.

Key outcomes of the study are summed up below:

> The procedure developed by the macro model provides a quantitative tool for the optimization of massive water supply allocation from desalination plants to demand areas.

> The cost of the optimal solution is considerably lower than other water production and transfer options [Techno-Economic Assessment of Water Infrastructure Projects, p. 72].

> The macro model suggests a solution that may not be the preferred one in Jordan and or in Palestine. It is beyond the scope of this work to recommend the preferred solution. However, the macro model provides to the stakeholders and decision-makers a tool that will allow them to evaluate the economic implications of their decisions (the extend of the additional investment required for the implementation, maintenance and operation of a different solution).

> The suggested approach (optimization of water allocation) is not new. What is new is its implementation to a complex transboundary water management challenge.

Figure 2: Optimal Transfer Route as Defined by the Model

> The optimal solution depends on the initial setting of the network. It is possible that a different layout of the network could result in a different optimal solution.

> The optimization assumes that there are no limitations on the pipe diameters, on the size of the power boosting stations and on the size of the temporary storage facilities. The cost of pipe installation per unit length (m) is assumed to be a linear function of the diameter (constants provided by Dorsch) with no limitation on the diameter size. Similarly, the cost of the power/temporary installation per kW is a linear function, as provided by Dorsch. Should there be limitations on the size of the diameter or the power boosting, this would have a an impact on installation costs (positive or negative, depending on other factors). Overall, the impact on the optimization would be negligible for the following reasons: 1) a small number of pipes and or power boosting facilities would be affected; 2) the factor dominating the cost is the energy consumption over the operation period.

The network comprises nodes connected to links for which the flow directions are determined as part of the optimization process. The first version of the script, which is presented in this paper, does not fully represent the mass balance at these „complex" nodes, which is why the script was further improved. The new outcome of the optimization further emphasizes the advantage, cost-wise, of seawater desalination in the Mediterranean Sea over seawater desalination in the Red Sea. In the new solution 98% of the demand is supplied by desalination in the Mediterranean Sea (Haifa: 67%, Ashdod: 18% and Netanya: 13%).

The Macro-Model is integrated to the [SALAM Information and Expert System, p. 86]. Users can visualize the path, the technical characteristics, and the specific water costs of the cost-optimal solution for a given set of freshwater deficits in the demand centers and capacity constraints of the desalination plants. Figure 3 shows the user-friendly interface of the tool.

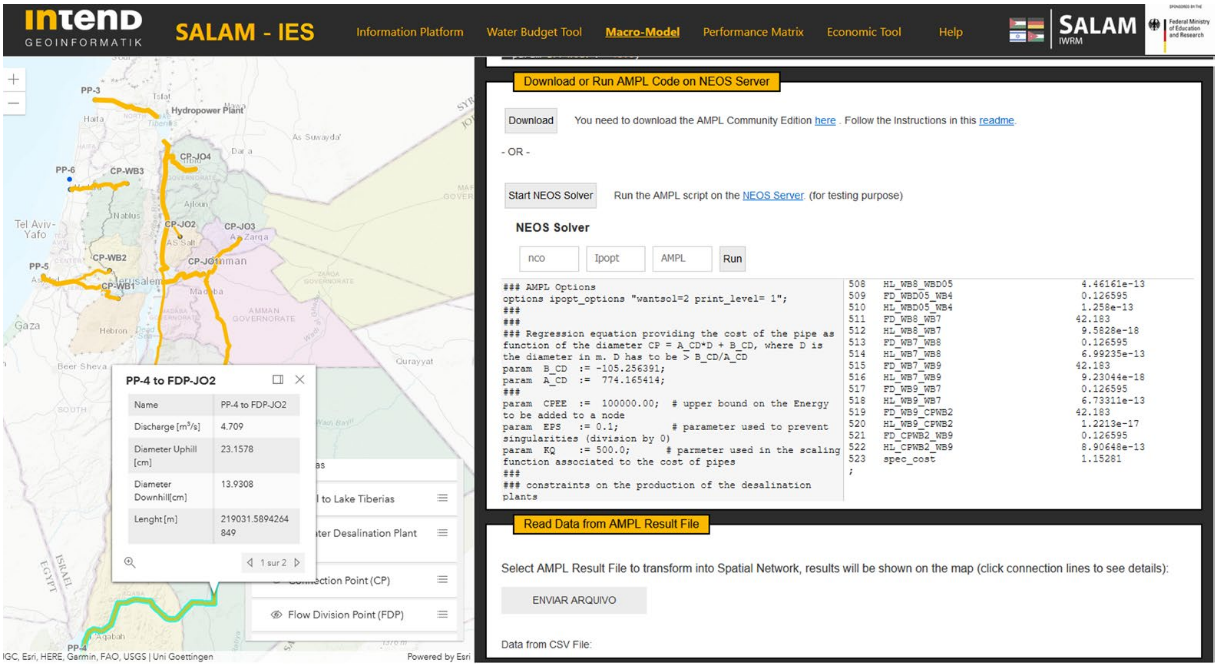

Figure 3: Interface of the Macro-Model in the SALAM Information and Expert System

THE MACRO-MODEL

The macro model developed in SALAM2 aims at finding an optimal solution of the water allocation problem from possible locations for the installation of desalination plants (on the Mediterranean Sea coast and on the Red Sea coast) to the demand points of the clusters in Jordan and in the West-Bank. The problem is formulated as Mixed Integer Non-Linear Program (MINLP) but solved as Non-linear program (NLP). The optimization problem consists of decision variables (the production at the desalination plants), discharges, energy head and diameters for link in the network (pipeline between two nodes). The objective function is composed of three costs items (infrastructure, desalination, and energy) and one benefit (hydropower related to the operation of a desalination plant at Haifa). Constraints include mass conservation, energy conservation, consistency, and bounds on the decision variables. The problem is solved using the AMPL Community edition version which can activate the Interior Point Non Linear Solver IPOPT.

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IPOPT - Interior Point Optimizer - Ipopt: Documentation (coin-or.github.io)