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# Assessing water quality management options in the Upper Litani Basin, Lebanon, using an integrated GIS-based decision support system

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ABSTRACT

The widespread and relentless discharge of untreated wastewater into the Upper Litani Basin (ULB) river system in Lebanon has reached staggering levels rendering its water unfit for most uses especially during the drier times of the year. Despite the call by governmental and non-governmental agencies to develop several wastewater treatment plants and sewage networks in an effort to control this problem, these efforts do not seem to be coordinated or based on comprehensive and integrated assessments of current and projected conditions in the basin.

This paper provides an overview of the development and implementation of an integrated decision support system (DSS) designed to help policy makers and other stakeholders have a clearer understanding of the key factors and processes involved in the sewage induced degradation of surface water quality in the ULB, and formulate, assess and evaluate alternative management plans. The DSS is developed based on the WEAP model, which provides a GIS based and visual simulation environment and scenario management and analysis capabilities. The DSS was used to assess two main water quality management plans taking into consideration hydrological, spatial and seasonal variabilities. An incremental cost-effectiveness analysis was conducted to identify best buy plans. The results have confirmed the gravity of this problem and demonstrated the importance of taking immediate action on curbing this onslaught on this valuable and scarce fresh water resource.



## 1. Introduction

Situated at the heart of the world's most deprived region of fresh water resources, Lebanon enjoys a relative abundance that is rapidly spreading thin due to growing water demands, insufficient investment in water resource development and deteriorating water quality. Draining over fifth of Lebanon's total area of 10,500 km$^2$ and totally contained within the country's boundaries, the Litani River is the largest of all Lebanese rivers and the country's most important water resource. The river rises near the ancient city of Baalbek, 85 km east of the capital Beirut, and flows 140 km in southerly and westerly direction to meet the Mediterranean 70 km south of Beirut (Fig. 1). Few years after the country's independence, a comprehensive watershed master plan was developed for the Litani River Basin, which led to the construction of a major hydroelectric system in 1950s that taps the 800-m head between the river site at Qaraoun and the Mediterranean. The project involved is the construction of Qaraoun dam and diverting the Litani River through a system of tunnels and ponds to empty its water into the Mediterranean further north from its natural mouth (LRA, 2004). The diversion has led to a hydrological separation between the basin's upper reaches above Qaraoun Lake, known as the Upper Litani Basin (ULB), and the lower reaches.

The Litani's watershed master plan has originally called for further development of the irrigation and water supply potential of the basin. However, the advent of a protracted civil war followed by a prolonged occupation put a freeze on development across the country up to the late 1990s.

When the return to more stable conditions encouraged the Litani River Authority (LRA) to revive plans to divert substantial volumes from Qaraoun Lake for irrigation and municipal water supply in the long neglected southern and interior parts of the country. A $460 million construction project is underway for the Canal 800 water carrier to transfer up to 110 million cubic meters (MCM) per year from Qaraoun Lake to the south of the country. Another major project involved is the construction of canal 900, where up to 150 MCM per year from Qaraoun Lake and groundwater and springs in the ULB is pumped and channeled to meet

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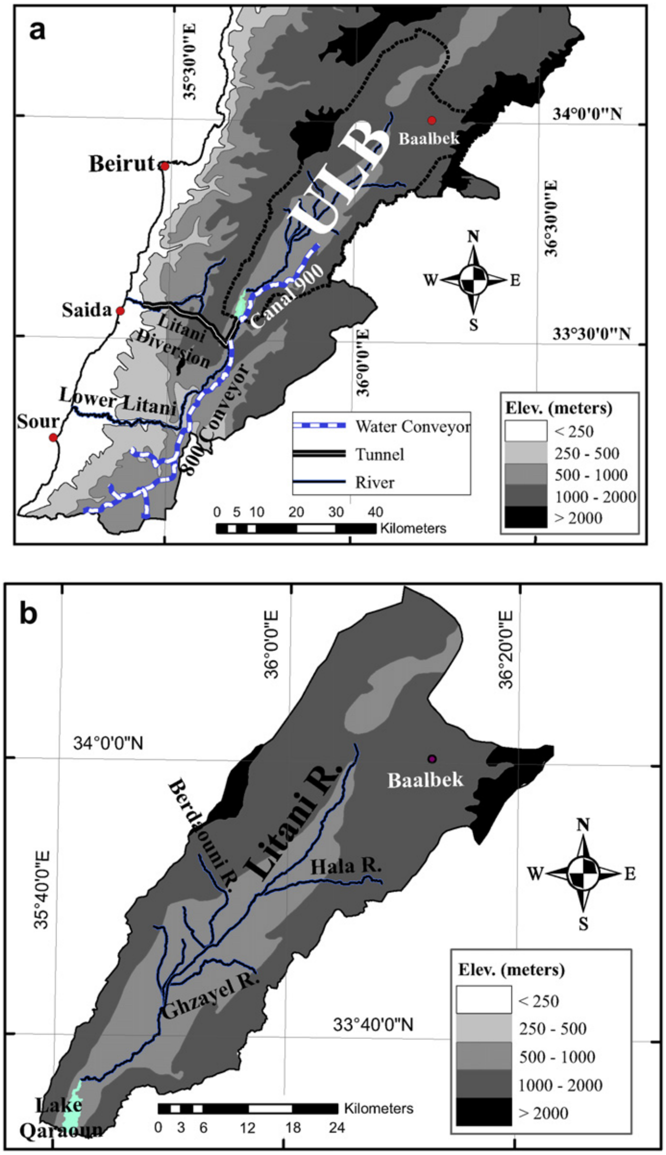


**Fig. 1.** (a) The Litani River Basin. (b) The Upper Litani Basin (ULB).

irrigation demands in the area (Fig. 1). Several other schemes are in the planning stage to serve coastal and interior regions (LRA, 2004).

The success of the above water development schemes hinge to a large extent on the reliability of the water resources in the ULB, which are subject to natural variability and uncertainty possibly influenced by a longer term climatic change. Another pressing and increasingly more limiting factor is the anthropogenic pollution of the ULB water resources which could make them unsuitable for most water uses. Over 10% of Lebanon's 4.5 million inhabits the ULB, mostly engaged in agricultural activities, and food processing and tourism industries. The bulk of urban and industrial waste is released untreated into the river. The impact of these releases is intensely felt during the summer months, when naturally dry conditions accompanied by major extraction of groundwater and surface water for irrigation reduce the river flow to a trickle. The situation has reached a flagrantly alarming stage that the upper Litani was described as an "open-sky sewer" by the Ministry of Environment in Lebanon (Kaskas and Awida, 2000). The problem is exacerbated by pollution from irrigation, leaching from landfills and the common practice of dumping solid waste near or into the river channel (FORWARD, 2003).

Findings from a recent extensive water quality survey conducted under the USAID-sponsored Litani Basin Management Advisory Services (BAMAS) project, show a river system under a great environmental stress with seriously and progressively degraded water quality (BAMAS, 2005a,b). Fig. 2 shows measurements of counts of Fecal Coliform (FC) (CFU/100 ml) at several locations across the basin for the winter and summer periods. The river system is obviously bacteria infested throughout the year, with extremely high counts of FC that exceed 1,20,000 CFU/100 ml at some locations during the summer. These results are indicative of a wide-scale pollution that escalates to epidemic levels during warm and dry summer conditions. This is particularly worrisome as water demand, particularly for irrigation, increases substantially during the long rainless summer season. Already many farmers are tapping into these extremely health hazardous waters in the summer. With lack of proper legislation and enforcement, this practice could have dire public health ramifications that can extend well beyond the basin (World Health Organization, 1989). The BAMAS study reported large number of waterborne diseases such as diarrheal illnesses, especially among the children.

The gravity of the unchecked, widespread and severe pollution of the ULB water has prompted governmental and non-governmental agencies to seek effective and long-term solutions. As the leading planning agency in Lebanon, the Council for Development and Reconstruction (CDR) has developed an environmental master plan that will oversee the establishment of wastewater drainage network and treatment facilities for most of the communities in the basin (CDR, 2005). The plan calls for the construction of seven secondary treatment wastewater treatment plants (WWTPs) across the basin (see Fig. 3) for a total cost of $94 million, to be secured through international funding (see Table 1). Upon completion, the CDR plants with a total capacity of about 4,46,000 $m^3$/day will serve 4,46,000 (2005 estimate) people spread over 75 towns. Despite its large scale, the CDR plan neglects to consider 65 towns within the same area (see Fig. 3) with a total estimated population of 63,000 (2005). These figures indicate that the excluded communities are those of smaller towns. There does not seem to be a clear rationale to explain this exclusion especially that many of these towns are within proximity to the planned WWTPs. However, several of these excluded towns are in the less hydrologically active northwestern corner of the basin and currently not releasing wastewater to the river system, and may have been perceived, inaccurately, to be less damaging to the basin.

Concurrently, the USAID has retained the services of Camp Dresser and McKee (CDM) to assess the feasibility of a decentralized wastewater treatment approach. Adopting a think-small approach that emphasizes serving smaller clusters of communities, the CDM plan calls for the development of six smaller WWTPs to serve 11

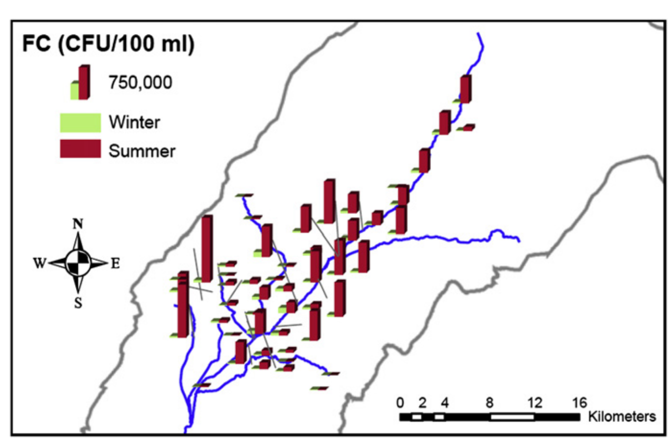


**Fig. 2.** FC measurements in the ULB (2005).

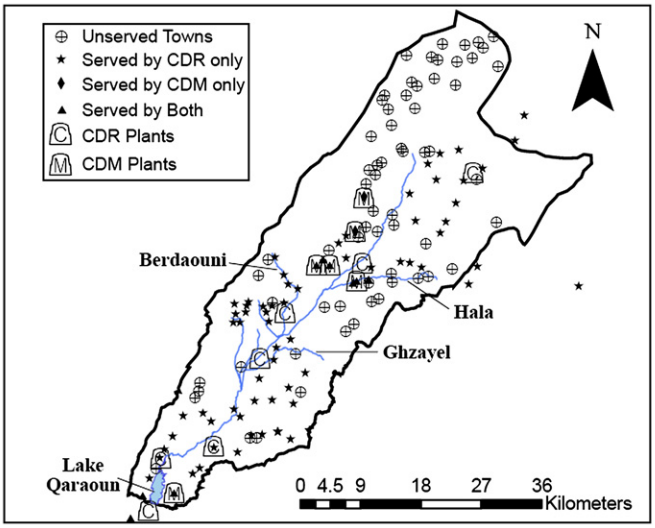


**Fig. 3.** Coverage of the CDR and CDM plans.

towns with a total estimated population of 51,550 (2005). With a total installed capacity of 14,840 $m^3$/day the plants are estimated to cost in the order of $9 million (see Table 1). Although the CDM plan provides coverage to few of the towns overlooked by the CDR plan, it overlaps with it in several locations indicating a lack of coordination between the two agencies. However, the CDM decentralized approach offers opportunity to incrementally augment gaps in the CDR plan.

It is not clear from published information if either of the two plans is based on a comprehensive assessment and analysis of current and projected conditions in the basin. The complexity of the problem and the significant financial obligations required for adopting these plans necessitate a thorough and comprehensive assessment of alternative management options utilizing state-of-the-art and proven water quality management and decision support tools. This paper presents a decision support system (DSS) designed to help policy makers and other stakeholders assess current conditions and alternative management strategies of surface water quality in the ULB. Based on the Water Evaluation and Planning (WEAP) model, the ULB DSS provides a GIS-based, interactive and user-friendly simulation environment to capture key information on elements of population, water bodies, wastewater treatment plants, etc that affect river water quality conditions.

## 2. Methodology

Ideally, a water quality management DSS should provide a user-friendly and effective platform to help stakeholders and experts arrive at an optimal policy that satisfies agreed-upon economic, environmental and social criteria. This decision making process involves several interrelated tasks/activities:

- understand and appreciate the setting of the current natural/man-made system and how it is expected to change under the influence of the water quality problem;
- formulate alternative policies to control the problem;
- project the impact of each alternative policy;
- assess the impact of each policy in terms of stated criteria; and
- select the policy that best meet the stated criteria.

Several water quality models including QUAL2E, QUASAR, MIKE-II and CE-QUAL-W2 provide highly detailed and comprehensive modeling of water quality conditions in river systems (see Cox, 2003 for an extensive literature review). However, the majority of these models provide minimal, or no, consideration to policy setting issues including selection and formulation of policy alternatives and financial analysis. A common approach is to carry out policy and financial analysis related tasks externally in non-integrated and rigid fashion which makes data sharing and feedback difficult.

Developed by the Stockholm Environmental Institute (SEI), the WEAP model provides a tightly integrated planning and water resources simulation environment that draws upon expertise in policy and decision making, water resources, and financial analysis (Sieber et al., 2005). Although WEAP water quality module is not in par with those of highly detailed water quality models, it supports extensive environmental master planning functionalities based on a disaggregate representation of wastewater and water treatment facilities in terms of their design specifications, distribution and financial costs.

As a simulation environment, WEAP provides a GIS-based interface to graphically represent water demand sources, natural and man-made water resources supply and treatment systems including towns, irrigated areas, river systems, water and wastewater treatment plants, hydroelectric plants, etc. The core planning module in WEAP is scenario-based, where policy alternatives are formulated to represent current and future conditions under different development schemes. Scenarios can be evaluated and assessed based on several criteria representing water supply conditions, water demand, environmental impact and financial cost and benefits. Input and output information can be presented in several charting options and tabular formats.

In the current study, the WEAP model was used to set up a DSS to simulate and assess water quality management and policy alternatives in the ULB. The DSS was used to identify cost-effective WWTP combinations based on a selected environmental indicator. The long-term spatio-temporal impact of the CDR and CDM plans were assessed in terms of the selected environmental indicator under different hydrological conditions. These activities are presented and discussed in the following sections.

## 3. Setting up the DSS simulation environment

The objective of this step is to create a virtual representation of the area composed of objects that represent relevant and significant

**Table 1**
Highlights of the CDR and CDM proposed wastewater treatment plants

| Plan | Plant name | Capacity ($m^3$/day) | Population | | Capital cost ($) |
|---|---|---|---|---|---|
| | | | Total (2005 estimate) | # Towns | |
| CDR | Baalbeck | 12,500 | 1,18,070 | 16 | 10,000,000 |
| | Timnine Et-Tahata | 11,720 | 35,300 | 13 | 10,000,000 |
| | Zahle | 37,260 | 1,45,050 | 5 | 20,000,000 |
| | El-Marj | 39,830 | 77,300 | 17 | 20,000,000 |
| | Joub Jannine | 10,030 | 41,620 | 18 | 17,000,000 |
| | Saghbine | 530 | 6300 | 2 | 7,000,000 |
| | Qaraoun | 6660 | 22,300 | 4 | 10,000,000 |
| Total | | 1,18,530 | 4,45,940 | 75 | 94,000,000 |
| CDM | Chmistar | 1740 | 8810 | 1 | 1,078,000 |
| | Bednayal | 1630 | 5970 | 1 | 1,215,000 |
| | Ablah | 1360 | 2140 | 2 | 1,154,000 |
| | Fourzol | 980 | 1520 | 1 | 1,138,000 |
| | Reyak | 4130 | 12,840 | 3 | 2,092,000 |
| | Qaraoun | 5000 | 20,270 | 3 | 2,192,000 |
| Total | | 14,840 | 51,550 | 11 | 8,869,000 |

elements in the area which contribute to the state of water quality in the ULB using WEAP. These objects are classified and described as follows.

- Demand centers that represent towns, industries and agriculture activities where water is used and returned fully or partially with given degraded quality characteristics to the surrounding environment. In the current study only domestic demand centers, i.e., towns, are considered since the system is currently designed to address domestic wastewater treatment. Domestic demand centers are described via their attributes describing population, consumption and wastewater pollution loads per capita, water supply source and wastewater return destination and access to sewage facility. Dynamic attributes, e.g. population, are described as functions of time.
- WWTPs which represent current or planned WWTPs with given design specifications including total capacity, removal rates of pollutants and losses. Other attributes include capital and maintenance costs necessary for financial analysis.
- River system which is composed of river reaches, confluence nodes, and water supply and wastewater return nodes. Rivers are represented as directional line elements with the direction representing the upstream–downstream gravity driven water flow. Headwater flow is specified as a time series input to the upstream end of a river reach. Several alternative headwater time series can be specified for a given river reach, with only one time series active for a given scenario. Water is routed downstream a river reach. At a confluence or a return flow node, the river discharge is calculated as the sum of all upstream flows. Water quality performance indicators are determined based on several algorithms that model the generation, mixing, decay and movement of pollutants in the basin and river reaches.
- Return flows represent wastewater released from demand centers or WWTPs to the destination which could be a water body, ground water or unspecified in the model. The quantity and quality of return flow are determined by the source.

Global parameters that are applicable to all objects in the model include years of run, interest and discount rates, conversion factors in addition to user defined ones.

A total of 141 towns representing all towns in the basin, 13 WWTPs and eight rivers were modeled in the DSS. Fig. 4 is a computer screen snapshot of the DSS interface which includes a zoomable overview of the ULB showing all modeled towns, WWTPs and river reaches. Wastewater return flows from towns to rivers and WWTP are not shown to avoid obscuring other elements. Information on each object can be easily retrievable through clicking its corresponding graphical element. Information can be presented in a tabular or graphical form at individual or aggregate levels facilitating analysis and comparison among objects of similar type, such as demand centers or WWTPs.

It is important to note that the simulation environment is set up to contain all elements regardless of the time they become active. For example, Fig. 5 depicts a close up of the lower third of the basin which shows the Litani River, one of the CDR WWTPs, several towns and their corresponding current and potential wastewater return flows. Under current conditions, represented by the reference scenario, only the river, towns and corresponding wastewater return flows, designated by perforated lines, are active. In an alternate scenario, wastewater from towns is collected at the planned WWTP, with treated water routed into the river. Under this scenario the WWTP and corresponding wastewater return flows, designated by solid lines, are activated, while those associated with the no-treatment reference scenario are deactivated. For towns which are not covered by the water quality control plan, e.g. the three towns shown in the upper left corner, corresponding wastewater return flows persist through the two scenarios.

## 4. Selection of water quality criteria and calibration of the water quality model

In this study, water quality is assessed based on the Biochemical Oxygen Demand (BOD), which is defined as the amount of oxygen, measured in milligram of oxygen per liter of water (mg/l), required by aerobic microorganisms to decompose organic matter in a sample of water. The BOD is a widely used environmental performance indicator that determines the strength or concentration of biodegradable pollutants in water bodies, for example those introduced by sewage effluents (Chapman, 1996).

In the WEAP model, the BOD in the river is calculated based on several routines that track its generation by individuals at towns down into the river if released untreated or routed to a WWTP and get partially removed with the remainder released into the river. During its travel in the river, the BOD is reduced by a decomposition and sedimentation algorithm based on the BOD characteristics, river flow and hydraulic parameters and weather conditions (Sieber et al., 2005).

The WEAP water quality module is based on the Streeter–Phelps model, which simulates the oxygen balance in streams driven by two processes: consumption by decaying organic matter and reaeration induced by oxygen deficit, which are represented by the two following equations (Chapra, 1997):

$$L = L_0 e^{-\frac{k_r}{U}x} \quad (1)$$

$$D = D_0 e^{-\frac{k_a}{U}x} + \frac{k_d L_0}{k_a - k_r}\left(e^{-\frac{k_r}{U}x} - e^{-\frac{k_a}{U}x}\right) \quad (2)$$

where $x$ = the distance downstream of the point of entry of organic matter into the stream; $L$ = oxidizable organic matter in the water (mg/l); $L_0 = L$ at $x = 0$; $k_r = k_d + k_s$, is the rate of removal of BOD in the stream (1/day); $k_d$ = decomposition rate of BOD in the stream (1/day); $k_s$ = settling rate of BOD (1/day); $D$ = oxygen deficit (mg/l); $D_0$ = oxygen deficit at $x = 0$; $k_a$ = reaeration rate in the stream (1/day); and $U$ = stream mean velocity.

The dissolved oxygen concentration is determined based on the oxygen deficit and dissolved oxygen saturation calculated as follows (Chapra, 1997):

$$O = O_s - D \quad (3)$$

$$\ln O_{s1} = -139.3441 + \frac{1.575701 \times 10^5}{T_a} - \frac{6.642308 \times 10^7}{T_a^2} + \frac{1.243800 \times 10^{10}}{T_a^3} - \frac{8.621949 \times 10^{11}}{T_a^4} \quad (4)$$

$$O_{sp} = O_{s1}\left[\frac{\left(1 - \frac{p_{wv}}{p}\right)(1 - \eta p)}{(1 - p_{wv})(1 - \eta)}\right] \quad (5)$$

$$p = 1 - 1.2416 \times 10^{-4} EL - 6.6429 \times 10^{-9} EL^2 \quad (6)$$

$$\ln p_{wv} = 11.8571 - \frac{3840.70}{T_a} - \frac{216961}{T_a^2} \quad (7)$$

$$\eta = 0.000975 - 1.426 \times 10^{-5} T + 6.436 \times 10^{-9} T^2 \quad (8)$$

$$T_a = T + 273.15 \quad (9)$$

where $O$ = dissolved oxygen concentration (mg/l); $O_s$ = dissolved oxygen saturation (mg/l); $p$ = atmospheric pressure (atm); $O_{s1}$ = dissolved oxygen saturation in fresh water at $p = 1$ atm;

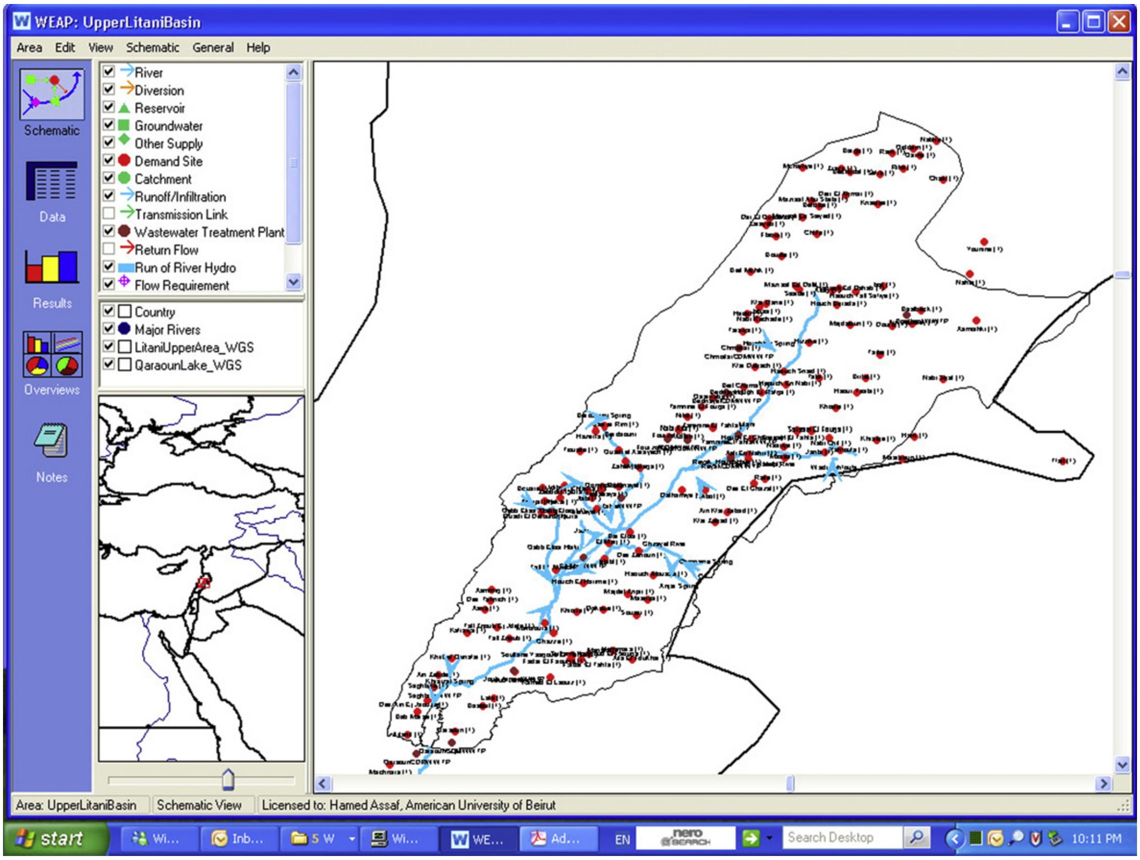


**Fig. 4.** The ULB DSS simulation environment.

$O_{sp}$ = dissolved oxygen saturation in fresh water at a given $p$; EL = elevation above sea level (m); $p_{wv}$ = partial pressure of water vapor (atm); $T_a$ = absolute temperature (K); and $T$ = temperature (°C).

Application of the water quality model requires estimates of the $k_d$, $k_s$ and $k_a$ coefficients. Ideally these parameters are obtained through analysis based on field measurements. However, the extensive requirements of calibration based on field data make this approach unfeasible for many studies (Eckenfelder and O'Connor, 1961). Consequently, most of the water quality modeling efforts are based on estimates obtained from established literature resources (Bowie et al., 1985).

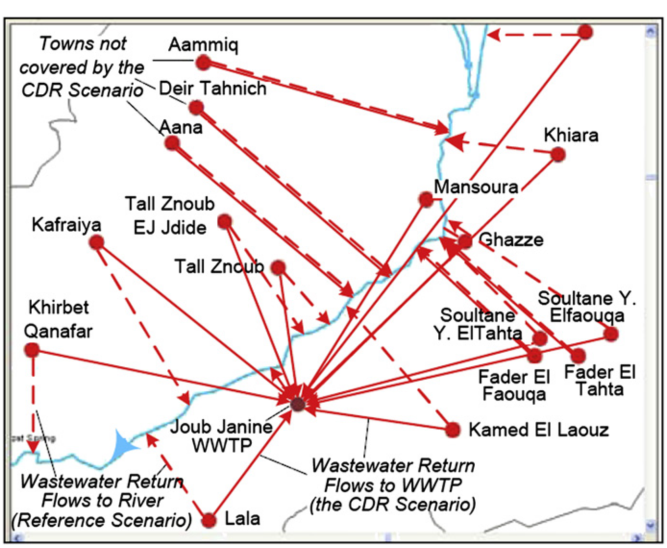


**Fig. 5.** A snapshot of the ULB DSS simulation environment.

Although the BAMAS water quality survey is considered extensive in terms of the area covered, number of measurements and parameters, the collected data are not readily amenable for a complete water quality analysis due to the following reasons.

- Water quality was measured in concentration terms only with no corresponding flow measurements, thus wastewater influxes could not be determined.
- A significant number of measurements were collected close to pollution sources. Consequently, these measurements were not representative of the general state of the river and could not be applied directly to the Streeter–Phelps model which assumes complete mixing.
- Many of the measurements were taken at different dates, spanning at times a period of more than 2 weeks.

However, an elaborate analysis and calibration procedure was developed to estimate key parameters for the water quality model. The calibration process involved a preprocessing and screening process designed to select the most representative measurements. Calibration preprocessing is composed of the following steps.

- Measurements were ported into a GIS and superimposed on a satellite image of the area, showing river course and layout of the area.
- Points of pollution were determined based on field surveys, BAMAS records and the satellite image.
- Measurements made at a short distance (100 m) downstream of a pollution source were excluded from calibration.
- Measurements were organized into sets each representing a series of two or more measurements obtained in the same day and represents reaches of the river that has no influxes of pollution.

The following procedure was then carried out for each set of the water quality measurements to obtain initial estimates of model parameters.

- $BOD_5$, the amount of oxygen consumed after 5-day incubation, measurements are converted into equivalent BOD using a factor of 1/0.83 representing untreated sewage (Chapra, 1997).
- Natural logarithm of BOD (ln (BOD)) is plotted against river kilometers. The slope of the fitted line ($\phi$) is used to calculate the observed BOD rate of removal, $k'_r$, as follows: $k'_r = 3.6\phi U$ ($U$ is in m/s)
- It is assumed that $k'_r = k_r + k_{d,e} = k_d + k_s + k_{d,e}$, where $k_{d,e}$ is a factor that represents the lack of representation of dispersion effects and other sources of errors. This is an important consideration, since $k_{d,e}$ can be quite significant for measurements collected at an insufficient distance downstream of pollution sources to allow for complete mixing. $k_s$ is also quite high near pollution sources (Eckenfelder and O'Connor, 1961). According to Bowie et al. (1985), some investigators have mistakenly reported observed BOD removal rates as $k_d$. Although measurements very close to pollution sources were screened out in the preprocessing stage as stated above, the majority of measurements are still relatively close to pollution sources due to the short distances between pollution sources along the Litani River.
- The reaeration rate, $k_a$, is calculated using the well established O'Conner-Dobbins and Owens-Gibbs formulas based on the stream mean velocity and depth ($U$ and $H$) and adjusted for the effect of water temperature (Chapra, 1997) as follows:

$$\text{O'Conner-Dobbins}: \; k_a = 3.93\frac{U^{0.5}}{H^{1.5}}1.024^{(T-20)} \quad H > 0.6\text{ m} \tag{10}$$

$$\text{Owens-Gibbs}: \; k_a = 5.32\frac{U^{0.67}}{H^{1.85}}1.024^{(T-20)} \quad H \le 0.6\text{ m} \tag{11}$$

- The settling rate, $k_s$, is calculated based on the settling velocity, $v_s$(m/day), and the water depth as follows (Chapra, 1997):

$$k_s = \frac{v_s}{H} \tag{12}$$

with $v_s$ set equal to 0.25 m/day.

- Eqs. (1)–(9) are applied through an iterative procedure, where $k_{d,e}$ is adjusted to arrive at a BOD decomposition rate $k'_d = k'_r - (k_s + k_{d,e})$ that results in calculated dissolved oxygen concentration matching measured one.

The $k'_d$ values calculated for the water quality measurement sets are compared against those estimated using the following equations, which accounts for the effects of riverbed and water temperature (Chapra, 1997):

$$k''_d = 0.3 \times 1.047^{(T-20)}\left(\frac{H}{2.4}\right)^{-0.434} \quad 0 \le H \le 2.4\text{ m} \tag{13}$$

$$k''_d = 0.3 \times 1.047^{(T-20)} \quad H > 2.4\text{ m} \tag{14}$$

Fig. 6 shows a plot of $k'_d$ values vs. $k''_d$, with a fitted line based on linear regression, which produces a relatively weak yet acceptable

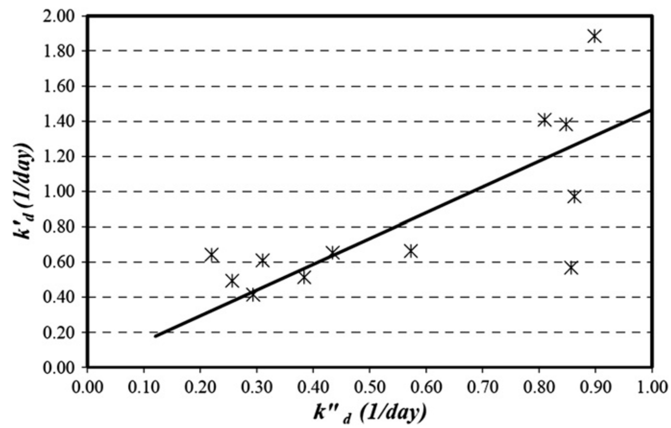


**Fig. 6.** Data-based BOD decomposition rate vs. formula-based one.

$R^2 = 0.55$. Based on the linear regression results, the BOD decomposition rate used in the model is calculated as follows:

$$k_d = 1.25k''_d + 0.15 \tag{15}$$

## 5. Setting up water quality baseline and management scenarios

In general, the scenario-based planning approach stems from the concept of predicting and assessing future state(s) of given phenomena that could develop from current conditions without intervention (business-as-usual) vs. those that would evolve as a result of intervention or mitigation measures designed to modify the given phenomena. In the current study, the ULB DSS is used to formulate scenarios that represent current conditions and those representing measures introduced by the CDR and CDM plans. Regardless of the perceived shortcomings of these plans, they are modeled as in the DSS since the former represents the official environmental master plan for the ULB and consequently serves as a benchmark for other alternate or complimentary plans, and the later represents a more incremental and affordable alternative which has been adopted successfully in other parts of the world (Pinkham et al., 2004).

In setting up scenarios in the DSS, all elements designated as currently active are by default made part of the reference scenario, which represents business-as-usual conditions. An alternative management scenario is one that introduces changes to the reference scenario, which include activating, deactivating and modifying attributes of elements and/or modifying global parameters. However, all scenarios share the same time frame, which could range from 1 year to several years depending on the planning horizon. Scenarios are managed as a hierarchy with the reference scenario representing the root of all scenarios. Consequently, the CDR and CDM environmental management plans are modeled as scenarios represented in terms of their deviations from the parent reference scenario. These "deviations" include introducing WWTPs, corresponding wastewater return flows from towns and treated wastewater return flows from plants to the river system.

## 6. Representation of river flow variability

River water quality is influenced by both natural and man-made conditions. In particular, the impact of untreated sewage discharges on water quality is highly sensitive to river flows. Higher runoffs bolster the river's natural "cleansing" capability due to their diluting effect. Consequently, a given pollutant influx which has hardly an impact on river water quality during high runoffs can significantly degrade water quality during dry and warm periods. This phenomenon is responsible for the wide seasonal and annual disparities in water quality conditions in the Litani River, which is characterized by high winter runoff and dry summer conditions, and large variability in yearly runoff.

To identify the impact of the Litani River discharge variability in relation to water quality management alternatives, the reference, the CDR and the CDM scenarios are simulated under three hydrological records representing dry, average and high river discharge conditions. The Litani River discharge historical records were examined to identify 3 years each representing one of the three river discharge conditions. Although some of these records date back to the 1930s, they are dotted with many gaps reflecting the long years of neglect and civil strife. Fortunately, the Litani River Authority (LRA) has kept a steady record of yearly discharges into Qaraoun Lake which extends back to the 1962 as shown in Fig. 7. The record shows that the water year September 1999–August 2000 is lowest on record, while the year September 1967–August 1968 is the highest followed by the year September 2002–August 2003. Considering that river discharge records are available for most of the ULB tributaries during the period September 1999–August 2004, the year September 2002–August 2003 was selected to represent high river conditions in the simulation runs, while low river conditions are represented by the year September 1999–August 2000. The last year on record (September 2003–August 2004) is characterized by an average yearly river discharge, and is therefore selected to represent the average water year.

The monthly discharges of the three selected years are shown in Fig. 8. The high water year is characterized by sustained above normal discharges for the 4 months from February to May, with hardly any discharge for the months of September–November, July and August. It also shows a January discharge lower than that of the average year despite having a peak monthly discharge twice that of the average water year. The low discharge year has only 4 months (December–March) of measurable discharge. For the other months, the monthly discharge is either extremely small or nil. The discharge for the average year is more distributed over the year than the other two years with very low discharges during July and August.

## 7. Analysis of the long-term spatio-temporal impact of the CDR and CDM plans under different hydrological conditions

The long-term saptio-temporal impact on the Litani River water quality of maintaining the status quo vs. implementing the CDR or the CDM plans is assessed with respect to different hydrological conditions. Three sets of 20-year monthly discharge time series for the Litani River and its tributaries were assembled. Each series is composed of monthly discharges corresponding to one of the low, average and high water years repeated over for a 20-year period. The reference, CDR and CDM scenarios were then simulated against each set of the river discharge time series. A sample of the BOD levels generated by the DSS is presented to characterize the domestic wastewater induced pollution of surface water in the ULB from five key perspectives of seasonal variability, spatial extent, future trends, hydrological conditions, and alternative water quality management options. Figs. 9–11 show sets of monthly BOD plots at three locations on the Litani River, listed in upstream order with river kilometers from the Litani headwater as follows (Fig. 1): below the confluence with Hala River (24.2 km), below the confluence with the Ghzayel River (42.1 km), and at the entrance to Qaraoun Lake (64.5 km), respectively. For each location, a set of nine plots are presented that depict calculated monthly BOD levels for the reference and the two management options under the three river discharge conditions and for the present year (2005), and year 10 (2015), and year 20 (2025) projected conditions. The plots are organized in a tabular format, where rows represent changes over time and columns show variations due to river discharge conditions.

A general overview of Figs. 9–11 shows a consistent seasonal variation in BOD levels strongly associated with river discharges (Fig. 8), with BOD reaching a high level of 140 mg/l during the driest months of the year (July–September), and values lower than 5 mg/l during heavy runoff months (February and March), especially during the wettest year. In comparison unpolluted waters generally have BOD values lower than 2 mg/l, wastewater polluted waters have values higher than 10 mg/l and BOD levels reaching 600 mg/g for raw sewage (Chapman, 1996). It should be noted, however, that the calculated BOD values in this study are monthly means. Daily or hourly values are expected to vary more considerably, especially in relation to corresponding variability in river discharges and pollutant loadings.

Plots (b), (c), (e), (f), (h) and (i) of Figs. 9–11 show that the implementation of the CDR master plan would greatly blunt the impact of domestic wastewater on water quality especially in the middle and lower reaches of the river. BOD levels are still excessive in the Litani reach at the confluence with Hala River during the drier months of the year. These observations are attributed to the disproportionately large number of towns excluded from the

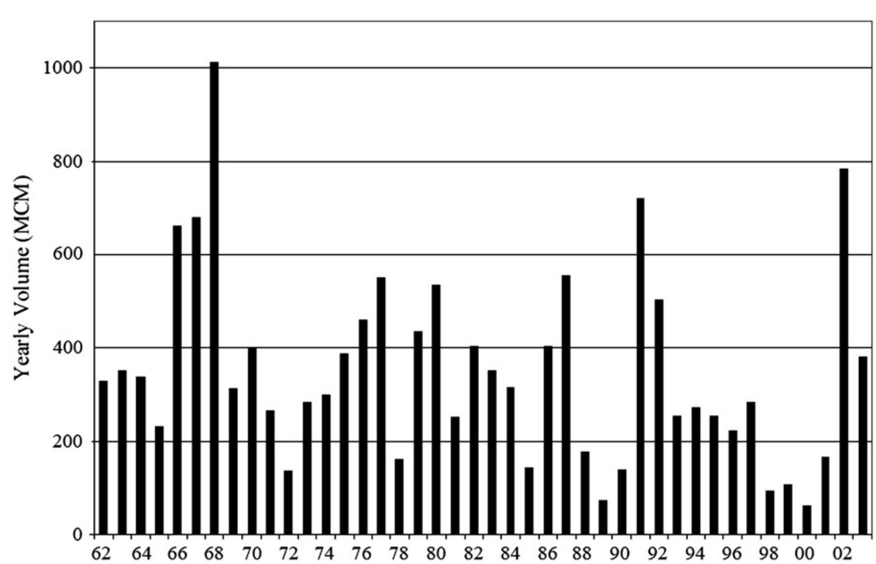


**Fig. 7.** Historical record of inflows to Lake Qaraoun.

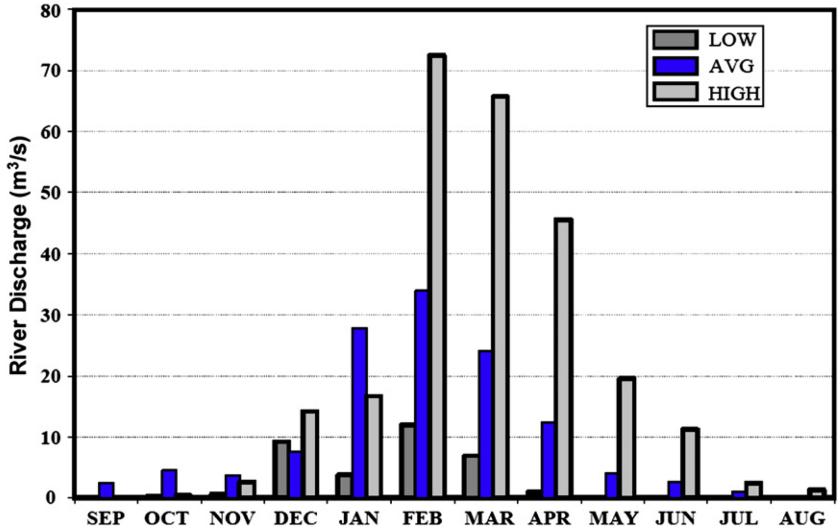


**Fig. 8.** Monthly discharges for the selected water years.

plan (see Fig. 3), and the typical lower water yield of this sector of the ULB in comparison to the middle and lower sectors. The CDM plan is expectedly less effective overall than the CDR plan due to its limited scope and coverage as an incremental approach geared towards serving smaller communities. However, the effect of CDM plan is quite similar to that of the CDR plan in the upper region above the confluence with Hala River since five of its six proposed WWTPs are located in this area (see Fig. 3).

An interesting observation of the BOD results is that very high monthly BOD levels appear to decrease over the simulation period, despite that the population and consequently pollutant loadings are projected to grow over the same period. For example, the September BOD level for the low water year below the confluence with the Ghzayel River are around 140, 130 and 120 mg/l for the present, year 2015 and 2025, respectively (see plots (a), (b) and (c) of Fig. 10). Although this observation may appear at first to be a modeling anomaly, it does capture a unique situation, where natural river discharge is virtually nil during this time of the year and consequently most of the water in the river channel essentially originates as a wastewater effluent. Consequently, the BOD concentrations are mostly reflective of the strength of the released wastewater, which is modeled to decline over the projected time horizon as water consumption per capita is assumed to increase, while the BOD release per capita in weight is assumed to be fixed.

## 8. Incremental cost-effectiveness analysis of wastewater treatment policy options

Output from WEAP can be used to conduct incremental cost-effectiveness analysis and identify best buy plans. WEAP was simulated for 25 years, representing the lifetime and the refinancing cycle of WWTPs, for individual CDR WWTP plants and the group of CDM plants under average river flow conditions. Measuring environmental effectiveness in terms of the amount of BOD removed from the river at the point of entry to Qaraoun Lake during the 25-year period, the output from WEAP was compiled and processed into the US Army Corps of Engineers IWR-PLAN decision support software to assess the cost-effectiveness of alternative wastewater

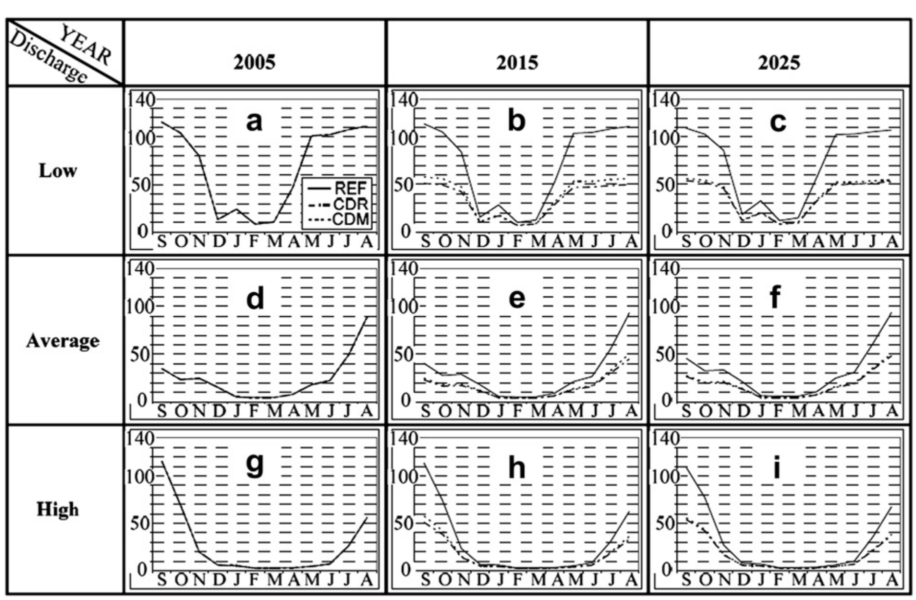


**Fig. 9.** Monthly BOD (mg/l) in the Litani River below Hala River.

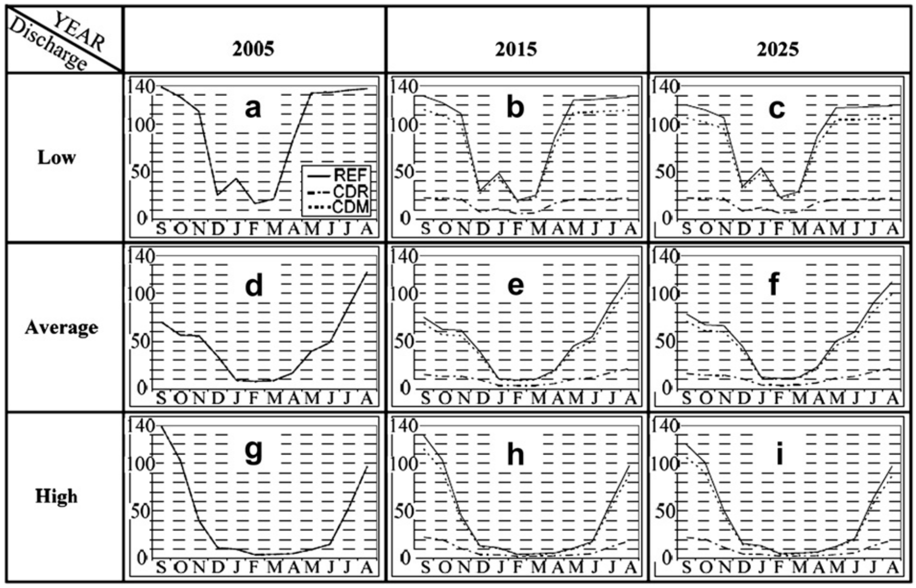


**Fig. 10.** BOD (mg/l) in the Litani River below the Ghzayel River.

treatment policy options and identify the best buy plans. The cost included capital and operation costs amortized over the 25-year project life span at 7% discount rate. IWR-PLAN facilitates comparison among different alternative plans made up of independent and additive solution measures. Although reduction in BOD levels due to the operation of a given wastewater plant is expected to be dependant on the operation of other plants as a consequence of the non-linear nature of the BOD removal rates, analysis of the results has shown that the assumption of independence generally results in insignificant underestimation of the removed BOD. This is mainly due to the relatively short length of, and consequently the short BOD travel times in, the river.

The results of the incremental analysis are presented in Table 2. The costs are presented in terms of the present value. Zahle's WWTP stands out as the best buy option costing on average $0.85 to remove one killogram of the BOD, which is considerably lower than those for the other WWTPs. The exceptional cost-effectiveness of the WWTP at Zahle is directly attributed to it serving the largest and most sewage network-connected population in the area. The cost of removing the BOD by other plants range from $2.59/kg for the El-Marj WWTP to $41.4/kg for the Saghbine WWTP. The excessively high costs at Saghbine and to a lower extent at Baalbeck are due to the smaller served population in the first and small percentage of population currently releasing raw sewage in the latter. At a BOD removal cost of $1.55/kg, the group of CDM WWTPs provides a better return for the investment than the CDR WWTPs with the exception of Zahle's. This finding is in agreement with results from other studies which indicate the cost-effectiveness of the decentralized approach in wastewater treatment (Pinkham et al., 2004).

It is important to emphasize that the above analysis is based on one environmental performance criteria, i.e. removal of the BOD

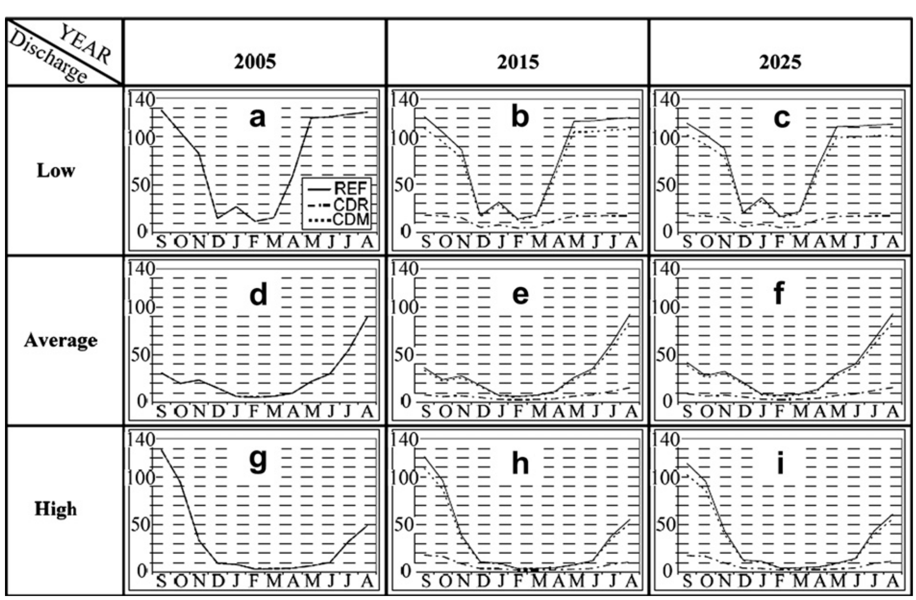


**Fig. 11.** Monthly BOD (mg/l) in the Litani River above Lake Qaraoun.

**Table 2**
Incremental analysis of wastewater treatment alternatives in the ULB

| # | Plan | Cost ($ million) | | BOD removed (1000 kg) | | Cost per unit of BOD removed ($/kg) | |
|---|---|---|---|---|---|---|---|
| | Combination[a] | Total | Incremental | Total | Incremental | Average | Incremental |
| 1 | Z | 22.33 | 22.33 | 26,235 | 26,235 | 0.85 | 0.85 |
| 2 | Z and M | 44.66 | 22.33 | 34,863 | 8628 | 1.28 | 2.59 |
| 3 | Z, M and Q | 55.83 | 11.17 | 38,984 | 4121 | 1.43 | 2.71 |
| 4 | Z, M, Q and J | 74.69 | 18.87 | 44,136 | 5152 | 1.69 | 3.66 |
| 5 | Z, M, Q, J and T | 86.03 | 11.34 | 46,848 | 2712 | 1.84 | 4.18 |
| 6 | Z, M, Q, J, T and B | 97.31 | 11.28 | 47,525 | 677 | 2.05 | 16.67 |
| 7 | Z, M, Q, J, T, B and S | 105.13 | 7.82 | 47,714 | 189 | 2.20 | 41.4 |
| | CDM plan[b] | 9.91 | 9.91 | 6376 | 6376 | 1.55 | 1.55 |

[a] Z = Zahle, M = El-Marj, Q = Qaraoun, J = Joub Jannine, T = Timnine Et-Tahata, B = Baalbeck and S = Saghbine.
[b] CDM WWTPs were simulated together as one plan separate from CDR WWTPs.

near entrance to Qaraoun Lake, and consequently may not address other important issues, such as the extent of sewage pollution governed by the upstream/downstream location of the WWTP, equity of access to public services, health hazard of septic tanks, impact of other pollutants not represented by the BOD indicator. These factors can be assessed through an extensive process involving different stakeholders and using a range of other quantitative and qualitative indicators and tools.

## 9. Summary and conclusions

In response to the excessive and progressive wastewater induced pollution of the Upper Litani Basin surface water and its dire consequences on its socio-economical development, governmental and non-governmental agencies have embarked on water quality management initiatives that involve the construction of several waste water treatment facilities and supporting sewage networks. A GIS-based decision support system has been developed to help policy makers and other stakeholder assess the value of these plans and other future ones. Based on the WEAP model, the decision support system provides a virtual integrated simulation environment and a scenario management module to represent disaggregately the Upper Litani Basin and examine in detail the impact of alternative water quality management scenarios.

Current wastewater pollution conditions and two water quality management plans, one proposed as a master plan by the CDR and another small scale plan sponsored by the USAID, have been simulated for a 20-year projection and assessed in terms of expected BOD levels. The extent of pollution caused by releasing untreated domestic sewage into the river system and the impact of the two management plans have been determined in relation to three water years representing low, average and high river discharge conditions.

The simulation results show that the current practice of discharging untreated sewage into the river system is already causing a wide-scale pollution that escalates to an alarmingly hazardous state during drier times, which last for the longer part of the year, and possibly for several years in a row during drought spells. The CDR plan is found to be generally effective in reducing the extent and duration of surface water pollution. However, the plan is not as effective in the upper reaches of the basin, especially during the drier times of the year since it neglects a large number of towns in that sector. The CDM plan has smaller influence due to its limited scale.

Cost-effectiveness of the CDM plan and alternative combinations of CDR plants were assessed based on incremental analysis of output from corresponding 25-year WEAP simulations under average river flow conditions. Environmental effectiveness was assessed by the amount of BOD removed from the river at the point of entry to Qaraoun Lake for the 25-year duration. The WWTP at Zahle is found to be the best buy plan with a present value cost of $0.85 to remove one killogram of BOD. BOD removal costs of other WWTPs range from $2.59/kg at the El-Marj to $41.4/kg at Saghbine. Costing $1.55 per kilogram of removed BOD, the group of CDM WWTPs provides a better buy plan than CDR WWTPs, less Zahle's. Therefore, the decentralized and small community approach adopted by the CDM plan is found to provide a cost-effective, less capital intensive and scalable option to manage water quality in the ULB.

In summary, the severe deterioration of water quality in the ULB requires immediate and effective action. The situation is particularly worrisome considering that the current levels of pollution have already made these scarce fresh water resources unusable especially during peak demand times. "Quality is compromising supply" as articulated by Cadham et al. (2005) in reference to the environmental degradation of the water quality in the Akkar watershed in Lebanon and Syria, is equally applicable to the similarly grave conditions in the ULB.

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