Assessment of wastewater investment plans using DSS

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Abstract

This study presents a Decision Support System (DSS) developed to assist in defining the impact of wastewater discharge on river water quality and prioritizing alternatives for locating and constructing wastewater treatment plants at a river basin scale taking into consideration environmental and economic indicators. The DSS allows the assessment of water quality improvements associated with the implementation of various investment options and translates this improvement into socio-economic benefits that feed into a cost-benefit analysis to support informed decision-making in adopting appropriate policies towards improving water quality in the river. The economic benefits of improving water quality and sanitation revealed a yield of 10.7 % of the GDP in the study area as cumulative economic returns over a 25 year period. Corresponding water quality improvement can reach 94 percent depending on investment plans.

Introduction

Integrated and sustainable river basin management represents a challenge due to the complexity of natural water systems coupled with conflicting objectives and priorities of involved stakeholders (Aulinas *et al,* 2011). Wastewater treatment plants (WWTPs) are critical in ensuring the sustainable use of river water, as they directly affect the quality of the aquatic environment and subsequently, human water use (Barjoveanu *et al.*, 2010). This highlights the need for simple, reliable and flexible tools for impact assessment and prioritization of actions, such as a Decision Support System (DSS), which is a computer-based information system that assists stakeholders and decision makers articulate their points across while benefitting from expert knowledge and experience, thereby enabling better decision-making in terms of impact assessment and prioritization of actions.

In Lebanon, the Litani River constitutes the most important freshwater resources. The Litani basin is subject to various sources of environmental stresses, raising the need of a support system for water quality management at a basin scale. The river stretches nearly 170 km before discharging into the Mediterranean Sea, draining a 2,168 km^2 watershed (Figure 1) with an estimated average annual discharge rate of 770 million m^3 / year. The Qaroun lake divides the watershed into two sub-basins, with the upstream of the lake where more than 90% of the overall basin's population reside, forming the focus of this study. The direct discharge of untreated domestic wastewater into the river and its tributaries is by far the main contributor to the degradation of water quality (USAID 2005; MoE, 2011). Consequently, the master plan towards improving water quality in the basin envisage amongst several other programs, the construction and operation of several WWTPs along the river.

This paper presents a DSS designed to assess the environmental and socio-economic impacts of a Wastewater Treatment Plant scheme and prioritize investment in WWTPs at a river basin scale (in the upper Litani river basin and Qaraoun Lake) by analysing alternatives and "what if" scenarios related to surface water. The aim is to assist decision-makers to adopt informed decisions regarding water quality management at the basin scale.

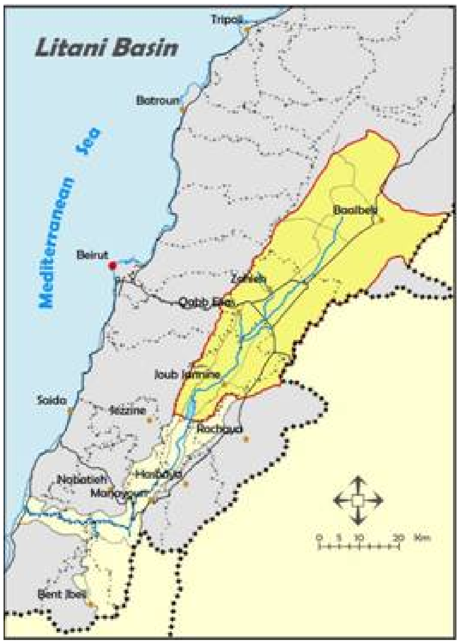


Figure. 1 Geography of the Litani basin

Methods

The study area was divided into seven catchments each to be served by a WWTP that treats the wastewater generated from the towns within the catchment, and discharges the treated effluent into the river or its tributaries. Analysis of alternatives for the prioritization of investment options in these plants relied on user-defined environmental, economic, and financial criteria with the DSS targeting water quality and cost benefit analysis besides the prioritization process.

Prioritization of Investment Options

The prioritization of investment options in domestic WWTPs uses a Matrix Analysis to evaluate and rank the proposed options. Expert and experience–based performance indicators (**Error! Reference source not found.**) were defined for this purpose with corresponding weighing factors to analyze and rank the options. Since the selection of weighing factors for performance indices can be subjective, the DSS was structured to allow the user to enter the value of these factors. The Matrix Analysis uses a score-range of 0 to 100 for each indicator, and assumes a highest weighted score of 100 after all scores are normalized to 100 when the total cumulative score exceeds 100.

Table 1. Matrix Analysis and performance indicators to evaluate and rank WWTPs

Indicator	*Weighting factor*	*Score*			*Weighted score*
		WWTP1	…	*WWTPn*	
Load Reduction Efficiency (LRE, d, p)	25 points (5 points for each of the five pollutants)	Score$_{(LRE,\ d,\ p)}$ = (WWTP$_{LRE,d,p}$ / Highest WWTP$_{LRE,d,p}$) x 100 Where: Score$_{(LRE,\ d,\ p)}$: Score for the load reduction efficiency indicator of pollutant p and investment option d. WWTP$_{LRE,d,p}$: Percent load reduction efficiency of pollutant p by investment option d (from the total pollution p generated and discharged into the river). Highest WWTP$_{LRE,d,p}$: Highest percent load efficiency reduction of pollutant p by all the investment options (from the total pollution p generated and discharged into the river			
Pollutant Load Reduction /Increase from each Investment Option (LR/I, d, p)	25 points (5 points for each of the five pollutants)	Score$_{(LR/I,\ d,\ p)}$ = (L$_{R/I,d,p}$ / Highest L$_{R/I,d,p}$) x 100 L$_{R/I,d,p}$ = Pollutant Load$_{p/capita.day}$ x PGF$_{Y,2005}$ x [(P$_{(before,\ 2005)}$) – ((P$_{(after,\ 2005)}$ x LRF$_{d,p}$)] Where: L$_{R/I,d,p}$: Load Reduction/Increase for pollutant p in investment option d. Pollutant Load$_{p/capita.day}$: Load (kg) of pollutant p per capita per day. PGF$_{Y,2005}$: Population Growth Factor for design year Y, given population at base year 2005. With n being the number of years (Y-2005) and PGR being the population growth rate with PGF$_{Y,2005}$ = $(1+PGR)^n$ P$_{(before,\ 2005)}$: Population connecting to the sewer line (discharging into river) in 2005 assuming WWTP is not installed (current situation). P$_{(after,\ 2005)}$: Population connecting to the sewer line (discharging into river) in 2005 assuming WWTP is installed.			
Population Downstream (PD$_{d)}$	15 points	Score$_{(PD,\ d)}$ = (PD$_d$ / Highest PD$_d$) x 100			
Population Served at Year of Analysis (Y) (PS$_d$)	5 points	Score$_{(PS,\ d)}$ = (PS$_d$ / Highest PS$_d$) x 100			
Population Discharging into the Groundwater (GW$_d$)	7.5 points	Score$_{(GW,\ d)}$ = (GW$_d$ / Highest GW$_d$) x 100			
Construction Costs (CC$_{d,}$)	12.5 points	Score$_{(CC,\ d)}$ = [(Highest CC – CC$_d$) / Highest CC) x 100			
O&M Costs (O&MC$_d$)	12.5 points	Score$_{(O\&MC,\ d)}$ = [(Highest O&MC – O&MC$_d$) / Highest O&MC) x 100			
Direct discharge into the lake	2.5 points				
Total score					

Water Quality

Following the evaluation and ranking of proposed WWTP options based on key performance indicators, the impacts of each option on water quality were assessed through the second DSS component, which simulated pollutant concentrations in the river and lake. Accordingly, available hydrologic data including time series on monthly surface stream flow at three locations as well as the monthly lake inflow and outflow, were coupled with the effluent discharge from proposed WWTPs to simulate corresponding impacts on several water quality indicators. The general configuration of the system is recognized by the DSS through a *System Matrix* that takes into consideration the upstream-downstream routing of all potential sites for proposed WWTPs along the river. Indicator levels are determined and routed within the whole system by multiplying this matrix by the mass balance governing equations in Table 2, below.

Table 2. Water quality simulation equations

River simulation	*Lake Simulation*
Estimates of monthly wastewater discharge rates (m^3/month), from proposed WWTPs, by multiplying the total number of population connected to a particular plant by the average monthly discharge per capita in the Basin. Field measurements were used for calculating the pollutants' loadings as such: $L_p = V_s \times C_{Sp}$ L_p Loading of pollutant P (kg/month) V_s Monthly wastewater discharge rate (m^3/month) C_{Sp} Pollutant level (kg/m^3) Pollutant concentrations in the river are dependent on the simulated investment option as expressed below. $C_P = L_P / F$ if WWTP is not within the simulated investment option $C_P = (L_P - R_P) / F$ if WWTP is within the simulated investment option $R_P = L_p \times RF_P$ C_P Concentration of pollutant P (kg/m^3); L_P Loading of pollutant P (kg/month); F Monthly stream flow (m^3/month); R_P Total pollutant reduction through treatment (kg/month), and RF_P Pollutant reduction factor Water quality indicators include biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), total Nitrogen (N), and total Phosphorus (P) for the river and lake water.	Average monthly BOD levels in Lake Qaraoun are estimated using a mass balance approach that is based on a *volume-balance state equation* as expressed below: $S_{t+1} = S_t + I_t - O_t - L_t - Sp_t$ $S_{min} \leq S_t \leq S_{max}$ $Sp_t = 0$ if $S_t + L_t - O_t - L_t \leq Smax$ $Sp_t = (S_t + L_t - O_t - L_t) - S_{max}$ if $S_t + L_t - O_t - L_t$ Smax S_t lake storage volume in month t; I_t Inflow to the lake during month t; O_t Outflow (controlled) from the lake during month t; L_t Losses in month t (mainly evaporation and seepage); S_{min} Minimum storage level in the lake; S_{max} Maximum storage level in the lake; Sp_t Spill (uncontrolled) during time stage t. Tthe monthly mass balance of BOD load in the lake is defined by: $BOD_{t+1} = BOD_t + BOD_{I\,t} - BOD_{O\,t}$ $BOD_{I\,t} = C_{BOD\text{-}t} \times I_t$ $BOD_{O\,t} = BOD_{C\,t} \times O_t$ $BOD_{C\,t} = [(BOD_t + BOD_{t+1}) /2] / [(S_t + S_{t+1})/2]$ BOD_t Load within the lake storage during month t; $BOD_{I\,t}$ Load received by the lake with the inflow I_t during month t; $BOD_{o\,t}$ BOD load leaving the lake with the outflow O_t during month t; and $C_{BOD\text{-}t}$ Average BOD concentration in the river during month t. A *decay factor* is used in the lake simulation due to the relatively long residence time of water. $BOD_{t\text{-}final} = BOD_t \times (1 - D_t)$ D_t Monthly BOD decay factor in the lake.

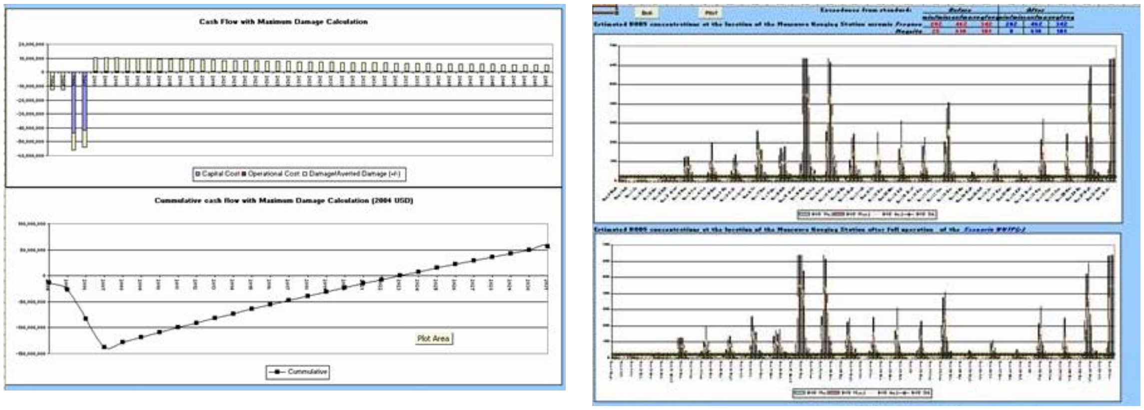
Various investment scenarios can be simulated, ranging from the "*do nothing*" scenario (current situation) to the "*do everything*" scenario (building all proposed WWTPs). The monthly average values of pollutants indicators are tabulated and presented graphically to assist in understanding how the pollutant levels fluctuate temporally according to hydrologic trends (seasonal/annual dry and wet hydrologic cycles). Water quality standards are included to allow for comparison and determination of frequency of non-compliance and magnitude of exceedance of such standards.

Cost Benefit Analysis (CBA)

The purpose of the third component of the DSS is to conduct a cost-benefit analysis of various WWTP options and provide decision makers with an estimated range of capital and operational expenditures (CAPEX), as well as expected conservative benefits resulting from potential water quality improvement. The costs of each option are defined as the level of investment in terms of CAPEX, which are a function of the technology adopted and the capacity in terms of population served. The benefits due to improvement in water quality relate to health and irrigation practices using the averted cost approach. Averted health-related costs focused on premature mortality and morbidity as outcomes associated with water-borne illnesses, namely diarrhea and typhoid (El Fadel *et al.* 2011). The methodology adopted for averted irrigation costs, correspond to the installation of water filters to avoid the clogging of drip irrigation infrastructure due to eutrophied water in irrigation canals. Accordingly, the CBA assumed that the benefits accrued are the result of the averted damage of pollution. If no investment option is implemented, the damage is assumed to grow proportionately to the population growth rate. This is normally a conservative approach particularly when the ecosystem assimilation capacity, or its ability to accommodate pollutants without causing damage to aquatic life and humans, is exceeded. It is also assumed that the damage converges to zero when effluent discharge standards are met. Finally, it is assumed that the damage cost of pollution is following a linear function between a maximum for the "Do Nothing Scenario" and zero for a pollutant level below recommended standards.

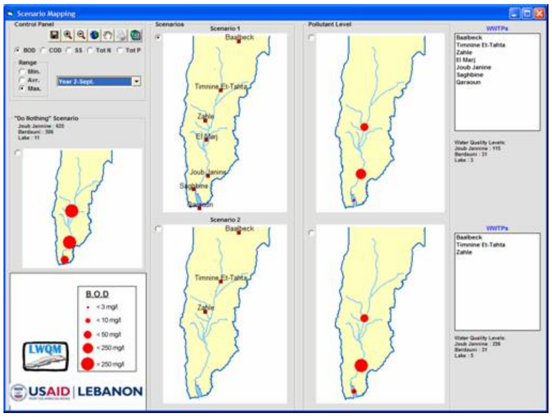
Results

The DSS allowed for testing WWTP investment scenarios in terms of impact on improving water quality in the basin with associated financial benefits in the form of cost-benefit analysis and water quality in chart and GIS format (Figure 2). For demonstration purposes, a scenario for investment in all WWTPs was simulated. The results indicated that this scenario is most desirable in terms of *return on investment*, which can be attained in 17 years after investment. Similarly, this scenario yielded a maximum frequency of exceedance of the BOD and total Nitrogen standards of 13 and 8 percent, respectively. The GIS interface showed that the maximum BOD concentration in the river and the lake is 33 mg/L, which is significantly lower than the simulated levels under the *do nothing* scenario (548 mg/L).



a) Cost benefit analysis

b) Water quality level in chart format



c) Water quality levels in GIS interface

Figure 2. Typical outputs of DSS Scenario analysis

Conclusion

Investing in upstream WWTPs will improve the quality of the water throughout the river basin and will avert more socio-economic costs than downstream investment. Total nitrogen levels did not drop significantly upon investing in WWTPs since secondary treatment is adopted which have a low removal efficiency for nitrogen and phosphorous. While at the level recorded the latter are beneficial to soil and plants, they have been associated with algae growth causing damage to irrigation equipment and creating a perception of pollution in the area.

Worldwide, the intricacy of river basin management is growing as the uses of water and the objectives to be fulfilled continue to increase. To guarantee a successful planning and operational management of such systems, the application of expert system tools becomes of utmost importance in assessing the environmental and socio-economic impacts of such plans and helping decision-makers and funding agencies to address specific questions and needs.

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