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MODELLING NITRIFICATION IN THE RIVER ZARKA OF JORDAN

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Abstract—The Zarka, a shallow, relatively small river flowing through a semi-arid region of Jordan is the country's main water course. Its prime source is discharge from a large overloaded waste treatment plant centred on stabilization ponds. Between May 1990 and January 1992, NH_4–N concentrations of up to 130 mg/l were recorded at the river source, and an average 76 mg/l NO_3–N at the discharge into a strategically vital supply reservoir. Proposed revisions to the structure of a model to simulate nitrification, take into account the influence of very high algal and bacterial populations (10^6–10^7 cfu/ml), as their activities are both important factors. With respect to algae, high solar radiation intensities appeared to inhibit activity, such that for modelling, activity was related to the maximum/minimum diurnal DO ratio, rather than measured biomass or chlorophyll *a*.

Key words—nitrification, river Zarka, algae, bacteria, modelling

INTRODUCTION

Water quality models used to assess the effect of discharged effluents are not generally designed to accept the challenge of shallow rivers flowing in arid and semi-arid regions. This is despite the inevitable extremely high importance of these streams to the local population and economy. Added to this are often problems of very variable flow, high temperatures and heavy pollution loads from intensive local farming, industry and habitation.

One such region is the Amman–Zarka area of Jordan, which is inhabited by around 2.2 million people and houses 90% of the country's light to medium size industries. Contained within the area is a single river system, the Zarka (Fig. 1), which has a length of around 44 km and an average base-flow of 80,000 m^3/day in the dry season. This small river receives most of the region's treated, semi-treated, and untreated domestic and industrial waste water, and is as a consequence, heavily polluted, particularly with nitrogenous compounds (Fig. 2). The Zarka is also the main continuous source for the King Talal reservoir, the country's largest supply reservoir.

Before 1985, the river was a fresh water stream originating from springs and wells. Waste water was treated in a conventional activated sludge plant (Ain Ghazal), until it became quantitatively and qualitatively overloaded due to rapid population growth. In 1985, the es-Samra waste water treatment plant was constructed to serve the capital Amman and surrounding towns. Since then, the only significant tributary (the Sukhneh stream which constitutes less than 10% of the Zarka flow), has served the region's domestic requirements, leaving the main river sourced by treated waste water from es-Samra.

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Due to the availability of large tracts of semi-arid land, the es-Samra plant was based upon stabilization ponds of a total area of 181 ha. The layout is three parallel trains, each a series of ten ponds (two anaerobic, four facultative, and four maturation). After a total retention period of approximately 40 days, the effluent, which is occasionally chlorinated, is discharged into the Wadi Dhuliel which in turn flows to meet the Sukhneh tributary, 15 km downstream of the outlet. The combined streams flow through a natural course until impounded in the King Talal reservoir.

The es-Samra treatment plant was soon overloaded (Saidam, 1988), with discharge quality often at a level that would be deemed only acceptable in other situations for influent to secondary treatment plants (Bino, 1990). The result was very low quality river water, particularly with respect to high levels of NH_4–N (Salameh and Rimawi, 1987). It is also for the entire length, devoid of fish or rooted plants, the latter considered due to a combination of total bed scour from flash floods and a high upstream level of boron (3 mg/l). The metal, originating from local industries, has been implicated in adverse effects on crops irrigated with Zarka water.

The high input levels of NH_4–N (78–130 mg/l), have led to significant nitrification (Fig. 2) and importantly to the region, high NO_3–N concentrations at

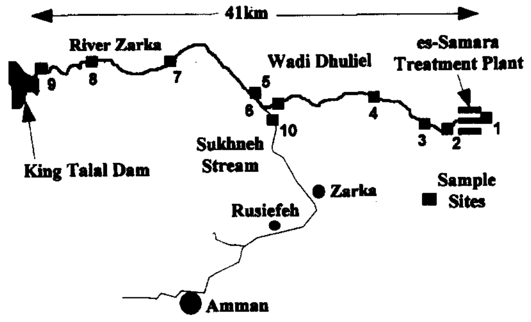

Fig. 1. Sampling sites (1–10) in the river Zarka and Sukhneh stream basin.

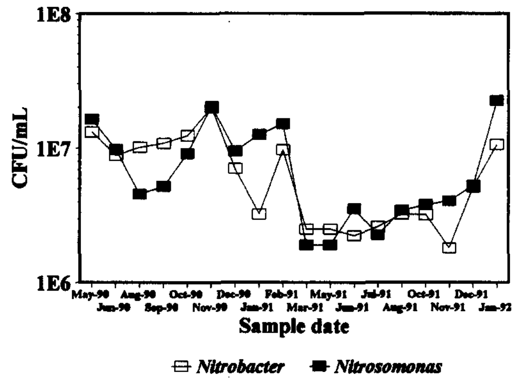

Fig. 3. Levels of nitrifying bacteria recorded in the river Zarka at Site 5.

Site 9 (up to 132 mg/l recorded, although the average was around 76 mg/l). The levels of NO_3–N entering the reservoir cause concern, by promoting eutrophication (Hashwa and Marzolf, 1987; Salameh and Rimawi, 1987). Not surprisingly, we have also found very high levels of nitrifying bacteria (Fig. 3), in the order of 10^6 cfu/ml (Site 2), rising to a maximum of 10^7 cfu/ml (Site 5), before falling back to 10^6 cfu/ml (Site 8). Due to these high numbers, direct oxidation of NH_4–N would be in competition with microbial activity (both suspended and associated with the sediment), for any oxygen provided by re-aeration and photosynthesis.

Microbial sponsored nitrification is a two step bacteria dominated process (Thomann and Mueller, 1987; Gee *et al.*, 1990a, b). It is considered optimal at mesophyllic temperatures (25–35°C) and at a slightly alkaline pH of 7.5–8.0 (Curtis *et al.*, 1975; Prosser, 1990), conditions similar to those found for long periods in the Zarka. Initially, NH_4–N is oxidized under aerobic conditions to nitrite by *Nitrosomonas europaea*, and the nitrite subsequently oxidized to nitrate by *Nitrobacter winogradskyi*.

The work described in this article is part of a study on the Zarka's water quality, centred specifically on the unusually high concentration of nitrogenous compounds. The aim was to identify the structure of a practical water quality model to help in making decisions necessary to improve the present situation and also plan for future developments (Abumoghli and Scott, 1992). As part of this programme and illustrated in this article, are limitations of existing models in predicting nitrification when applied to the Zarka, and as a consequence of measured and experimental data, suggestions for a revised approach.

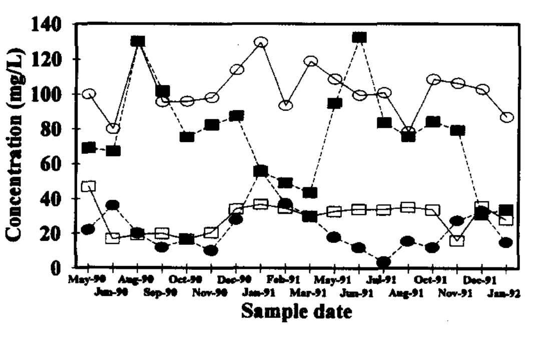

Fig. 2. Ammonium and nitrate levels found in the river Zarka at Site 2 and Site 9.

MATHEMATICAL MODEL

Simulation of nitrification by existing models, is generally stated in combination to direct NH_4–N oxidation, to be regulated by either bacteria (e.g. the Blackwater Model, Crabtree *et al.*, 1986), or by algae (e.g. Qual 2EU, Van-Benschoten and Walter, 1984), but not both. The Blackwater model is one dimensional deterministic and operates in steady state, apart from diurnal DO changes due to photosynthetic activity. Qual 2EU numerically solves one-dimensional advection dispersion equations for quality variables by representative differential mass balances based on the volume of each element in the system (Brown, 1987). We applied both models to the Zarka, but as illustrated in the Results and Discussion section, neither approach adequately predicted nitrification trends, an expected result considering marked differences in nature between the Zarka and the rivers that formed the basis of the two models (Table 1).

In the Zarka, the extremely high and persistent, bacterial and algal loading along the river were

Table 1. Difference in summer conditions found in the Blackwater, Winooski, and Zarka rivers

Parameter	Blackwater	Winooski	Zarka
River length (km)	35	32	44
Major waste water inputs	6	7	1
Population served by waste water plants	163,000	90,000	2,200,000
Mean annual flow (m^3/s)	3.0	4.2	1.7
Max NH_4–N (mg/l)	6.0	1.2	130[a]
Max NO_3–N (mg/l)	12.5	4.0	132[b]
Max BOD (mg/l)	9.0	3.5	130[a]
Max DO (mg/l)	8.5	10.5	9.5[b]

[a]Site 2, May 1990–January 1992 (discharge from the es-Samra treatment plant).
[b]Site 9, May 1990–January 1992 (prior to inflow to the King Talal reservoir).

considered likely to be predominant factors in dictating changes in water quality. With regards the algae, comparison between measured chlorophyll *a* content and the maximum/minimum DO diurnal ratio (Fig. 4), highlighted an unusual situation. Above Site 6, chlorophyll *a* was very high, but diurnal DO levels remained fairly constant (i.e. ratio close to one), suggesting little photosynthetic activity. Whereas over the same period, the Sukhneh stream at Site 10 had a ratio of 3.4, and below its confluence with the river, the marked increase in the Zarka's ratio, indicated introduction from the stream of significant photosynthetic activity, despite a continuing fall in bulk chlorophyll *a*.

Linking photosynthetic activity directly to chlorophyll *a* concentration would prove therefore misleading, as the large quantity of algae entering at Site 2 appears to be relatively inactive. Under the region's strong incident light, photo-inhibition is possible, as algae discharged into the river from the stabilization ponds, are abruptly exposed to much shallower water (i.e. from 2–5 m deep, to less than 0.6 m). This sudden change in light intensity for the bulk of the algal population could inhibit photosynthesis and also nitrification activity (Nixon and Berounsky, 1984), although it will not necessarily result in a substantial loss in bulk mass (Barber, 1987).

The progressive fall in chlorophyll *a*, would appear therefore, a reflection of dead algae, which originated primarily from the waste treatment plant, settling out. This was supported by increased sediment oxygen demand with distance from Site 2. Consequently, for work on the Zarka, as an alternative to chlorophyll *a*, the maximum/minimum diurnal DO ratio was found to provide a much better reflection of algal activity. This adoption was considered reasonable, as at all the sites, levels of bacterial and sediment activity remained, diurnally, fairly constant.

To provide simulation of the Zarka, changes in both NH_4–N and NO_3–N were mapped by combination of various process components, including direct NH_4–N oxidation. Considering the problems

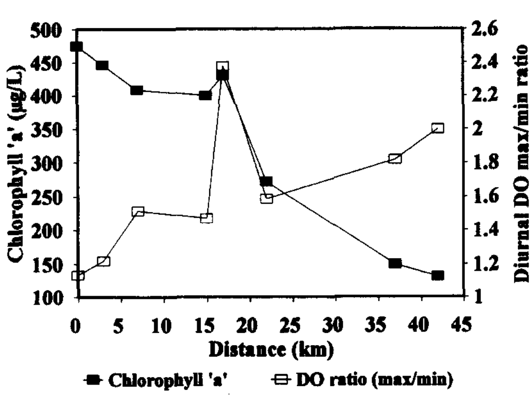

Fig. 4. Longitudinal variation along the river Zarka in chlorophyll *a* concentration and the maximum/minimum diurnal DO ratio.

of access to such rivers, a prerequisite was that each component must contain data readily obtainable from direct measurement and/or experimentation. They were developed over a range of 15 to 25°C, such that to each parameter, a temperature correction factor could be applied:

$$K_T = k_{20}\theta^{(T-20)} \qquad (1)$$

T = water temperature (°C), K_T = rate coefficient at T°C, k_{20} = rate coefficient at 20°C (dimensionless), θ = correction factor (dimensionless).

For the model components described below, which were revised to provide an acceptable simulation of the Zarka's conditions, experimentally determined temperature correction factors are presented in Table 2 and derived coefficients in Table 3.

(i) Bacterial activity

A wide range of expressions, including standard descriptors such as Monod kinetics, were examined as to their effectiveness in describing microbial activity in the Zarka. We subsequently adopted a modified expression of the type used by Wong-Chong and Loher (1978), to describe bacteria sponsored oxidation kinetics of NH_4–N and NO_2–N through to NO_3–N. However, the Zarka's bacterial contribution was related to mg/l of nitrifying bacteria, rather than to the total suspended volatile solids (SVS) used by Wong-Chong and Loher (*op cit.*). The high total suspended solids content in the river is primarily algae, which if assessed as SVS effectively "masks" the bacterial content. Laboratory cultures of water samples which assessed the number of colony forming units (cfu) per ml of nitrifying bacteria, were used therefore, to determine concentration in terms of mg/l. Their influence on nitrogenous compound levels was related to:

$$= K_T \frac{r_m k[X]}{r_m + k[X]} \qquad (2)$$

$[X]$ = total nitrifying bacterial concentration (mg/l), k = reaction rate constant for NH_4–N oxidation or NO_3–N production (l/min), r_m = maximum reduction/production rate of NH_4–N or NO_3–N [mg($N_x - N$)/l/min].

(ii) Algal activity

Unlike most river systems, algal activity can not be directly related to measured biomass, as interpreted by total chlorophyll *a*. Consequently, expressions

Table 2. Temperature correction factors (θ)

Temperature dependent parameter	θ
Microbial activity	1.047[a]
BOD decay	1.016[b]
Re-aeration	1.061[b]
Ammonium decay	1.035[b]
Nitrate production	1.118[b]
Sediment oxygen demand	1.061[b]

[a]Crabtree *et al.* (1986).
[b]This study.

Table 3. Parameters used in revised modelling of NH_4-N and NO_3-N in the river Zarka

Coefficient	Description	Value
r_{mA}	Maximum bacterial NH_4-N reduction rate coefficient [mg(NH_4-N)/l/min]	−0.308
k_A	Reaction rate constant for suspended bacterial NH_4-N reduction (l/min)	−0.004
r_{mN}	Maximum suspended bacterial NO_3-N production rate [mg(NO_3-N)/l/min]	0.065
k_N	Reaction rate constant for bacterial NO_3-N production (l/min)	1.1×10^{-5}
r_{AA}	Algal NH_4-N source rate (mg/l/min)	0.089
r_{AN}	Algal NO_3-N source rate (mg/l/min)	0.038
r_{SA}	Sediment source rate for NH_4-N (mg/l/min/kg)	5.6×10^{-6}
r_{SB}	Sediment source rate for NO_3-N (mg/l/min/kg)	9.8×10^{-6}
C_I	Algal inhibition coefficient (dimensionless)	0–1
C_S	Sediment age coefficient (dimensionless)	0–1

centred on microbial (chlorophyll *a*) concentrations, such as that used to describe bacterial activity, were found misleading in the way they described the impact of the algal population. With the requirement for using readily obtainable data, suspended algal influence on the level of nitrogenous compounds was best described by

$$= K_T r_A \phi_{DO} C_I \quad (3)$$

r_A = algal decay/source of NO_3-N or NH_4-N [mg($N_x - N$)/l/min], ϕ_{DO} = ratio of maximum to minimum diurnal DO (dimensionless), C_I = inhibition correction coefficient (dimensionless).

(iii) Sediment

Due to the region's two or three aggressive floods per year, and subsequent complete bed scour, contribution to a mass balance by deposited sediment needed to take into account material quantity. That is, the material is shallow (no more than 5 cm) and loosely packed, such that a reasonable approximation is to assume that it all can act as a source/sink. The increase with distance downstream in sediment load per square metre, was found to be approximately linear (Fig. 5), and that the gradient of this line divided by the value derived from when depositions were at a maximum, provided a simple, dimensionless and normalized correction coefficient (C_s), to take into account sediment age. The contribution to the level of nitrogenous compounds in the overlying water was subsequently evaluated by using

$$= \frac{K_T r_S C_S W A}{V} \quad (4)$$

r_S = sediment source/sink for NO_3-N or NH_4-N [mg($N_x - N$)/(kg sediment/min)], C_S = sediment age coefficient (dimensionless), W = quantity of sediment (kg/m^2), A = cross-sectional area (m^2), V = volume of overlying water (l).

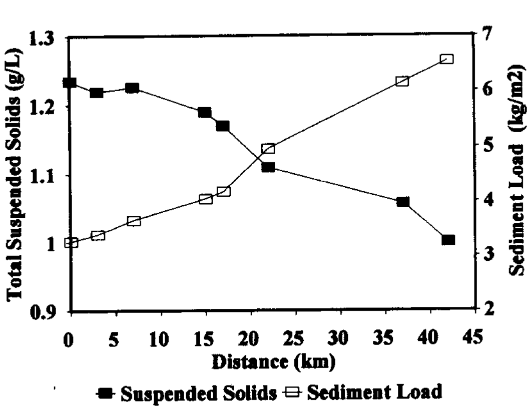

Fig. 5. Longitudinal variation along the river Zarka in total suspended solids and sediment load.

MATERIALS AND METHODS

Sampling sites

To reduce evaporation and prevent stagnation zones, the Zarka's supervising authorities confine the first 15 km in a 2–4 m wide, 0.5–0.6 m deep channel. After confluence with the Sukhneh stream, the river is left to flow naturally, taking a much wider (up to 17 m) and shallower (0.2–0.3 m) course. Eight sample sites were selected (2–9), to represent different river development stages and another two to determine the es-Samra treatment plant influent and Sukhneh stream quality (1 and 10 respectively).

A standard sampling regime was always followed, collecting samples in strict order (Sites 2 to 9), under a time schedule that approximated to river flow rate, in order to "follow" downstream transit of the same parcel of water. Samples were collected in 18 monthly surveys (May 1990 to January 1992). On several occasions, diurnal variations were followed by sampling hourly at the different sites over 24 h.

On-site and laboratory physical, chemical and biological analysis schedule

On site measurements were DO, temperature, pH, turbidity, depth, width, velocity and sediment load. Collected samples were placed in an ice box and returned to the laboratory within 6 h and set up for analysis of NO_3^-, NO_2^-, NH_4^+, PO_4^{-3}, BOD_5, COD, TOC, total suspended solids and chlorophyll *a*. Samples were also prepared and incubated for total bacterial count, *Nitrosomonas* sp. and *Nitrobacter* sp. Standard test methods were used (Greenberg *et al.*, 1980; Abumoghli and Ghuneim, 1990).

Site based rate experiments

DO consumption rates were measured on-site by submerging freshly filled sealed glass 15 cm diameter sample columns in the river and fall in DO concentration recorded over 30 min. Similar experiments were also carried out with the column covered to prevent light penetration, such that difference in DO depletion rates could be used to provide indication of both photosynthetic activity and oxygen consumption rate (Boyle and Scott, 1984). Sediment oxygen demand was estimated by deduction through replicating the experiments after carefully adding river bed sediment (at the site's ratio of weight per surface area). Typical results for Site 8 are illustrated in Fig. 6.

Laboratory based rate experiments

Samples were shipped in an ice-box and used within 3–4 h of collection. A series of batch experiments were carried out to determine various activity rates at different initial concentrations (NH_4-N, NO_3-N or DO), or temperatures (15–25°C), by using temperature controlled 15 cm diameter glass columns containing river water at the same depth as the sampled site. The same series of physical conditions carried out at the river site were also used in the laboratory (light or dark, with or without sediment). DO was maintained through forced aeration at 6.9 ± 0.2 mg/l (unless otherwise stated) and the experiments carried out to provide the data tabulated in Tables 3 and 4 were:

(i) Rate of change in nitrogenous compounds followed under different initial NH_4-N, or NO_3-N concentrations.

(ii) For contribution of suspended solids (primarily algae and bacteria), samples were filtered through either Whattman No. 40 to remove algae, but keep bacteria, or 0.3 μm filters to remove all microorganisms.

(iii) Effect of temperature on nitrification processes obtained by incubating at 15, 20 and 25°C (typical seasonal values).

(iv) Influence of initial bacterial cell concentrations by serially diluting samples with filtered (0.3 μm) river water. Changes in nitrogenous compounds were then measured over three hours (a period less than the doubling time of the nitrifying bacteria, i.e. greater than 8 h).

RESULTS AND DISCUSSION

To demonstrate the effectiveness of incorporating the suggested revisions, data collected in the summers of 1990 and 1991 (average water temperature, 25°C), were used to provide the model parameters for the Blackwater, Qual 2EU and Zarka revision. To illustrate the "robustness" of the models as applied to the Zarka, they were then used to predict data recorded in late autumn, when water temperature averaged around 20°C.

Measured values for the first upstream site, below the es-Samra treatment plant outlet, were used as initial inputs to the system, with the predicted change in conditions implemented as inputs to the next reach, and so on. Each reach was assumed to be well mixed and homogeneous with, where required, the physical parameters of temperature, velocity, geometry and flow rate of the Zarka used. Along with the actual measured data, the results of predicting longitudinal changes in DO, NH_4-N and NO_3-N with the three models are presented in Figs 7–9.

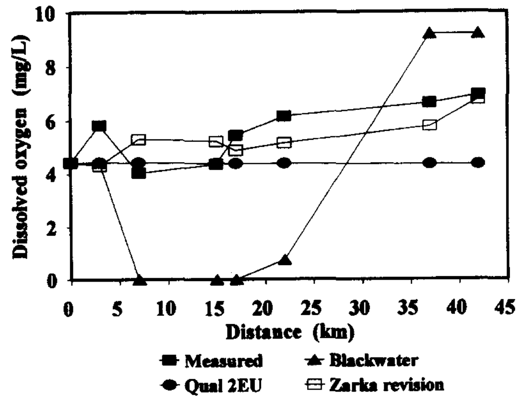

Fig. 7. Measured and modelled DO levels along the Zarka.

Dissolved oxygen (DO)

Re-aeration rates and DO saturation values described by both existing models are related to actual temperature, velocity, river depth, along with empirical factors, but subsequent simulation of river DO was not satisfactory (Fig. 7). One immediate problem is that the specified re-aeration criteria incorporated in the models may hold for average quality fresh water, but these were exceeded by the Zarka's high average water salinity (around 400 mg/l as chloride), and total suspended solids (1000–1250 mg/l, Fig. 5).

Furthermore, although sediment DO demand was recognised to affect supernatant DO, this is seasonally and longitudinally, a variable factor in the Zarka. This shallow river is affected by floods two or three times each year, which results in rapid and total scour of sediments deposited during the preceding low flow period. Subsequent redeposition produces a very pronounced longitudinal gradient in sediment quantity (Fig. 5) and activity.

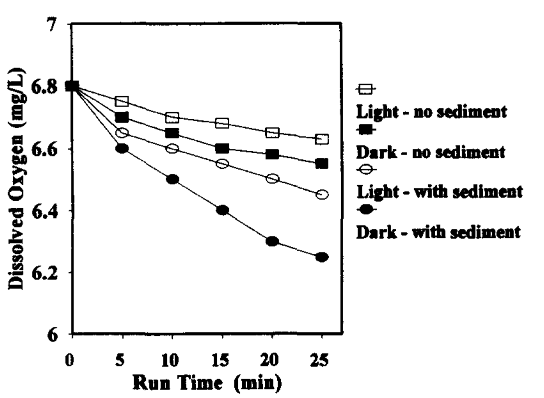

Fig. 6. Example of DO consumption curves obtained from field trials at Site 8.

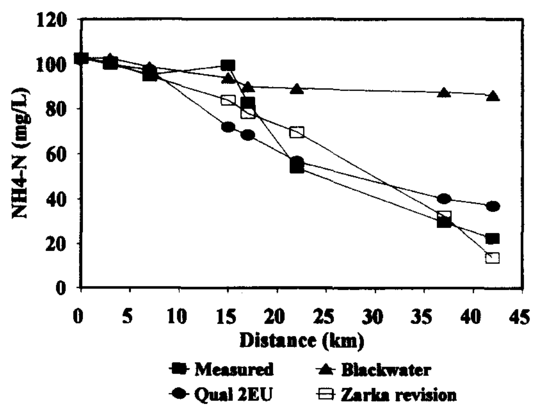

Fig. 8. Measured and modelled ammonium levels along the Zarka.

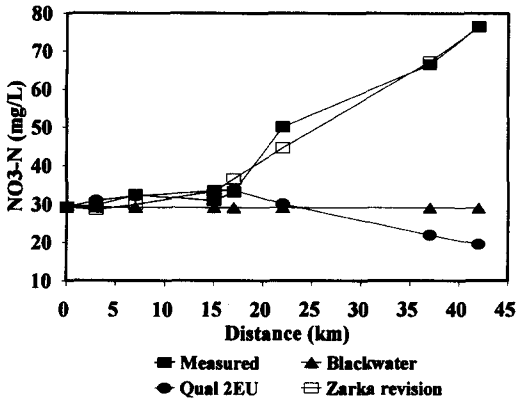

Fig. 9. Measured and modelled nitrate levels along the Zarka.

Consequently, implementation of a fixed value to account for sediment oxygen demand along the entire river (as in the two models), would not adequately describe prevailing conditions.

The Zarka is devoid of rooted plant life, but does contain a very high loading of algal biomass and any photosynthetic influence it has on DO was assumed in the existing models, to be related to light intensity and water depth. The Blackwater model, for example, suggests that oxygen concentration due to photosynthesis increases with light intensity and decreases with depth. With the chlorophyll *a* profile and shallowness of the Zarka, this should lead to very high (although decreasing) activity along its length, but prevailing high light intensities, particularly upstream, had an apparent adverse effect on photosynthesis. That is, the sudden exposure of algae grown in deep (2–5 m) and sluggish treatment lagoons to high light intensities in the much shallower river (0.2–0.6 m), may have reduced algal activity through photo-inhibition.

With Qual 2EU, the model does not limit the user with predefined equations of re-aeration, air saturation coefficient etc. However, the result using the Zarka conditions (Fig. 7), was a prediction that longitudinal DO follows a more or less constant concentration, suggesting that oxygen sources and sinks are almost equal. Whereas, in reality, below the confluence (15 km), DO begins to increase, which reflects a much more active algal population introduced from the Sukhneh stream, which is in apparent contradiction to the measured, falling bulk levels of chlorophyll *a*.

Ammonia nitrogen (NH_4-N)

Other than by direct oxidation from aeration, the existing models rely on the activity of either algae or bacteria to dictate the fate of NH_4-N. Qual 2EU, particularly below the confluence, provided a reasonable simulation of the fall in NH_4-N (Fig. 8). However, on closer inspection, applying the assumptions behind the prediction to the Zarka was unsound, as local algal respiration was taken by the model to be 5% of maximum growth rate, which in turn was directly related to biomass through measured chlorophyll *a*. Whereas, our work indicated low upstream algal activity with respect to a very high chlorophyll *a* level, and furthermore, there was not a direct relationship between activity and suspended biomass. However, Qual 2EU by adopting the high respiration rate determined for the river Winooski (Van-Benschoten and Walker, 1984), at least in part, compensated for the perceived loss in algal activity due to the progressive fall in measured biomass.

On the other hand, the Blackwater model clearly failed to predict changes in NH_4-N after Site 6. This reflected the style of model which relates microbial influence on rate of NH_4-N change to bacterial biomass (mg/l of *Nitrosomonas europaea*). As a consequence, the model can only sensibly predict the first part of the river water, when natural re-aeration and photosynthetic activity was far less than was found below Site 6, and consequently provided only a minor contribution to NH_4-N decay. For the remainder of the river, the rapid decline in NH_4-N was not followed, as microbial sponsored change was tied to a relatively stable *N. europaea* population, and failed to accommodate increasing algal activity.

Nitrate nitrogen (NO_3-N)

It was with prediction of the important longitudinal NO_3-N profile, in terms of the receiving reservoir, that both existing models breakdown, particularly below the confluence. The Blackwater model related change in NO_3-N to only variation in NH_4-N levels, and since it predicted little change in NH_4-N, the result for the Zarka will invariably be little or no change in NO_3-N (Fig. 9). The model does include a term to allow for loss of NO_3-N by denitrification, but as this process takes place after nitrification and under anoxic conditions, it has little or no impact on the Zarka.

Qual 2EU predicted a slight fall in the amount of NO_3-N, as its level was again linked to algal respiration, which in turn was directly correlated to the falling chlorophyll *a* levels. However, by simply using the maximum/minimum diurnal DO ratio as a modification factor, a straightforward, but effective measure of algal activity is provided. The introduction from the tributary into the main river of an active, albeit relatively small algal population (in terms of net chlorophyll *a*), could be therefore accommodated. The result of including this factor is highlighted by the excellent fit provided by the Zarka revision's interpretation of prevailing conditions.

CONCLUSIONS

The river Zarka of Jordan is typical of a river flowing in a semi-arid region. It is small, but strategically vital as the only continuous flowing resource feeding the King Talal reservoir during the eight month dry season. This is the country's largest reservoir and its water is used to irrigate Jordan's most fertile regions. However, problems associated with the highly polluted state of the river, necessitate a revised management strategy. As part of this requirement, a study was initiated to monitor the water quality of the river, focusing specifically on nitrogenous compounds which are contributing to eutrophication in the receiving reservoir.

On-site and laboratory experiments were carried out to assess nitrification in the Zarka, and two well known river quality models, the Blackwater and Qual 2EU, applied to try and simulate the data. The Blackwater identifies bacterial biomass as the key microbial factor and Qual 2EU, algal biomass, but applying them to the conditions of the Zarka highlighted aspects of their basic structures which prevented adequate simulation. The prime reasons were that the Zarka is subject to unusually high input levels of NH_4–N, solar radiation, and in particular, bacteria and algae. Although bacterial and algal influences on nitrification processes have been extensively studied separately, they have not been combined and applied before to a river such as the Zarka.

Presented is the initial working of a straightforward revised model strategy which explicitly takes into account both forms of microbial activity with respect to nitrification. This approach stems from a demonstrable need to include both factors, either directly or indirectly, when operating under conditions prevalent in the Zarka. Included, is a novel approach to represent algal activity by the ratio of minimum to maximum diurnal DO values, rather than by the more usual method of algal chlorophyll *a* levels. Furthermore, the river is shallow, and the sediment can play an important role in dictating water quality. However, as the river is subject to regular, complete scour of its sediment, factors were incorporated to take into account sediment age and the marked longitudinal variation in load.

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