
Nitrate concentrations in the thames basin

Howden et al. (2010[1]; 2011[2]) related the historical measured nitrate concentrations in the Thames to nitrate inputs in the catchment.

**Thames time series**

Figure 6.1 shows the continuous monthly record of average nitrate concentrations for the Thames at Hampton for 140 years starting in 1868. Nitrate concentrations rose during World War II (WWII) and then stabilized at almost double their previous level (\(\sim 2 \text{ mg NO}_3\text{l}^{-1}\) 1868–1940, \(\sim 4 \text{ mg NO}_3\text{l}^{-1}\) 1945–1970). There was a further step change in the early 1970s, when the average concentrations jumped from around 4 mg NO\(_3\) l\(^{-1}\) to almost 8 mg NO\(_3\) l\(^{-1}\) and, in common with the WWII increase, these concentrations have remained stubbornly high despite continent-wide interventions to decrease catchment nitrogen inputs since the early 1980s (EU Nitrates Directive 91/676).

Such shifts in concentration may be driven by changes in the climate, flow regime, land use or population. However they are not explained by changes in monthly precipitation, average temperature or abrupt changes in population in the Thames basin.

**Nitrate input**

Howden (2010)[1] considered that land use change is the only basin-wide driver that can account for the shifts in concentration shown in Figure 6.1. Figure 6.2 shows their estimates of the fraction of the Thames Basin under arable crops and the total modelled nitrate input to the catchment system. By far the most sudden changes were during WWII and in the mid-1960s; these are reflected in the nitrate record shortly after.

![Figure 6.1](image-url)  
*Figure 6.1* Time series plot of nitrate concentrations in the River Thames at Hampton (from Howden et al., 2010[1]).
Differences in the relative magnitudes of the two step changes were explained as follows. The extensive ploughing of permanent grassland in WWII was achieved through mechanization, but there is no evidence of increased fertilizer application. In contrast in the 1960s, a smaller area of grassland was converted to arable but this was accompanied by increases in the grant-aided land drainage (Green, 1979) and considerable intensification, especially a substantial increase in fertilizer application: annual fertilizer use in the UK was 485 kt N in 1960, increasing to 921 kt N by 1970 and peaking at 1588 kt N in 1984 (Green, 1979).

The 1960s shift in concentration was more rapid because increased drainage reduced catchment residence time and increased quantities of inorganic fertilizers were immediately available for leaching. Reversions from arable to grassland are not reflected in the nitrate record and concentrations remain obstinately high after each increase. Since the early 1980s, attempts to manage high nitrate concentrations have focused on control of nitrogen fertilizer inputs. While fertilizer input is certainly a contributing factor to rising nitrate concentrations, the stepped increases are driven by longer-term processes following land use change: release of soil N and groundwater transport both operate on at least decadal timescales.

Howden et al. (2011) collected data for calendar years from 1868 onward from the following sources:

- landuse from parish records and interpolated from national data from 1988 onwards;
- N loading data from the UK literature;
- N loading from sewage from population data from census returns;
riverflow mean daily flows from Kingston.

Landuse combined with N loading were combined to provide the elements of the loading shown in Figure 6.3.

**Figure 6.3** Estimated loading components: a) animal inputs; b) fertilizer inputs; c) inputs from enhanced mineralization because of ploughing of permanent grassland; d) losses from uptake from crops and grasslands; and e) estimated nitrogen available for leaching. Dashed lines 5th and 95th percentiles (from Howden et al., 2011[2]).

**Transport model**

Howden et al. (2010)[1] used a simple two reservoir transfer function to route the loading through a rapid runoff and a slow groundwater pathway. All processes were lumped together over the whole catchment to the lack of spatial information to define inputs at a sub-basin scale over such a long period. The split between runoff and groundwater was assumed to be similar to the baseflow index
of the Thames at Kingston (BFI = 0.65) but this was adjusted during model calibration to approximately 0.55. A 1D advection dispersion equation was used to attenuate nitrate loading for both the fast and slow pathways.

**Results**

Figure 6.4 shows observed and modelled nitrate concentrations in the Thames at Hampton. The model appears to replicate the observed increases in concentrations reasonably well. A 30 year lag in the groundwater component of the model was required in the calibration of the model. Consequently it is argued that the step increases in nitrate concentrations in the Thames in the 1950s and 1970s are the result of intensification of agriculture during the 1920s and 1940s (the ‘Dig for Victory’ campaign). Using a number of input function scenarios, it is shown that changes in basin-wide land use would take decades to be effective. Howden et al. (2011) also argue that an accurate input function is more important than a complex flow model, as demonstrated in the case of the Thames.

![Image](image.png)

**Figure 6.4** Median predictions from the 12 000 top-performing parameter sets predicting nitrate concentrations in the Thames, from 1868 to 2008 (Howden et al., 2011).

**Other approaches to predicting nitrate concentrations in groundwater**

In addition to the work discussed above, numerous other approaches to numerical modelling of legacy nitrate have been adopted in the UK and internationally. Examples from both the peer-reviewed and grey literature are discussed herein. Table 6.1 summarises this work.

**Chesapeake Bay, United States**

Sanford and Pope (2013) undertook a study attempting to quantify the role of groundwater in delays in improvements in nitrate concentrations in Chesapeake Bay, United States. A 3D steady state groundwater flow model was developed in MODFLOW and MODPATH was used to calculate
the travel time for groundwater recharge in each cell to reach the river or coast. An input function was derived for each model cell using fertilizer and manure histories for the catchment. This input function was dissolved in an amount of recharge calculated using a water-balance regression approach, and then transferred to the river based on the travel time. Riparian and groundwater denitrification were included as zero-order model terms, but in the final model calibration groundwater denitrification was very small. The model was able to simulate observed trends in groundwater and stream nitrate concentrations, and forward predictions were made using a number of nitrate loading scenarios.

**Upper Dyle Basin, Belgium**

César et al. (2014) undertook simulations on nitrate concentrations at a regional scale in the Upper Dyle basin, Belgium. A similar water balance model was used to derive spatially distributed steady-state recharge values for the aquifer. This was linked to a steady-state numerical groundwater flow model and transient transport model with no dispersion. Simplified nitrate input functions are used based on cultivation and land use patterns. Very limited data were available for calibration so it is difficult to assess the success of the modelling effort. It is clear, however, that the input function dominates the modelled trends.

**UK water industry approaches**

In addition to the approaches reported in the peer-reviewed literature, a substantial body of work on modelling of nitrate in groundwater has been undertaken by the UK Water Industry. Whilst peer-reviewed studies generally consider catchment-scale impacts of nitrate loadings on rivers, water industry studies focus on impacts on specific public water supply boreholes. Continued rises in groundwater nitrate concentrations to over the drinking water standard have resulted in significant regulatory pressure to develop long term sustainable solutions to this problem. The high costs of nitrate treatment and blending have resulted in a focus on catchment management as a possible approach. In order to provide evidence that catchment management could improve source water quality, water companies have undertaken nitrate modelling studies to assess the potential impact of catchment mitigation options on groundwater nitrate concentrations. These studies are briefly reviewed below.

Nitrate concentrations at 8 Wessex Water chalk boreholes in the Frome, Piddle and Wey catchments were modelled by Rukin et al. (2008). Historic fertiliser inputs and observation borehole nitrate data were used to derive a nitrate input function for 1990 to 2007. Unsaturated zone travel time was derived from the infiltration rate (derived from the South Wessex Recharge Model), matrix porosity and depth to water. Using the travel time and estimates of borehole catchment areas, nitrate concentrations at abstraction points have been estimated. Seasonal variations and spikes in nitrate were modelled empirically based on observed seasonal water level changes and bypass recharge from the South Wessex recharge model respectively. Current nitrate trends are the result of leaching from the soil zone 10–60 years ago. Forward predictions of nitrate concentrations at public water supply abstractions have been made based on a number of different soil leaching scenarios.

A total of 44 Severn Trent Water and United Utilities public water supply borehole catchments in the Permo-Triassic Sandstone aquifer were investigated by Buss (2013). A source term of nitrate leaching into the unsaturated zone was derived from NEAP-N data interpolated with national fertilizer use data and county-scale livestock numbers in conjunction with annual recharge estimates. A lag function is then applied to the input to fit the timings of the observed borehole nitrate concentrations. In-borehole dilution and mixing from other sources of water are represented as simple percentage dilutions to match the observed concentration magnitudes. The modelling
showed that typical transport times were 15–35 years, with the peak in nitrate inputs in the 1980s having passed, or will imminently pass through the aquifer. Predictions of future nitrate concentrations at each of the sources were used to assess the feasibility of catchment management options.

Anglian Water’s North Pickenham boreholes penetrate the Chalk and have shown increases in nitrate concentrations from the start of monitoring in the 1980s to present. Concentrations now consistently exceed the drinking water standard. Price et al. (2011) linked an Environment Agency regional groundwater model with MT3D and the WAVE (Water and Agrochemicals in the soil, crop and Vadose Environment) model to estimate unsaturated zone transport and saturated zone nitrate transport to abstraction boreholes. The model was calibrated using historic nitrate concentrations at the abstraction point and land use change scenarios were undertaken to estimate potential future nitrate concentrations. This approach was extended to other supply boreholes (Price and Andersson, 2014). This included an unsaturated zone travel time based on the approach of Wang et al. (2012) where the long-term average recharge is divided by the porosity.

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