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THE ROLE OF THE HYPORHEIC ZONE IN THE NITROGEN DYNAMICS OF A SEMI-ARID GRAVEL BED STREAM LOCATED DOWNSTREAM OF A HEAVILY POLLUTED RESERVOIR (TAFNA WADI, ALGERIA)

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ABSTRACT

Nitrogen retention was measured along the Tafna wadi downstream of a heavily polluted reservoir in North-West Algeria to understand the role of the hyporheic zone (HZ) in nitrogen dynamics. Nutrient concentrations were measured monthly for 2 years within the bed sediments of a 300 m reach located 20 km downstream from the dam. Due to strong hydrological fluctuations hyporheic water was analysed during natural low and high water (HW) periods, and during water reservoir releases. Nutrient concentrations in surface water (SW) increased during water releases and in the HZ during the low water (LW) periods. Surface/hyporheic water interactions were characterized by determining the vertical hydraulic gradient (VHG) and the chemical signature of the ground water (GW). The latter was obtained from regional GW monitoring. Hyporheic chemistry was strongly influenced by patterns of surface flow. Hyporheic and SWs had similar chloride concentrations during high flow when they were significantly lower than those of the regional GW. GW was generally richer in nitrates and nitrites, but was lower in ammonium concentrations than interstitial and river waters. Nitrates decreased significantly from upstream to downstream within the HZ throughout the hydrological period even though temporal fluctuations were high. Ammonium concentrations in interstitial water (IW) were significantly higher than in SW and generally increased from upstream to downstream. This study demonstrates the importance of the HZ in altering the dissolved inorganic nitrogen composition and concentrations of heavily polluted arid streams. The study is of interest because it documents a large 'natural experiment' that being the effect of periodic water release from a reservoir with serious water quality problems on the water quality dynamics (particularly nitrogen) of subsurface and SWs downstream.

KEY WORDS: nutrients; reservoir; hyporheic zone; pollution; semi-arid stream; ecology

INTRODUCTION

Water management is an acute problem in most countries with a semi-arid climate, including Algeria. For several decades, new programmes of reservoir construction have been underway to address water management issues. Dam construction on the Tafna wadi (North-West Algeria) provided the opportunity to evaluate the effects of waste water storage and release on surface water (SW) quality and downstream hyporheic ecosystems (Belaidi *et al.*, 2004), by comparing the physicochemical parameters before and after the release of reservoir water (Taleb *et al.*, 2004). While human activities have a great influence on the characteristics of 'river' systems (Hannan and Young, 1974; Egborge, 1979), little data are available concerning the effects of reservoir management on downstream aquatic ecosystems in semi-arid areas.

The functional analysis of a complex aquatic system like the Tafna requires considerations of both hyporheic and phreatic (ground water (GW)) zones, which are partly dependent on the river itself. The hyporheic zone (HZ) is defined as the subsurface water flowing in riverbed sediments and contains at least 10% SW (*sensu* Triska *et al.*, 1989). Physical, chemical and biological interactions between SW and interstitial water (IW) influence the

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functioning of aquatic systems (Danielopol, 1980, 1989; Grimm *et al.*, 1981; Hynes, 1983; Bencala *et al.*, 1984; Triska *et al.*, 1989; Stanford and Ward, 1993; Findlay, 1995).

Several studies on the nature and mechanisms of exchange and interaction between SW and IW have determined that the HZ is a critical dimension of the river ecosystem (Ward, 1989; White, 1993; Jones and Holmes, 1996). The HZ exhibits its greatest influence on the ecological function of the system during the surface–subsurface water exchange. Although it has been shown that solutes are generally retained by hyporheic sediment (Bencala *et al.*, 1984; Vervier *et al.*, 1993), hyporheic water can be rich in dissolved organic carbon (DOC) (Rutherford and Hynes, 1987; Ford and Naiman, 1989), and in nitrogen and phosphate (Grimm *et al.*, 1981; Duff and Triska, 1990) which might subsequently enrich the stream channel. Such retention, production and transformation processes can generate a different chemical environment in hyporheic and in SW.

Although the role of the HZ in the biogeochemistry of river systems has been established for low biogenic concentrations in streams (Jones and Holmes, 1996), the relationship between the HZ function and the quality of heavily polluted SW has received little attention. However, some general studies have examined the impact of pollution on hyporheic chemistry (Mestrov and Lattinger-Penko, 1977, 1981) and on the distribution of the interstitial fauna (Notenboom *et al.*, 1995; Wood *et al.*, 2002). For the North African wadis, very little information is currently available concerning the hyporheic biotope, except for some data concerning the role of the HZ during drying periods (Gagneur and Chaoui-Boudghane, 1991).

The role of the HZ in the stream ecosystem is mainly determined by the rate at which subsurface biogeochemical processes occur and the proportion of stream discharge which exchanges with the HZ and flows through the porous sediment (Findlay, 1995). In arid zones, downwelling is the characteristic mode of exchange between SW and GW. The exchange occurs in the HZ.

The objective of this study was to test the hypothesis that the HZ plays a purifying role in the wadi ecosystem. To address this objective we (i) evaluated the water quality in the Tafna wadi, in the HZ and in GW, and (ii) examined strong changes in nutrient dynamics imposed by reservoir management leading to the release of polluted water.

MATERIALS AND METHODS

Study site

The study site was a 300 m reach located in the Tafna wadi bed (Figure 1), at an altitude of 184 m, 20 km downstream from the Boughrara reservoir. The average channel width was 7 m. The riverbed was primarily boulders and gravel in mid-channel and fine sediment near the banks. The stream morphology was riffle pool.

The flow, mainly controlled by the reservoir and side contributions varied during the study. Average water depth was 30 cm from June to December. The scarce riverine vegetation was dominated by herbaceous plants (*Sinapis arvensis*, *Nerium oleander*, *Calendula arvensis* and *Atractylis* sp.). The aquatic vegetation was represented by filamentous algae (*Zygnema* sp., *Spirogyra* sp. and *Ulothrix* sp.).

The Tafna wadi basin is located in northwestern Algeria, near the city of Tlemcen (Figure 1). The Tafna varies in elevation from sea level to 1100 m, with a drainage area of 7245 km². After 170 km, the river reaches the Mediterranean Sea, near the town of Beni-Saf. The catchment area of The Tafna can be divided into two very different geologic zones. The upper sector of the Tafna runs through a steep-sided valley dug into Jurassic limestone and dolomite, and the downstream sector runs through a tertiary basin characterized by marls covered by recent alluvia.

The Tafna wadi is a streambed that remains dry except during the rainy season. It drains into a semi-arid watershed where the annual average precipitation is lower than 300 mm and is exceeded by evaporation loss most of year. The area is also subject to intensive agricultural irrigation and industrial activities. The climate is Mediterranean, with sub-arid tendency, characterized by strong flow irregularities with a typically dry period from May to September. The Tafna wadi has five principal tributaries, the largest being the polluted Mouillah wadi, situated in the Maghnia region, an industrial activity centre with inadequate sewage treatment. The Mouillah wadi receives some domestic sewage and industrial effluent directly.

The Boughrara reservoir (N 34° 52', W 1° 39', 894 ha in area, 177 hm³ in volume, 18 m average depth) was installed in 1998 about 8 km Northeast of Maghnia, downstream of the confluence of the Tafna and the Mouillah

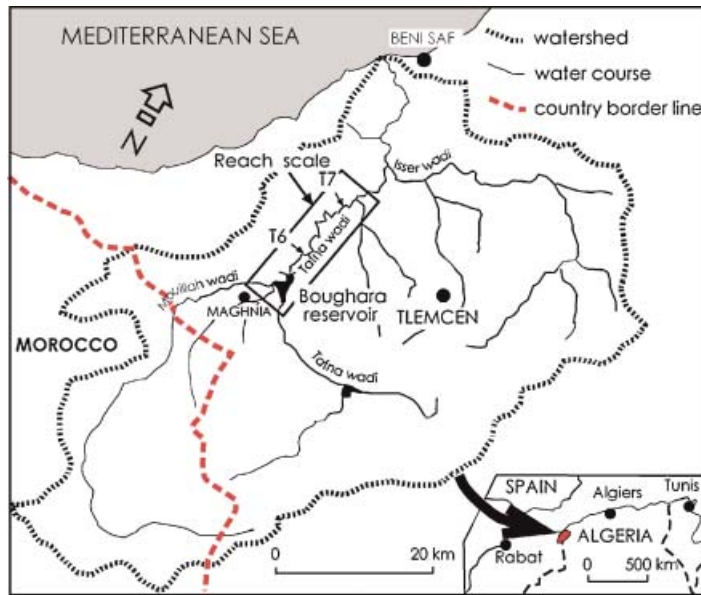


Figure 1. The Tafna basin and location of the study site. T6 is located directly below the Boughrara reservoir and T7 30 km downstream from the dam

wadis. The mean annual discharge of the Tafna is $0.44 \text{ m}^3 \text{ s}^{-1}$ and that of the Mouillah is $1.94 \text{ m}^3 \text{ s}^{-1}$ (for more details see Taleb *et al.*, 2004). Inter-annual monthly discharge calculated for the period 1993–1999, varied from $0.92 \text{ m}^3 \text{ s}^{-1}$ in February to $0.001 \text{ m}^3 \text{ s}^{-1}$ in August. Since dam construction in 1998 there has been no surface flow from the reservoir to the downstream part of the river during the period June to December. During this period releases occur for irrigation and water consumption. Water gates open at 6 or 14 m depth. Release discharges vary from 0.3 to $4 \text{ m}^3 \text{ s}^{-1}$. The river loses volume over the study reach.

Sampling procedures

Two sampling scales were considered for sampling waters (Figure 2): a reach scale for the sampling of SW and GWs and a site scale for sampling SW, IW and GW.

Reach scale. The studied reach was located between the city of Maghnia (at an altitude of 300 m) and the Tafna lowland plain (80 m a.s.l.). Two sampling sites for SW sampling were located on the axial course of the Tafna wadi: T6 directly below the Boughrara reservoir, T7 30 km downstream from the dam. GW samples were collected from 17 lateral wells situated on the left and on right banks along a 30 km long river section in December 1999, February and May 2000.

Site scale. IW samples were collected by a series of three pairs of piezometers installed in the main channel and noted P1–P6. Piezometer diameter was 4.5 cm; they were slotted and installed at the impermeable substratum depths (1–1.5 m). They were positioned along a 300 m reach on the right and the left banks (Figure 2). IW was sampled in piezometers using the Bou–Rouch method (Bou and Rouch, 1967; Bou, 1974). One litre of IW was collected from each piezometer by a peristaltic pump (10 min after the onset of pumping) from all the piezometers the same day. SW was sampled at three stations in the water course: site A upstream; site B mid-reach and site C downstream. The three stations were considered as independent, discrete geomorphological units.

Water samples were taken monthly during three hydrological periods from May 1999 to April 2001. Low water (LW) periods were sampled in May, June and July 1999 and April 2000. High water (HW) periods were sampled in December 1999, March 2000 and January 2001. Dam release water (DRW) was sampled in September and October 1999 and May, June, September and November 2000. SW was sampled at the same times upstream and downstream

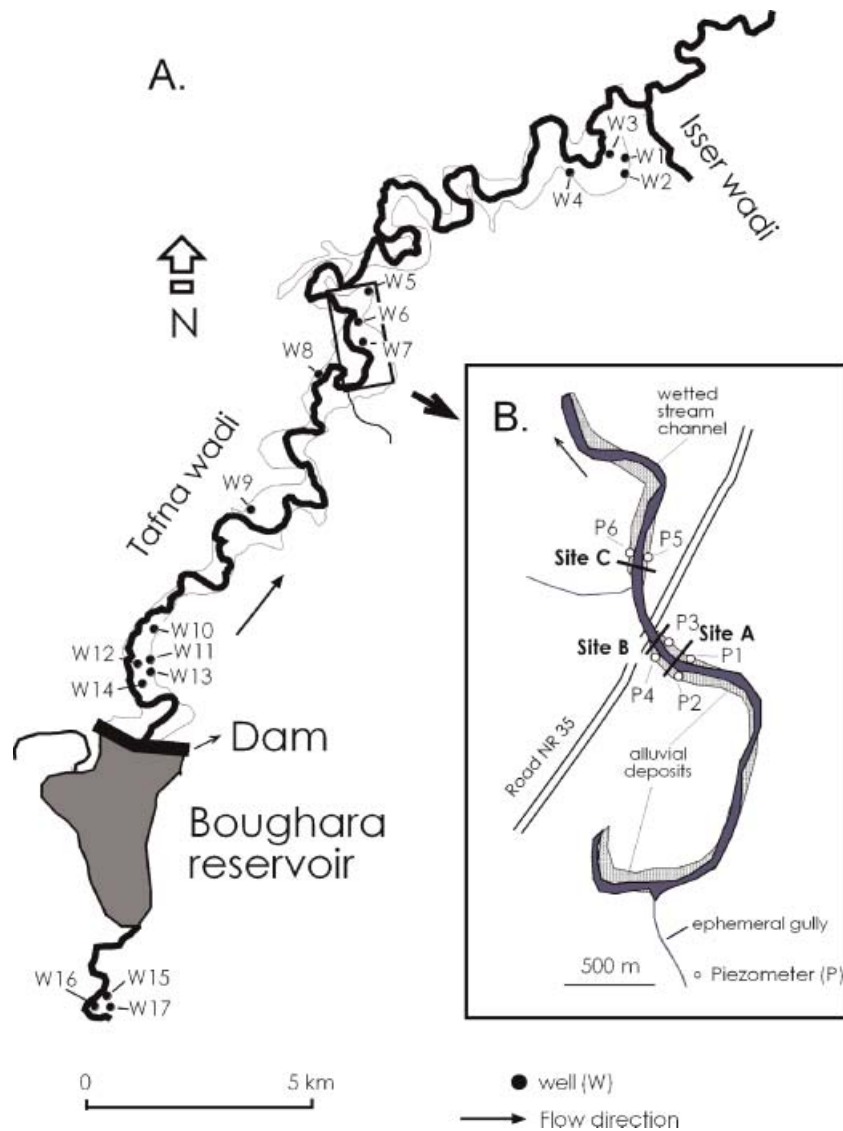


Figure 2. Location of wells in ground water (A) and localization of the study site at the reach scale (B): piezometers (P) for hyporheic zone water sampling, site A (upstream reach), site B (middle reach) and site C (downstream reach) for surface water sampling

of the study site and longitudinally along the Tafna wadi (stations T6 and T7). Instantaneous discharge was measured at stations A, B and C during the three hydrological periods with an Ott flowmeter.

During the study period, natural discharge during flow events ranged from 0.12 to $0.46 \text{ m}^3 \text{ s}^{-1}$ and release water discharges varied between 0.38 and $2.22 \text{ m}^3 \text{ s}^{-1}$.

Vertical hydraulic gradient (VHG)

VHG were measured monthly. The VHG is a measure of the pressure difference between surface and IW, and thus indicates the direction and strength of water exchange between the surface and subsurface water. Negative values indicate that water from the surface stream is entering the sediments (downwelling, greater pressure in the SW), positive values indicate the opposite direction of water movement (upwelling, greater pressure in the IW) and zero indicates that there is no water exchange at the site of the measurement.

Chemical procedure

Dissolved oxygen (mg L^{-1}), temperature ($^{\circ}\text{C}$), pH and specific conductivity (μS) were measured *in situ* using a specific probe (WTW model 96). Water samples were filtered through Whatman GF/F filter ($0.7 \mu\text{m}$) prior to analysis. Chemical parameters were measured in the laboratory of the National Agency of Hydrological Resources (ANRH, Tlemcen, Algeria). Biological Oxygen Demand (BOD) was measured using the modified Winkler method for water rich in organic matter (dilution method). Nitrate ($\text{N}-\text{NO}_3^-$), ammonium ($\text{N}-\text{NH}_4^+$) and nitrite ($\text{N}-\text{NO}_2^-$) were determined using colorimetric methods. Chlorides (Cl^-) were measured using colorimetric methods and volumetrically by the Mohr's method (silver nitrate titration with chromate indicator). Suspended solids (SM) were also estimated by the measurement of the dry weight of particles from 1 L of water retained on a Whatman GF/F filter after filtration. The procedures used are specified by Rodier (1996).

Subsurface sediment grain size

Sediment was collected on the first day of each water sampling period in each piezometer (six samples) to measure grain size fractions. Sediments were sampled through piezometers with a vacuum pump. Defrosted samples were then dried at 105°C prior to mechanical dry sieving. Two fractions were separated: sand ($200-2000 \mu\text{m}$) and silt and clay ($<200 \mu\text{m}$).

Organic matter was determined as loss on ignition by combustion of dried sample (pre-dried at 105°C to constant weight) at 375°C for 16 h (Davis, 1974).

Statistical analysis

Analysis of variance (ANOVA) was chosen to test differences between the different compartments (IW, SW and GW), the sampling sites and the hydrological condition for each parameter. In all the statistical methods, differences were considered significant at $\alpha < 0.05$. All statistical calculations were made using the MINITAB computer package (Minitab, Inc., USA), version 13 for PC.

RESULTS

Longitudinal variations in stream water chemistry

Profiles of the water quality parameters over the stretch of river studied suggest that the river is polluted by industrial activities affecting the Hammam Boughara reservoir (Figure 3). The reservoir water adds a pollution burden to the Tafna River. Pollution effects include high BOD, ammonia and chloride values increasing from station T6 to station T7.

The highest NH_4^+ concentrations were observed at station T6 during HW and LW and decreased significantly in station T7. Low NH_4^+ levels were recorded during dam water release (DWR) periods.

Nitrate concentrations increased during high and LW conditions between stations T6 to T7. However, nitrate and DO concentrations did not show significant differences between the three hydrological conditions.

BOD values were very high and exceeded 15 mg L^{-1} regardless of the hydrological period. Site T6 which directly receives release water and urban effluent had a very high BOD ranging from 20 mg L^{-1} (release period) to 72 mg L^{-1} (dry season) and showed a significant increase during LW conditions.

Chloride values were very high (up to 0.5 g L^{-1}) during all hydrological conditions in the two stations and showed a significant increase in LW.

Ground water quality on the reach scale

The highest levels of NO_3^- were observed in the GW. Nitrate concentrations varied from $13 \text{ mg L}^{-1} \text{ N}-\text{NO}_3^-$ in the upstream part of the reach (well 17) to 80 mg L^{-1} in the downstream part (well 4). Chloride in the GW showed a similar tendency (a maximum of 2472 mg L^{-1} in well 16 and a minimum of 272 mg L^{-1} in well 4). The GW was located at a mean depth of 8.6 m below the soil surface: at 15 m depth in the upper part of the reach and 2 m in the lower part.

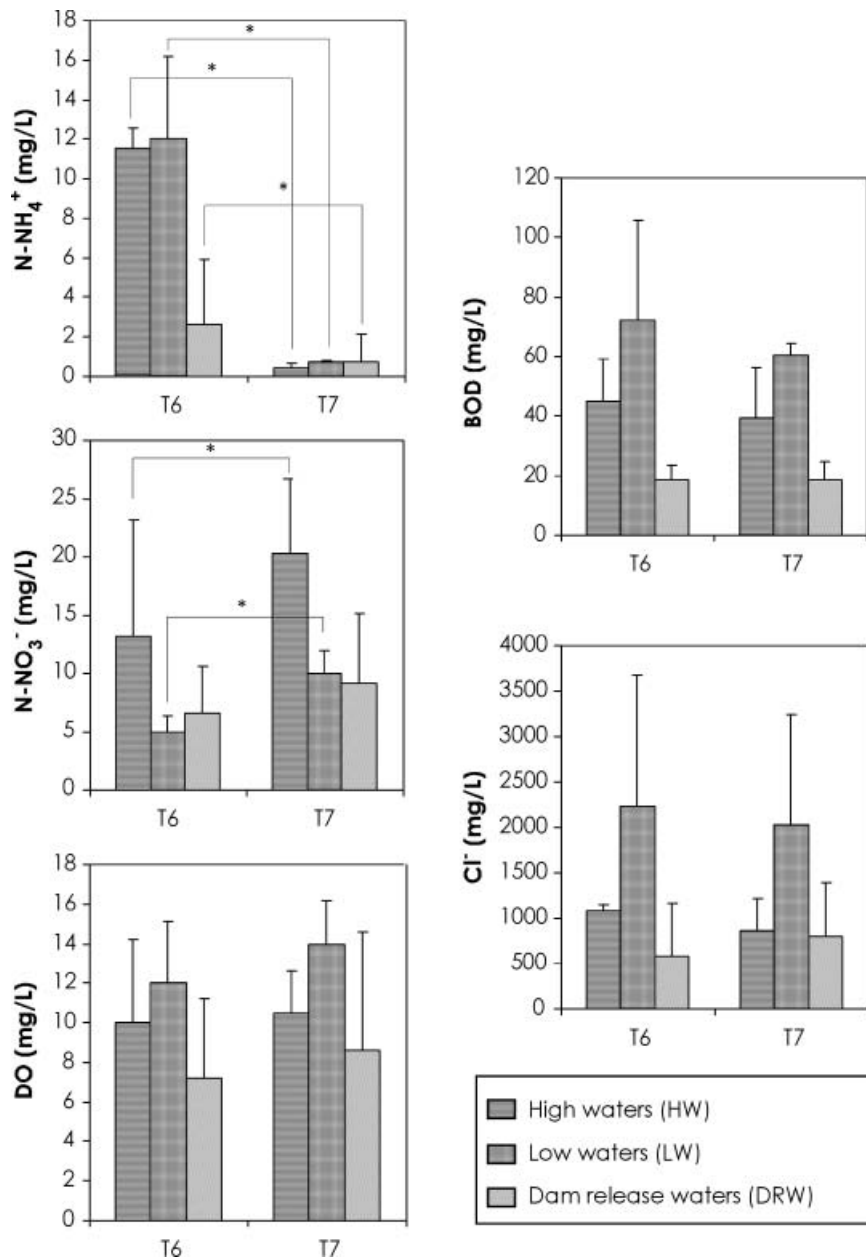


Figure 3. Spatio-temporal variation of nutrients in Tafna wadi for three hydrological periods. HW, high waters; LW, low waters; DRW, dam release waters; *, difference between sites significant at $\alpha = 0.05$

Comparison of SW, IW and GW over the study site

The assessment of pollution in SW observed at station T6 was confirmed over the whole reach in SW and IW, with high NH₄⁺, high BOD and low DO, all indicators of high organic pollution under all flow conditions.

From GW comparison, we use the data of wells W5 and W6 to characterize site A and wells W7 and W8 to characterize site C. The chemistry of IW differed significantly from that of GW, but was similar to SW, except for two parameters: NH₄⁺ and DO. NH₄⁺, NO₃⁻ and DO showed significant differences between the site A and the Site C within the IW. For SW only NH₄⁺ and DO were significantly different between sites A and C (Figure 4). Data from site B were similar to the data from site A.

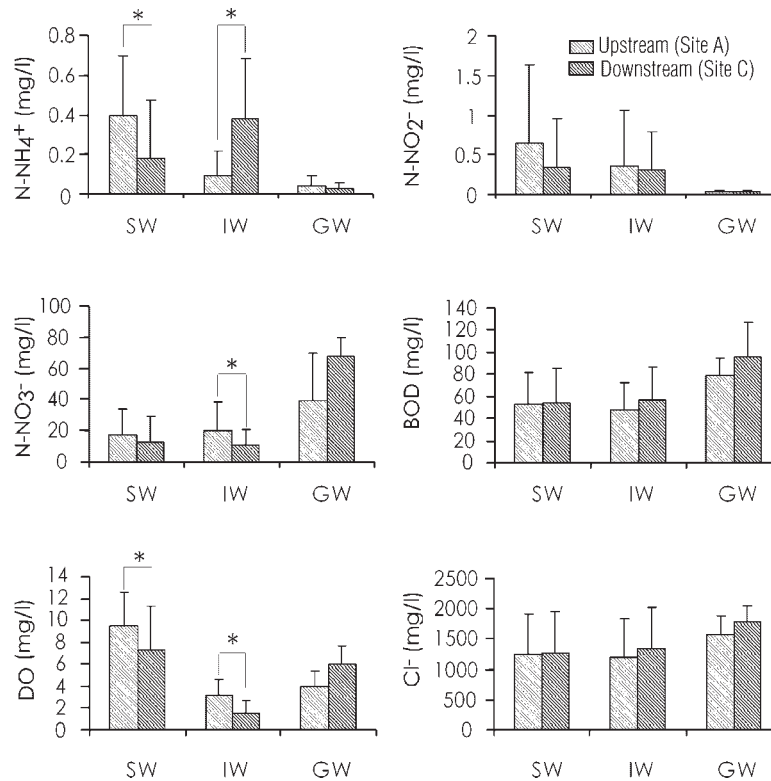


Figure 4. Chemistry of surface, hyporheic and ground water in the study site of Tafna River. Upstream–downstream comparisons. SW, surface water; IW, interstitial water; GW, ground water. Data for the hyporheic zone corresponding to the piezometers 1 and 2 for the upstream and piezometers 5 and 6 for the downstream site. Data for the ground water from wells 7 and 8 for the upstream and wells 5 and 6 for the downstream site (see Figure 2). *, difference between upstream and downstream significant to $\alpha = 0.05$

IW NH_4^+ values increased downstream, and were 40 times greater than those of GW and 3 times those of SW. NO_3^- was significantly lower in site C than in site A in IW. DO was always lower in the IW. DO decreased significantly in site C compared with site A in SW and IW. By contrast, GW was significantly higher in NO_3^- ($p < 0.05$) than SW and IW.

Chloride and BOD values were significantly higher in GW compared to those in IW and SW. Water BOD was about 50 mg L^{-1} in surface and IW and about 90 mg L^{-1} in GW.

Temporal profiles of the vertical hydraulic gradient (VHG) in all piezometers indicated downwelling, only two observations of upwelling were measured for all study periods one during HW at site B and one during water release at site C (Figure 5). VHG values for most hyporheic piezometers were negative and exceed 2 cm. Strong negative VHG was observed at site A during a discharge increase (November 2000 (DRW) and January 2001 (HW)) and at site C (January 2001 (HW)) during the high flow period. Summer release water (May 2000) had little effect on VHG in the downwelling zone of site C (P5) and produced only a slight positive VHG in piezometer 6. The spatial extent of the downwelling zone was altered by release water loads of suspended matter (SM) following the winter and spring high flow. Indeed, in May (when total flow was due to released water) downwelling was greatly reduced especially at the upstream site C (Piezometers 5 and 6). Downwelling was directly related to the particle size pattern of the stream sediment.

The granulometry showed a significant difference not only between sites (A, B and C) but also between the three hydrological conditions (Figure 6). Sediment at sites A and B was significantly rich in sand whereas sediment at site C was very rich in silt and clay during LWs. Silt and clay concentrations at site C were significantly lower during HW than during dry periods. In contrast, the granulometric composition at the two other periods (HW and DRW)

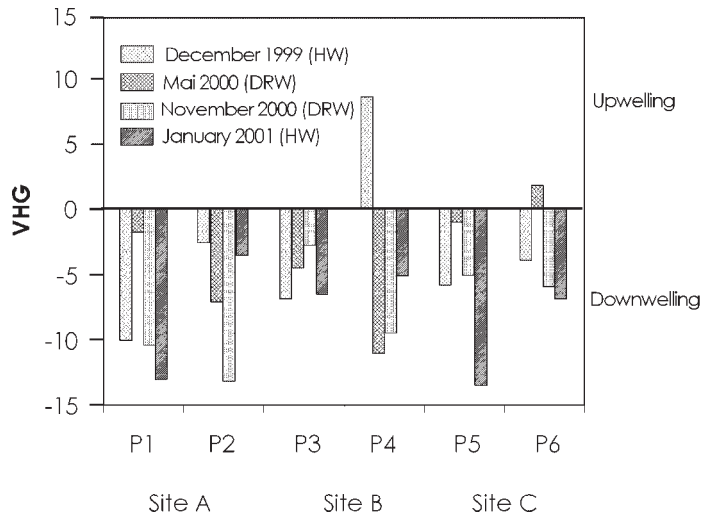


Figure 5. Seasonal and spatial variation of the vertical hydraulic gradient VHG at the study site scale for two high water periods (December 1999 and January 2001) and two Dam release water periods (Mai 2000 and November 2000). HW, high waters, DRW, dam release waters. P1–P6, piezometers

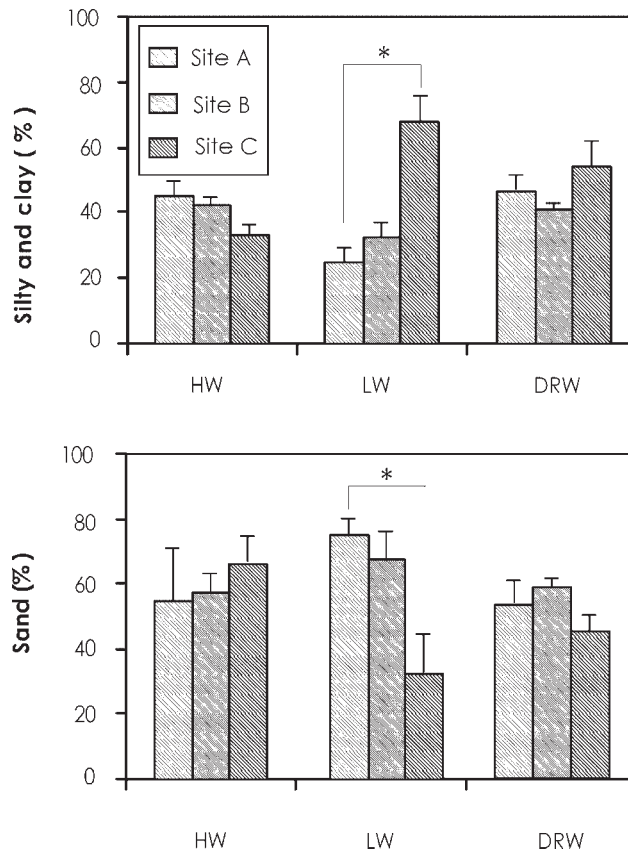


Figure 6. Granulometry characteristics of the sediments for the three sites (A, B and C) at three hydrological conditions (HW, high waters, LW, low waters, DRW, dam release waters). *, difference between sites significant to $\alpha = 0.05$

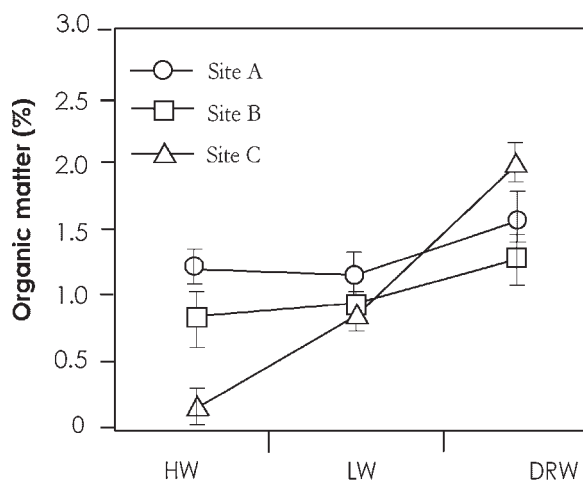


Figure 7. Mean spatio-temporal variation of organic matter in bed sediment for the three sites (A, B and C)

did not show a significant difference between the three stations. Organic matter content in the sediment was significantly higher during dam release compared to HWs and to LWs (Figure 7).

Spatial and temporal water chemistry at the reach scale

Overall, NH_4^+ increased significantly in the IW at site C compared to the site A, during LW and DWR (Figure 8).

The nitrate concentration was high during LWs in the IW compared to DRWs and HW. During water release, SW had similar concentrations over the whole studied reach but NO_3^- concentrations in IW decreased between sites A and C. The NO_3^- decrease in IW was significantly and positively correlated with DO decrease. In the same compartment, NH_4^+ was negatively correlated with DO (Figure 8). During the daily cycle, NO_3^- concentrations in IW decreased 50% during the day compared to night values (Figure 9).

DO was significantly lower at site C than at site A, in IW during the water releases and LWs and in SW during water releases. Hypoxic conditions (DO in water less than 0.5 mg L^{-1}) occurred during the release and drying periods in six of the eight C sites IW samples. No significant difference was found between seasons in both stations for DO concentration in the IW. A small tributary in station A upstream of station C may have supplied this station with oxygenated water during high flow.

Nitrate concentrations were significantly lower at site C compared to site A, in IW during water releases and LWs.

The chloride concentration increased during low flow in the IW compared to dam release and high flow. The chloride concentrations did not show significant spatial differences between site A compared to the site C and SW compared to IW.

DISCUSSION

Distinct regions of the HZ are affected by river pollution indicating variable exchange with SW (Mestrov and Lattinger-Penko, 1977). The HZ of site A, characterized by higher DO and lower NH_4^+ values than site C, led us to assume that nitrification was the dominant step in the nitrogen cycle (Valett *et al.*, 1990; Grimm *et al.*, 1991; Jones *et al.*, 1995). The highest NO_3^- values within the HZ occurred during summer and slightly decreased during natural HW.

On a site scale, we observed strong downwelling of SW, which was more marked during the HW period. Downwelling in conjunction with the presence of DO in the HZ indicates significant exchange between the stream and the HZ. High DO and similar chloride values between surface and hyporheic waters at site A further indicate

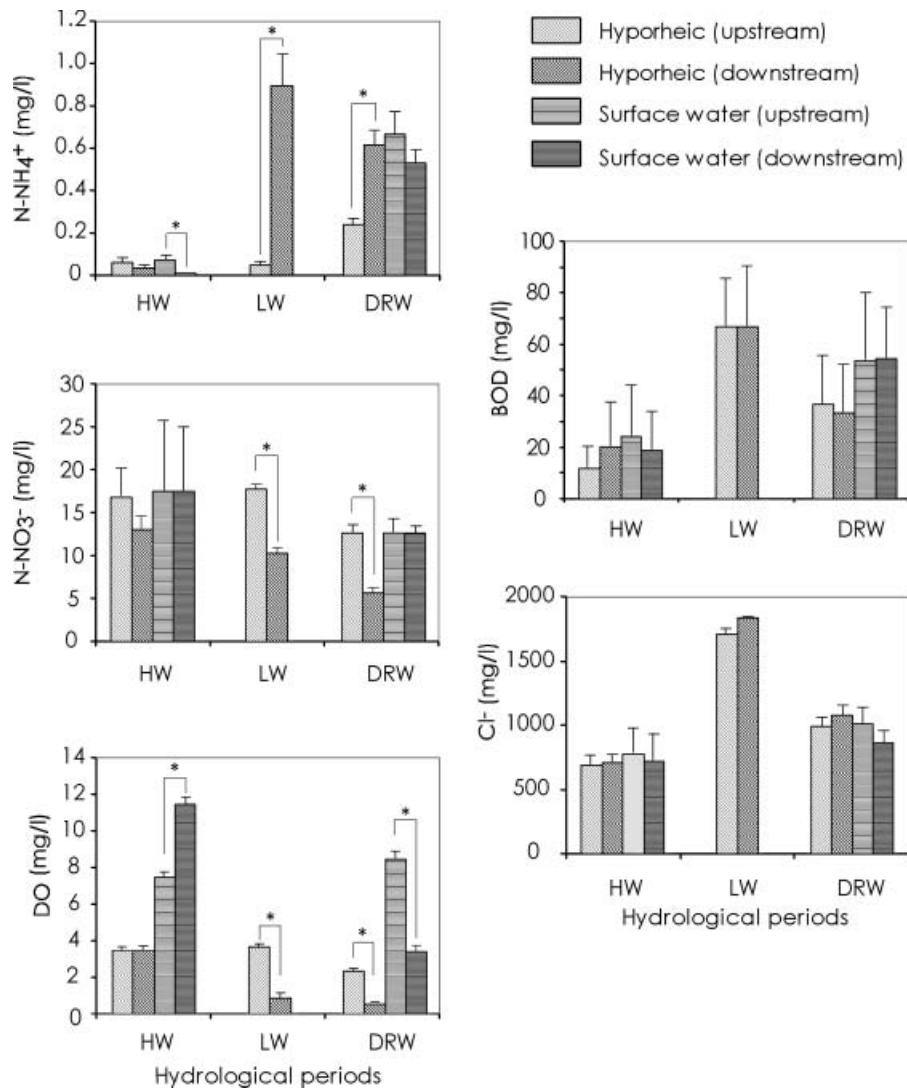


Figure 8. Spatio-temporal variations (upstream–downstream) of nutrients in hyporheic and surface water of the study site for three hydrological conditions. HW, high waters, LW, low waters, DRW, dam release waters

that the upstream hyporheic site is dominated by SW at all seasons. In contrast, low DO at similar chloride concentrations at site C especially during LW and water release resulted more from biological metabolism than from hydrological exchanges.

During LWs, the decrease of DO observed at site C, characterized by downwelling exchange and by a finer sediment size, supports the hypothesis that a long residence time within the sediment between site A and site C enhanced low DO in the IW (Brunke and Gonser, 1997). Indeed, hyporheic metabolic activity can explain the fall in DO saturation from 100% at the surface to 10–30% on average in the IW. During summer the Tafna wadi becomes dry, the HZ is disconnected from SW and the underflow consists almost entirely of GW.

During HWs at station C, compared to station A, DO was sufficient to allow nitrification at all places (low NH₄⁺, low BOD, low NO₂⁻ and high NO₃⁻). We concluded that ‘self-purifying’ mineralization processes are occurring.

During release and LW, hyporheic DO and BOD concentrations were lowered. Simultaneously the HZ was enriched with NH₄⁺ and degradable organic matter from SW, due to downwelling of polluted water released from

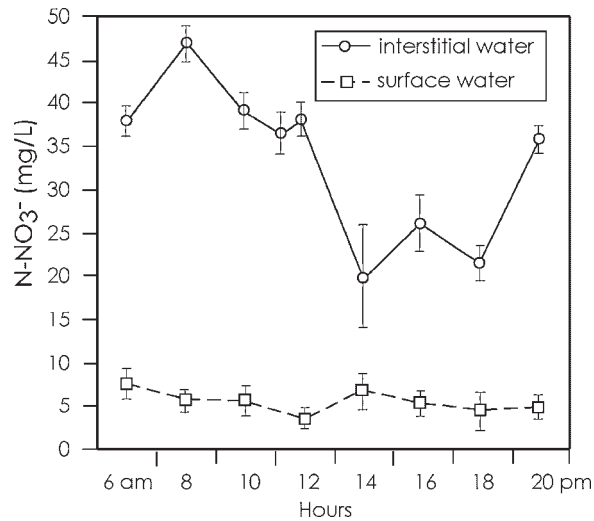


Figure 9. Diel gradient of nitrate concentrations

the dam. Such a process can result in DO depletion and anaerobic hyporheic conditions (Mestrov and Lattinger-Penko, 1981; Sprent, 1987). Contrary to station C, station A may be less influenced by water releases because it was richer in sand and more oxygenated because of SW richer in DO. This was confirmed by a decrease in NH_4^+ and an increase in NO_3^- .

A significant decrease in NO_3^- occurred in the IW at station C, where grain size is small, probably due to denitrification. Denitrification is likely considering the less porous bed sediment and the anoxic conditions (Duff and Triska, 1990; Hendricks and White, 1991; Triska *et al.*, 1993). This has been shown in other small streams (Triska *et al.*, 1989; Dahm *et al.*, 1991).

The SW NO_3^- results from interactions between surface and HZs. However, water exchange between surface and subsurface is not uniform at all locations. There are high exchange zones, next to places with low exchanges. This patch model is commonly used for arid-land ecosystems as described by Dent *et al.* (2001).

In LW periods, denitrification may be attributed to the great proportion of fine sediment (65–70% sediment <0.02 mm) which would limit lateral penetration of dissolved constituents notably DO. Pinay *et al.* (1995) determined that the riparian zone, containing fine sediment with HW holding capacity, had higher mineralization and denitrification rates than sandy zones. These published results and those of Chestnut and McDowell (2000) support our conclusion that during HW, fine sediment areas increased NO_3^- loss by denitrification, favoured accumulation of NH_4^+ through increased mineralization under reducing conditions and inhibited nitrification.

In contrast, the HZ in site A was considered as a nitrogen source for the SW of site C. This would explain nitrate output in the upwelling zone between sites A and C. Despite algal assimilation, nitrate in SW downstream was always higher. This observation is consistent with other studies suggesting that nutrient rich hyporheic water can be an important nutrient source for channel flora in streams and rivers (Fortner and White, 1988; Stanford and Ward, 1988).

On the regional scale, NO_3^- concentrations in IW showed diel, seasonal and upstream–downstream gradients. They decreased 50% during the day compared to night values (Figure 9) which can be attributed to the denitrification, activated by higher daytime temperatures (Grischek *et al.*, 1998; Garcia-Ruiz *et al.*, 1999). Nitrate was always higher downstream especially during low flow, indicating a nitrate source to the downstream part of the stream. In the absence of tributary influences, mechanisms for a downstream increase in SW NO_3^- levels include: (i) oxidation of organic matter; (ii) NO_3^- supply from GW upwelling (two positive VHGs were measured) and (iii) nitrification of hyporheic NH_4^+ taking place at the surface hyporheic interface (Boissier *et al.*, 1996). Indeed, higher NH_4^+ than NO_3^- in GW, and higher NO_3^- than NH_4^+ in SW indicated that DIN was transformed during its transfer through the HZ. In addition to NH_4^+ oxidation during hyporheic transport, nitrification in GW and/or agricultural contamination are additional explanations for rise in NO_3^- .

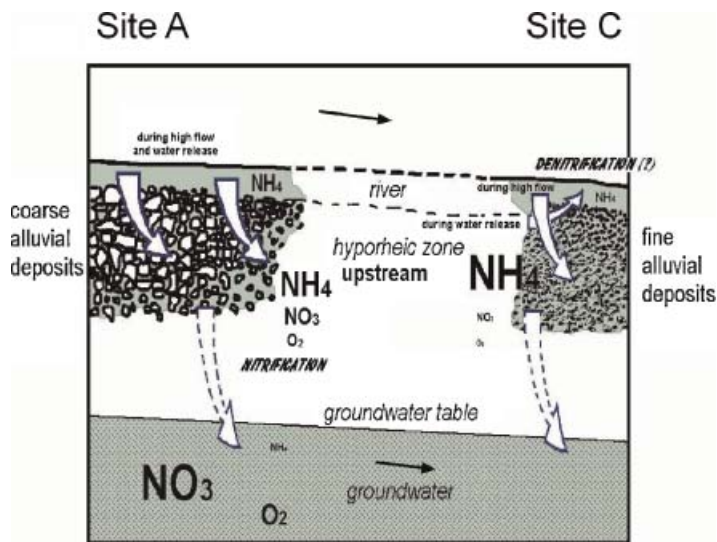


Figure 10. Conceptual model proposed for Tafna wadi surface water-ground water exchanges. This figure is available in colour online at www.interscience.wiley.com/journal/tra

BOD in GW indicates hydrological exchange (seeping) from the watershed upstream of the dam demonstrating that the GW is influenced more by SW during high flow. By contrast, during drying, the GW tends to create a significant organic matter source for the stream system.

Comparing hyporheic, SW and GW chemistry, we found higher NO_3^- concentration in GW suggesting that ammonium supplied to the HZ is oxidized into nitrates during the transfer to GW, especially during HW and dam release periods (Figure 10). The proposed mode of function for the Tafna wadi is that SW has higher DO and low NH_4^+ levels whereas low DO and high NH_4^+ in HZ. Atmospheric aeration of SW in conjunction with emerging hyporheic water contributed to the oxidation of NH_4^+ to NO_3^- in the Tafna wadi. Thus, nitrification in the HZ explains the nitrate output at the downstream site; this observation is similar to that of Triska *et al.* (1990, 1993).

In the Tafna wadi where the channel can be dry on the surface, the hyporheic process probably has a greater impact on stream chemistry both on a large scale (40 km) (Malard *et al.*, 2002) and on a small scale (200 m). It may thus be viewed as containing a longitudinal series of HZs alternating with upwelling zones having a cumulative effect on SW quality (Hendricks and White, 1991).

This study is of interest because it documents a large ‘natural experiment’ driven by the effect of periodic water release from a reservoir with serious water quality problems on the water quality dynamics (particularly nitrogen) of the subsurface and SWs downstream.

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