



The effect of weirs on nutrient concentrations



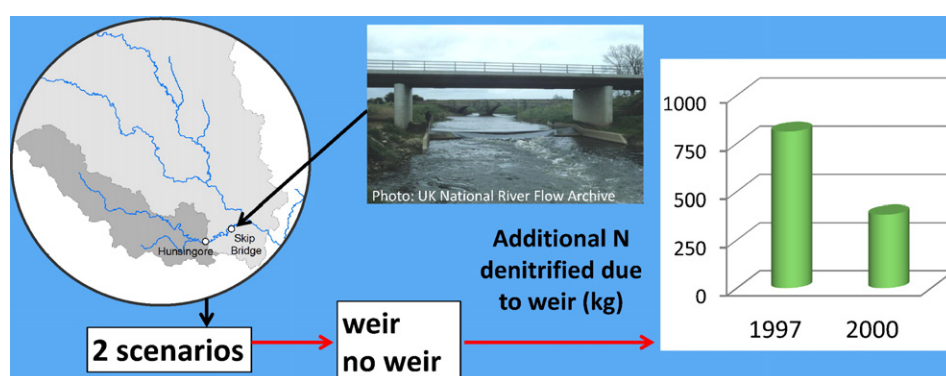
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HIGHLIGHTS

- A model of channel hydraulics and denitrification was set up for 15.8 km of river.
- Model performance pre- and post-removal of a weir was assessed.
- Fluxes of denitrification were estimated based on two years of daily simulations.
- It is estimated that 1.8–2.6% less nitrate is being retained annually since removal.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 20 August 2015
 Received in revised form 11 October 2015
 Accepted 11 October 2015
 Available online 4 November 2015

Editor: D. Barcelo

Keywords:

Weir removal
 Nutrient concentration
 Denitrification
 Surface water
 Modelling
 UK

ABSTRACT

The removal of a weir in 1999 from the River Nidd in Yorkshire, UK, was assessed in terms of its impact on in-stream nitrate removal along a 15.8 km long stretch of river. Models of channel hydraulics and denitrification quantified the impact on an annual basis, using, as inputs, river flow, water temperature, water quality data and cross-section geometry collected both before and after the weir was removed. To remove the confounding influences of year-specific conditions, two counterfactual simulations were set up whereby the pre-removal configuration was driven by data from the post-removal period (and vice versa). Results revealed the removal of the weir to have reduced the annual fraction of the upstream nitrate load being retained along the stretch by 2.6% (i.e. 812 kg) and 1.8% (382 kg) for the years 1997 and 2000 respectively. Differences resulting from the presence or absence of the weir were most marked during low flow summer conditions.

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1. Introduction

In over 65% of river basin districts in the EU the removal of structures such as dams, weirs, locks/slucices and bank enforcement is proposed as a hydromorphological measure to meet Water Framework Directive

(WFD) requirements (Kristensen, 2013). No other hydromorphological measure is proposed to such a widespread degree. Whilst the benefits described below that are accrued when weirs are removed are widely acknowledged, what is not known is the impact on many aspects of water quality. There are some studies that quantify impacts of weir removal but only in terms of hypothetical scenarios using models, and often as part of scenarios including other restoration practices (e.g. the impact of river restoration measures on the nitrate nitrogen concentration was

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analysed by Wagenschein and Rode, 2008). The self-purification of water by biotic communities with the potential to remove excess nutrients in river channels is a potentially important ecosystem service (Maes et al., 2013). The benefit of improved water quality due to reduced nitrogen concentration can be equated to the costs avoided at hypothetical downstream water treatment plants (La Notte et al., 2012) or by willingness to pay for improved water quality by every household in the region. These two approaches to economic valuation of this ecosystem service show the use of the replacement costs and a stated preference methodology (Maes et al., 2013; De Groot et al., 2012). Following the approach of the replacement costs for denitrification and load reduction the monetary value of this ecosystem service equals 3706 € ton⁻¹ (Gren, 1995; La Notte et al., 2012). For waste treatment service, De Groot et al. (2012) estimate the value of this ecosystem service for fresh water (rivers/lakes) biome to be 187 International \$/ha of fresh water/year (for 2007 price levels).

The removal or installation of weirs has a potential impact on ecosystem services (Bryan et al., 2013): notably provisioning services (food by easier fish migration), regulating services (water purification, hazard and water regulation in terms of flood control), supporting services (nutrient cycling) and cultural services (recreation: easier navigation on the river and fish habitat). Installation of a weir disrupts river longitudinal connectivity which affects fish distribution and migration, leading to population decreases and genetic deterioration. The fact that specific fish species cannot reach their optimal spawning and nursery habitat can have severe consequences for their survival. According to data shown by Martyn (2013), the estimated density of fish species caught upstream of a weir in a river in SE England Ouse, East Sussex) increased from 6 in 2009 (weir present) to 14 in 2011 after the weir was removed. Moreover, after weir removal the number of species present upstream dramatically increased illustrating the beneficial impact of weir removal on provisioning services. In terms of biological recovery in a more holistic sense, weir removal is clearly beneficial, although these effects may take years to be realized due to the gradual process of remobilization of accumulated fine sediment (Feld et al., 2011). Flow regulation downstream will benefit from control provided by sluice management. However, the removal of weirs may be beneficial upstream by reducing water depth and providing greater storage capacity at times of flood (POST, 2011). Quantifying the influence weirs have on the other services is intractable without detailed and site-specific studies. In this respect, specific emphasis is warranted on evaluating river restoration and its impact on river flows and water quality (Wagenschein and Rode, 2008), notably temperature, nutrients, dissolved oxygen, sediment, and algae. Weirs are useful to help gauge river flows and removing them has an adverse effect on quality of monitoring networks. Weirs also provide aeration, the benefits of which can last over many kilometres downstream and are important in very low gradient systems. Estimates using the QUESTOR model (Hutchins et al., 2010) suggested that the Skip Bridge weir on the River Nidd, the subject of the present study, served to elevate the 1997 daily mean dissolved oxygen content 1.3 km downstream by 0.46 mg L⁻¹ on average.

The objective of the present study was to evaluate the impact of a weir on the nitrate retention occurring in the channel of a lowland river (the River Nidd) in Yorkshire North East England, UK. As a case study, this provided a unique opportunity because of existing data and measurements before and after a weir was removed. Two National River Flow Archive (NRFA) gauging stations bound a 15.8 km stretch from which the weir was removed, the downstream station being downstream of the site of the former weir (at Skip Bridge). Furthermore the stretch is only influenced to a minor degree (less than 5% flow in the river) by abstractions and inputs from tributaries and sewage effluents. To achieve the objective, simulation using mathematical models of the hydraulics and water quality was undertaken for two calendar years, one before and one after 1999. To quantify denitrification it is very important to make detailed and accurate calculations at short timestep of velocity and depth (something not readily done when making

aggregated calculations of denitrification in river) (Boyer et al., 2006). Therefore, in the work described here hydraulic model HEC-RAS (Brunner, 2010; Brunner and CEIWR-HEC, 2010; Warner et al., 2010) is used to represent river hydromorphology (hydraulics, banks, river bed and basic vegetation characteristics) which when combined with river flow and quality models for river networks can be used to estimate water quality. Specifically here, the impact of presence or absence of a weir on the rate of river channel denitrification is estimated. These estimates are set in context of the assumptions inherent in the chosen modelling approach. From this we illustrate how quantification can be made of the impact weirs may have on the service of water purification (nutrient nitrogen removal) along a river stretch.

2. Method and case study area

2.1. Case study area

The 15.8 km river stretch of the River Nidd (a tributary of the Ouse) in Yorkshire UK between Hunsingore (gauging station ID¹ 27001, 18 m AMSL²) and Skip Bridge (gauging station ID 27062, 8 m AMSL) was chosen for the case study (Fig. 1). The weir was located until 1999 at the downstream end of the river stretch (Skip Bridge weir). The stretch of the River Nidd has three influences:

1. Hunsingore Sewage Treatment Works (STW)
2. Fleet Beck Tributary which includes the Tockwith STW
3. Kirk Hammerton Water Purification Centre (WPC)

The catchment areas drained at the upstream and downstream ends of this stretch are 484.3 and 516.0 km² respectively. Mean annual rainfall of the catchment is 972 mm. Flows are gauged at each end of the stretch and long term data reveal mean flow to increase from 7.95 to 8.29 m³ s⁻¹ along the stretch. The land cover composition in the catchment draining to Hunsingore is: grassland (50%), arable (19%), heathland (14%), woodland (9%) and urban (3%). The upland area (maximum 703 m AMSL) is characterised by moorland and numerous water supply reservoirs significantly affect runoff in this part of the catchment.

2.2. Calculation of hydraulic variables

Applications of the HEC-RAS model (Hydrologic Engineering Centre's (HEC); River Analysis System (RAS) – a hydraulic model developed by the US Army Corps of Engineers, Brunner, 2010; Brunner and CEIWR-HEC, 2010; Warner et al., 2010) were used to explore the hydraulic impact along a river stretch of removing or introducing a weir. HEC-RAS was used to represent the geomorphology of the stretch on the river Nidd and to perform river hydraulics calculations. Longitudinal variation between 48 measured, individual cross sections was modelled. Linear interpolation between the bounding, measured cross sections was carried out. This was based on a string model which consisted of cords that connected the coordinates of the upstream and downstream measured cross sections, and which gave a continuous interpolated river bed surface. From this surface, cross-section dimensions were taken at regular intervals and used in hydraulic calculations. The outputs of the model, velocity and hydraulic depth, were then transferred into a denitrification model used for simulating the impact of the weir on nitrogen retention (see below for model description). Two model run types were performed: with weir and without (see Table 1 for details).

Given the spatial extent of the study, the type of the study and the data available, steady flow was assumed. Therefore, the input data used to run the simulations specified in the Table 1 were: geometric

¹ <http://www.ceh.ac.uk/data/nrfa/data/search.html>; http://www.ceh.ac.uk/products/publications/documents/hydrometricregister_final_withcovers.pdf.

² Above mean sea level.

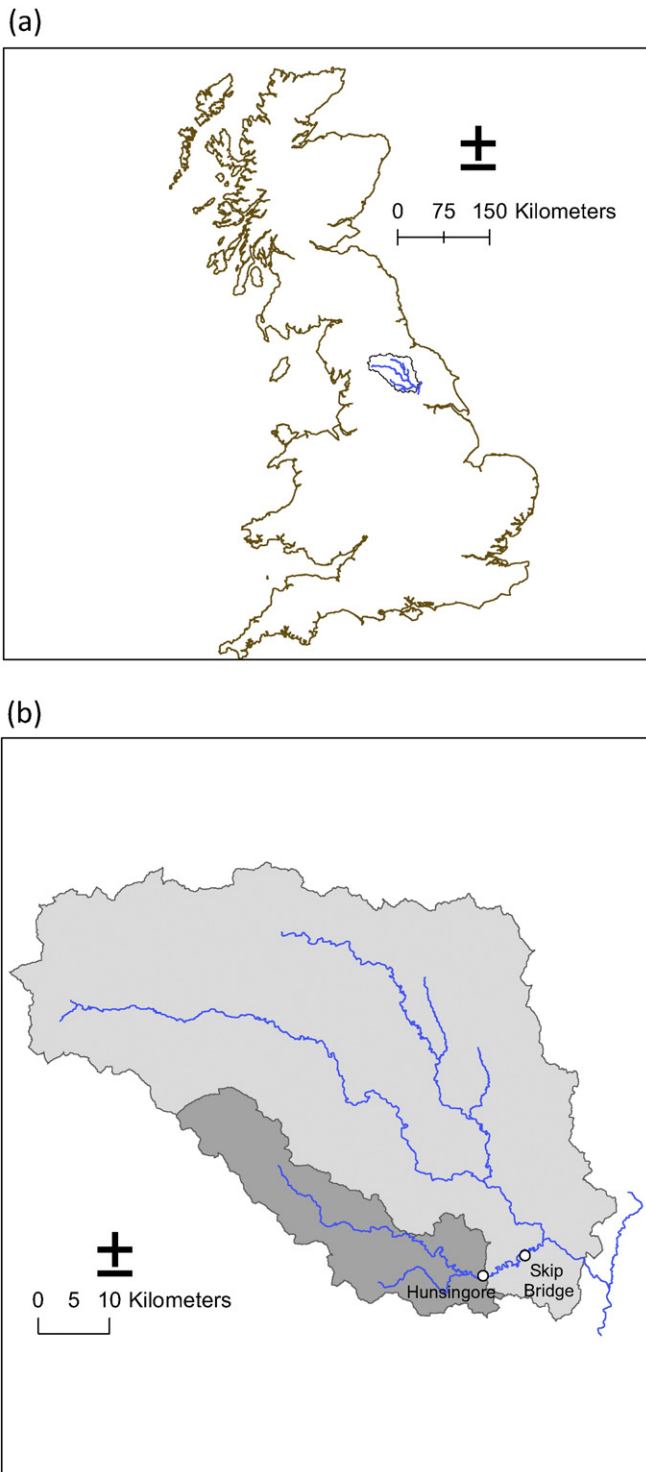


Fig. 1. Maps showing (a) location of Yorkshire Ouse catchment in which the River Nidd lies, (b) location of upstream (Hunsingore) and downstream (Skip Bridge) boundaries of the stretch of the River Nidd, and the 484 km² catchment upstream at Hunsingore.

data and steady flow data. The geometric data consist of connectivity information for the river system, cross-section data and data on hydraulic structures i.e. weirs, bridges etc. The geometric data is developed by first drawing in the river system. The cross-section data are entered afterwards and require information on the cross-section coordinates, downstream reach lengths, Manning's *n* values, main channel bank stations and contraction/expansion coefficients (since steady flow does not use the momentum equation for backwater computations,

those coefficients are used to approximate the contraction and expansion losses for every cross section). The hydraulic structure data (weir in our study) required information on a weir profile including station and elevation coordinates, width, weir coefficient, weir crest shape etc. After the geometric data are entered it is necessary to enter steady flow data which consist of the number of profiles (refers to the number of calculations to be performed i.e. the number of flows) that will be computed, the flow data and reach boundary conditions. At least one flow value must be provided for each reach but flow data can be changed in any cross section within a reach using the option "flow change location". In our study, the "change flow location" was defined as being approximately at a mid-point between the 2 gauging stations (Hunsingore and Skip Bridge). Once all of the geometric and flow data are entered the hydraulic calculations could be performed. The HEC-RAS software permits one-dimensional steady river flow hydraulics calculations (Brunner, 2010; Brunner and CEIWR-HEC, 2010; Warner et al., 2010).

Daily river flow data were provided by the English Environment Agency (EA) (for details see Booker and Dunbar, 2008). River geometry (slopes, elevations, dimensions of the 48 cross sections, and distances between cross sections) and the Manning's roughness coefficients of the river bed and banks were derived from the measurements provided by the EA. The design of the weir was provided by the NRFA (UK). It was assumed that all flow remained within the river banks. In the case study we conducted steady flow simulations for calculating water surface profiles for steady gradually varied flow (the longitudinal and transversal variation) which is characterised by minor changes in water depth and velocity from cross section to cross section.

2.3. Denitrification calculation

Data spanning a wide range of river environments worldwide has revealed the fraction of nitrate denitrified by micro-bacterial reactions in bed sediments to be closely related to the hydraulic load (Seitzinger et al., 2002). Hydraulic load is represented in the denitrification rate (*k*, days⁻¹) calculated on a daily basis through 1997 and 2000 using the equation applied by Whitehead and Williams (1982):

$$k = \frac{a}{h} \cdot 10^{0.0293 \cdot \theta} \quad (1)$$

where: *a* = 0.05 (a constant based on a range of UK river basin water quality studies), *h* = depth (m), *θ* = water temperature (°C). Temperatures were taken from Environment Agency's Water Information Management System (WIMS) of periodic (fortnightly or weekly) monitoring, and daily values interpolated from these.

When reformatted as a rate expression, the travel time (in days) is used to derive the nitrate concentration at the downstream end of the reach (*c_t*) from the concentration input at the top (*c₀*):

$$c_t = c_0 \cdot e^{-kt} \quad (2)$$

Where: travel time (*t*) is derived from velocity as estimated by HEC-RAS and the daily series of nitrate concentrations (mg N L⁻¹) at Hunsingore (*c₀*) are taken from an existing application of the QUESTOR water quality model (Hutchins et al., 2010).

2.4. Model runs performed

In making an assessment of the effect of a weir on the nitrate retention in the river channel, the impact of ambient hydro-climatological conditions is likely to be large and needs to be controlled. Therefore to remove the effect of confounding factors brought about by year-specific conditions five model runs were undertaken (Table 1).

Table 1
Performed model runs.

Run	Dates of inputs (daily flows and nitrate concentrations at the upstream boundary)	Weir present	Data for validation available?
1	1997	Yes	Yes
2	2000	No	Yes
3	1997	No	No. Counterfactual
4	2000	Yes	No. Counterfactual
5	21st June 2013	No	Yes

Table 2
Performance of HEC-RAS at simulating velocity, depth, and cross-sectional area at the downstream (Skip Bridge) end of the stretch for 9 days of monitoring: A. when the weir was still in place, B. after the weir was removed.

A.								
Date	Measurements		Model run, measured flow		% relative error		Absolute error	
	Velocity (m s ⁻¹)	Area (m ²)	Velocity (m s ⁻¹)	Area (m ²)	Velocity (%)	Area (%)	Velocity	Area
15/09/1995	0.39	3.883	0.32	4.28	17.95	−10.22	0.07	0.397
15/09/1995	0.389	3.903	0.32	4.28	17.74	−9.66	0.069	0.377
18/09/1995	0.369	3.684	0.32	4.28	13.28	−16.18	0.049	0.596
10/12/1997	0.785	42.556	0.67	49.57	14.65	−16.48	0.115	7.014
09/01/1998	0.763	95.768	0.81	90.02	−6.16	6.00	0.047	5.748
15/01/1998	0.548	28.192	0.6	25.54	−9.49	9.41	0.052	2.652
16/06/1998	0.493	22.783	0.57	19.75	−15.62	13.31	0.077	3.033
03/03/1999	0.826	51.225	0.71	59.99	14.04	−17.11	0.116	8.765

B.								
Date	Measurements		Model run, measured flow		% relative error		Absolute error	
	Velocity (m s ⁻¹)	Depth (m)	Velocity (m s ⁻¹)	Depth (m)	Velocity (%)	Depth (%)	Velocity	Depth
10/08/2000	0.25	0.71	0.24	0.70	4.00	1.41	0.01	0.01
20/03/2000	0.32	0.86	0.32	0.87	0.00	−1.16	0.00	0.01

3. Validation

The models were validated in terms of hydraulic parameters using the English Environment Agency Acoustic Doppler Current Profiler (EA ADCP) data collected as spot measurements before and after the weir removal, and nitrate removal using nitrate measurements along the reach.

3.1. Validating HEC-RAS model

The performance of HEC-RAS was assessed for specific days during 1995–2000 against data collected by the EA at Skip Bridge (Table 2). EA ADCP data at Skip Bridge were used to test modelled depth and velocity (variables required as input to the water quality model). In addition cross sections were measured at the time of ADCP, permitting flow area to be calculated and compared with the HEC-RAS model outputs. The results of validation can be found in Table 2.

The relative error in flow area was the largest for the date 03/03/1999, and in velocity for 15/09/1995. The mean absolute error (MAE) is a quantity used to measure how close predictions are to measured values. The MAE for the velocity was equal to 0.06 (11.8% of the average velocity), and for flow area 3.57 (11.34% of the average flow area). Analysis of measurements and predictions showed that model was practically unbiased.

3.2. Validating model against nitrate concentrations

In addition, the model was set up for 21st June 2013 when nitrate data were collected along the stretch covered by the modelling study (Table 1, Run 5). Information about change in nitrate concentrations along the stretch was not available. Therefore, data were collected during a low flow period in summer 2013 (21st June). It was necessary to make an estimate of the nitrate load entering the river along the

stretch. The values for flow and nitrate-N concentration in the influences of the river Nidd were set as follows:

Flows in the influences were based on people equivalents served by the works. For Fleet Beck, the catchment area was estimated as being approximately 15 km², the Q70 value from a nearby small river in the hydrometric register (0.06 m³ s⁻¹, at Cundall Beck NGR SE419724) was taken and scaled by catchment area. Q70 was chosen to represent the summer conditions when the flow is lower than average. Downstream of sewage effluent, ammonium is nitrified to nitrate (Chapra, 1997). It was assumed that all ammonium arising from effluent was nitrified between the STW and the main River Nidd. For Fleet Beck a mean summer value (5 mg N L⁻¹) for rivers in the nearby locality appearing in the EA WIMS dataset was used. For Hunsingore STW, no data were available and a concentration of 15 mg N L⁻¹ assumed. This value was based on an assumption of effluent concentration from national average data (EA WIMS) on water quality of effluents from small STWs. Therefore, effluent concentration of 10 mg NH₄-N/L and 5 mg NO₃-N/L which results in 15 mg NO₃-N/L entering the River Nidd following nitrification was assumed.

4. Results

In terms of hydraulic parameters the relative errors in velocity and flow area are all within 20%, and in the case of the situation in 2000

Table 3
Flow and nitrate-N concentrations of the small tributaries, and point sources joining the River Nidd along the stretch.

	Flow (m ³ s ⁻¹)	NO ₃ -N (mg L ⁻¹)	HEC-RAS Reach ID
Hunsingore STW	0.002	15	22243
Fleet Beck	0.05	5	15474
Tockwith STW	0.02	11.79	15474
Kirk Hammerton WPC	0.01	20.4	10676.2

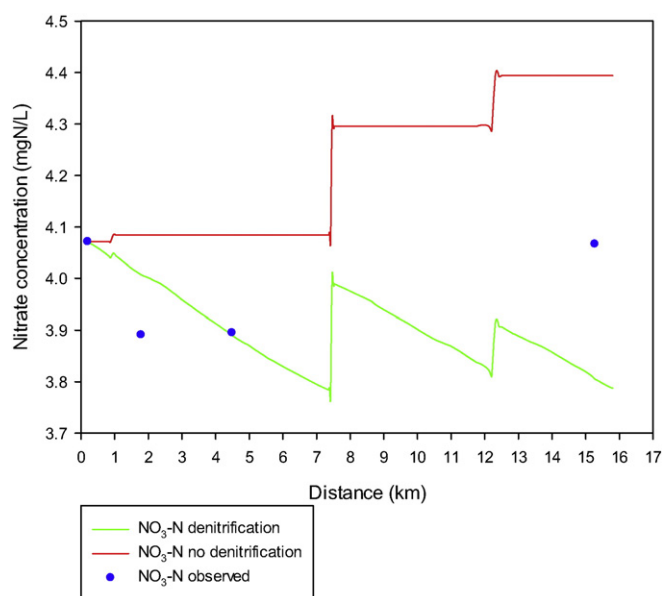


Fig. 2. Observed and modelled nitrate concentrations on the 21st of June 2013.

postdating weir removal, much smaller than this (Table 2). Validation of the nitrate concentrations is illustrated for 21st June 2013 (Fig. 2).

In the example without denitrification the concentrations between influences are unchanging as it is assumed other processes affecting NO_3 are in balance with each other.

The sharp jumps are because in this simplified model representation of the system we assume that water mix instantaneously. These occur where STW and tributaries join.

When running the models for 1997 (Run 1: weir present) and 2000 (Run 2: weir absent) results suggest at first glance the weir to be having a large beneficial effect, enhancing the removal of nitrate by denitrification (Table 4). It is apparent that denitrification is markedly more effective in percentage terms in the summer when conditions are warmer and flows lower (in both 1997 and 2000 respectively: Fig. 3A and B). The absolute flux of nitrate-N from denitrification is less dominated by summer conditions as the input loads are higher in autumn through to spring, as is typical in rural rivers dominated by diffuse sources of nitrate rather than sewage inputs. However, conditions in 1997 and 2000 were contrasting. When rerunning the model to remove the confounding influence of year-specific conditions (Runs 3 and 4) it became apparent that the impact of the weir is less marked although apparently still beneficial (Fig. 3C). Clearly the variability in weather conditions in specific years has a large influence on the amount of denitrification occurring along a stretch of river.

The variation in simulated velocity, hydraulic depth and nitrate concentration is illustrated for two individual days at low flow ($2.854 \text{ m}^3 \text{ s}^{-1}$ and $2.849 \text{ m}^3 \text{ s}^{-1}$: Fig. 4A and B, respectively). It can be seen that the profiles of hydraulic depth and velocity are very similar until approximately 13 km along the stretch at which point the influence of the weir (a further 1.3 km downstream) becomes noticeable. Downstream of the weir, the patterns again converge within 0.5 km. The profiles of nitrate concentrations are notably different throughout, a feature which will be discussed later.

Table 4

The amount of denitrification occurring along the stretch of river.

	1997: weir present (Run 1)	1997: weir absent (Run 3)	2000: weir present (Run 4)	2000: weir absent (Run 2)
kg N denitrified	31,752	30,940	22,045	21,663
Mean of daily % of N denitrified	9.52	9.22	5.93	5.86
% of total annual N load in river denitrified	5.72	5.58	3.02	2.97

5. Discussion

5.1. What is the effect of removing a weir on denitrification?

Under 1997 conditions, removal of nitrate by denitrification would have been 812 kg N less if the weir had already been removed. In 2000 if the weir had still been present, an extra 382 kg N would have been denitrified. The biggest benefits of a weir are seen at low flows in summer (Fig. 3C) but can be considerable at low flows during other times. At most times, the presence of a weir is beneficial and only during periods of elevated flow during 1997 was this not the case.

The land in the vicinity draining to this stretch of the River Nidd is predominantly agricultural. Results from the NALTRACES model (Hutchins, 2012) suggest approximately 42 kg N ha^{-1} was leached from approximately 24 km^2 of this land in 2000. The detrimental effect of weir absence in 2000 roughly equates to the nitrate-N leached from 9 ha of this land. Projecting back to 1997, the beneficial effect of the weir at that time could have equated to leaching from 19 ha of land.

In terms of denitrification it is clear that the impacts of a weir may be substantial. What is not clear is how the river downstream from the weir will deal with the increased flux of N following weir removal. The capacity of the channel downstream to process more N is crucial. The Nitrate Vulnerable Zones (NVZ) action programme has resulted in a benefit of reduced nitrate leaching loads in protected areas of 5% (Lord et al., 2009). To offset the shortfall brought about by weir removal (in a year such as 1997 having conditions where impacts are largest) over 3 km^2 of land would need to be designated as a protected area.

In terms of considering whether or not weirs and eutrophication work in synergy, it is clear they are antagonistic in this context, and that the removal of a weir could have an indirect effect of increasing eutrophication impact by exporting N downstream. There is therefore a choice for managers: do they retain weirs, and accept the local ecological impact and impact to migration, or do they remove weirs and accept that will enhance downstream nutrient flux. A key consideration in future studies is therefore to consider the cumulative impact of weir removal and to consider the river lengths effected by enhanced N flux downstream of removed weirs. It is likely that the impact will be related to the retention time of the rivers which in turn is likely to be related to the river hydromorphological properties.

5.2. Why is it important to remove confounding factors to avoid misleading conclusions?

We emphasize that it is important to remove confounding factors that are introduced via weather conditions. It is too easy to draw misleading conclusions by for example comparing model outputs between a dry year and a wet year (as illustrated by Table 4). As 2000 was in general a wetter and colder year than 1997 (as shown by comparing Fig. 3A and B) total denitrification was simulated to be approximately 50% lower. Also when comparing individual days (April 97 and August 2000 – see Fig. 4A and B which were specifically selected as being at low flow and in relatively warm periods) the simulated change in nitrate concentration is less in April 97 ($0.012 \text{ mg L}^{-1} \text{ km}^{-1}$) than in August 2000 ($0.045 \text{ mg L}^{-1} \text{ km}^{-1}$) despite our analysis revealing that a weir is beneficial. This is because the water temperature in August 2000 was considerably higher ($15.8 \text{ }^\circ\text{C}$) than in April 1997 ($9.4 \text{ }^\circ\text{C}$). As denitrification is modelled as a first order process with respect to nitrate

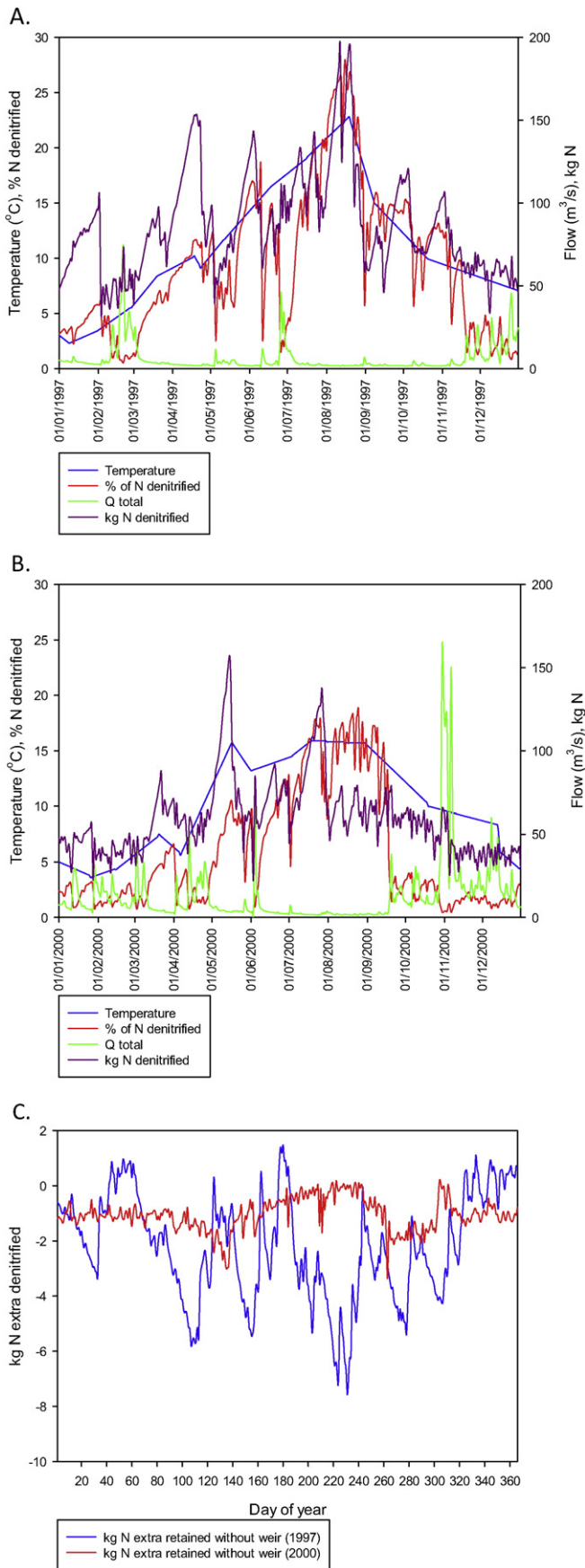


Fig. 3. Timeseries plot showing flow (Q total), temperature data and simulations of nitrogen denitrified (A. Year 1997, B. Year 2000, C. Impact of the weir on denitrification).

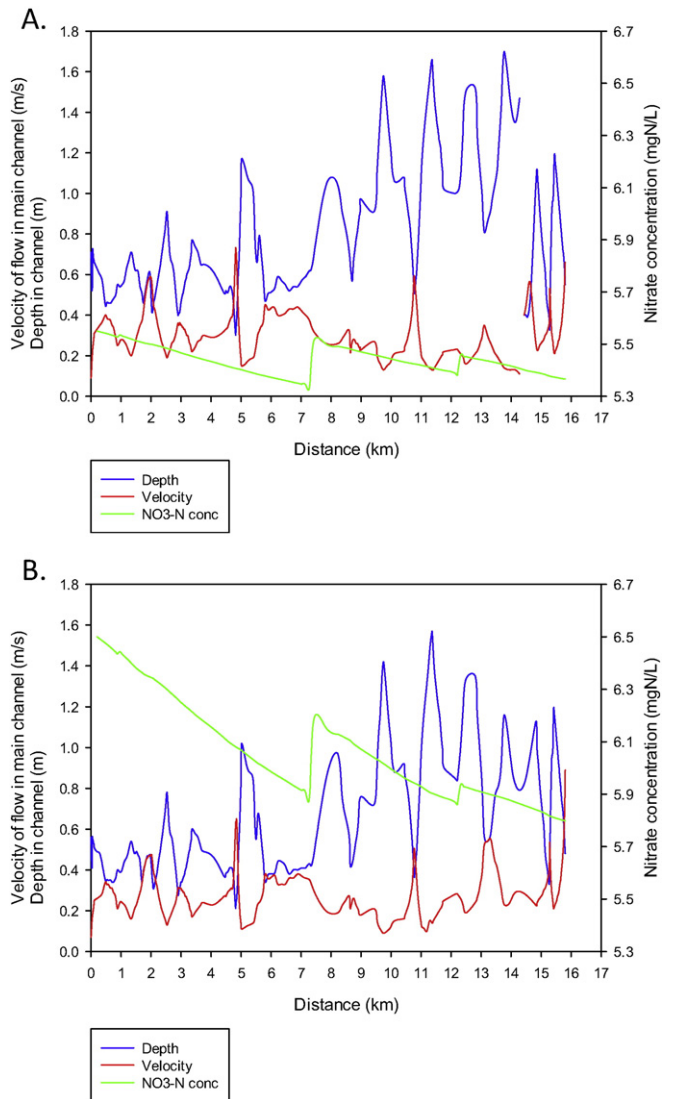


Fig. 4. Variation of average velocity of flow in main channel, hydraulic depth in channel and nitrate concentration along the stretch for individual days (A: weir present 25/04/1997, B: weir absent 10/08/2000).

concentration, the concentration of nitrate-N at the upstream end of the stretch is also significant in determining the rate of change along the stretch, concentrations being higher in August 2000 (6.5 mg L^{-1}) than in April 1997 (5.55 mg L^{-1}). Run 3 and Run 4 (see Table 1 for reference) were done in order to remove these confounding factors.

5.3. Assumptions

As illustrated on Fig. 4A and B, the small tributaries and point source effluents joining the River Nidd along the stretch (listed in Table 3) increase the nitrate concentrations in the main river channel (and thereby promote some additional denitrification). However the seasonality of these influences was not included in the whole-year calculations of nitrate retention because of lack of data on seasonal variation of flows and nitrate concentration in a natural tributary in this area. The input fluxes from Fleet Beck are likely to change seasonally. However, when comparing the two 1997 model applications (Runs 1 and 3) and the two 2000 model applications (Runs 2 and 4) undertaken to evaluate the impact of weir removal, the relative effects of these neglected influences will be the same.

Weir design dimensions were only available in the case of Skip Bridge. For Hunsingore Weir such dimensions were lacking. However,

given the evidence of weir backwater length in similar UK rivers (Samuels, 1989), it is not thought that the Hunsingore Weir is likely to influence the hydrological dynamics over 15 km downstream at Skip Bridge.

Using HEC-RAS it is not possible to include temporal variation of the coefficient related to roughness. The growth and die back of aquatic vegetation through the seasons is likely to have a considerable impact on channel roughness (Fathi-Moghadam and Drikvandi, 2012; Hamill, 1983; McGahey et al., 2008). However, there was lack of suitable survey information to include such variation. It is thought that the impact of the assumption would be that a constant Manning's roughness coefficient would be an overestimate in the winter and an underestimate in the summer whilst preserving a realistic annual average value. Underestimation in the summer is likely to have bigger implications for simulation of velocity, depth and nitrate removal than errors at other times of the year. However, the errors are introduced regardless of whether a weir is present and should not affect the relative values of nitrate removal (i.e. differences between model Runs 1–4).

Suitable topographic data describing the floodplain were not available for this stretch of river. Whilst an assumption that all the flow remains within channel may not be a valid under high flow conditions in winter, it is the low flow summer conditions that require study because the vast majority of annual denitrification occurs at this time as shown in this work and by others (e.g. Whitehead and Williams, 1982).

The characteristics of the bed sediment affect rates of denitrification. In the absence of observations, it was assumed that sediment characteristics are invariant along the stretch. In accordance with conclusions from other studies (Wagenschein and Rode, 2008), further investigations would be valuable to relate sediment characteristics to measured rates of denitrification, for example as determined by Pattinson et al. (1998) in the nearby Ouse and Swale rivers using the acetylene blockage technique. Such research would refine estimates of denitrification and reduce the inherent uncertainties in the calculations. Further research could reduce uncertainties in the calculation of denitrification with respect to weirs, for example measurements of sediment characteristics upstream and downstream of weirs could refine the denitrification rate constant.

6. Conclusion

A short stretch along the River Nidd in Yorkshire was studied. Here a weir was removed in 1999. Our model simulations suggest that weirs are beneficial in terms of denitrification, but only to a small extent. The benefits are largely seen during summer low flow periods.

Conceptually, the value of "a" (0.05) embodies the inclusion of factors that are attributable to the characteristics of the bed sediment. These characteristics are obviously highly localised in nature. The research has highlighted the importance of taking bed sediment measurements to identify the impact of local bed sediment characteristics on denitrification (to refine the value of "a" in Eq. (1)).

It would be important to put these results in terms of nitrate change in the context of other water quality measurements such as phosphorus, phytoplankton and sediment. This can be done using the same modelling tools/protocol.

In the context of the proposed widespread removal of weirs across European river, a thorough evaluation of the trade-off between denitrification versus habitat enhancement should be undertaken.

Acknowledgements

We thank the REFORM project from the European Commission (FP7 grant agreement No. 282656) and the PRESS project, which was largely funded by CEH's National Capability fund, for funding the research that resulted in this paper. We thank the EA for providing the cross section

data for the Nidd and Harry Dixon (NRFA), for providing documentation on the Skip Bridge design, and helping source additional hydraulic information. Cedric Laize provided information from the EA regarding spot gauging and ADCP profiles. We thank Keekee Kolade from Royal Holloway University of London who analysed water samples from the River Nidd for nitrate content. Finally, we would like to thank to our peer reviewers Egon Dumont and Richard Williams for their constructive comments and valuable feedback on this manuscript.

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