EVALUATING THE IMPACTS OF CLIMATE CHANGE ON CATCHMENT NITROGEN TRANSFER: A MODELLING STUDY ON THE RIVER WENSUM, UK.

By

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Abstract

This study assessed the impact of potential climate change on the nitrogen loads to surface and sub-surface waters and was conducted using the Soil and Water Assessment Tool (SWAT) model. The study focused on the 20km$^2$ Blackwater sub catchment located in the main 593 km$^2$ River Wensum catchment, Norfolk. The SWAT model was calibrated and validated using sets of measurements of nitrate concentrations and water flow from the Wensum Demonstration Test Catchment (DTC). The SWAT model was then run using a baseline scenario corresponding to an actual measured time series, and a UKCP09 climate change scenario was applied using a 'mid-term' (2050) and 'long-term' (2080) scenario assuming a medium emissions scenario (A1B). Both time frames saw increased temperatures and a significant increase in seasonality of rainfall towards a pronounced winter maxima. Overall it was found that there was a 14.3% and 20.7% decrease in total nitrogen loading in 2050 and 2080 respectively.

Keywords: Nitrogen, Climate, SWAT, Wensum.
1. Introduction

Climate change can result in significant changes in the variables and processes that affect water quality. One of such changes is an increase in the concentration of nutrients transferred to aquatic environments, which has a wide range of impacts on human wellbeing, economic services and flora and fauna, all of which depend on clean water directly or indirectly (Shiklomanov 2000, Solheim et al. 2010, UNEP 2012).

1.1 Pollution types

Sources of pollution can be split into two groups; point source and non-point source. Point sources discharge from single points, e.g. sewage treatment plants, and are therefore relatively straightforward to manage. Non point sources tend to pose difficulties to manage successfully as pollutant release can be over a larger area and often irregular (Carpenter et al. 1998). Identifying both sources of pollution is important to ensure effective management (Niraula et al. 2013). Non point sources are responsible for the majority of water pollution in the United Kingdom (Dunn et al. 2012). Agricultural practices have long been recognised as significant sources of non-point source water pollution (Johnes 1996, Dupas et al. 2015).

Significant quantities of nitrogen and phosphorous are transmitted to water bodies as a result of intensive agricultural practices, including excessive applications of inorganic fertilizer and increased sediment mobilization (Chaubey et al. 2010, Silgram et al. 2010). The leakage of these nutrients to watercourses can cause eutrophication which poses a serious threat to the freshwater, estuarine, and marine environments (Donner et al. 2002, Diaz and Rosenberg 2008, Vörösmarty et al. 2010).

1.2 Nitrogen transport

Knowledge of the nitrogen cycle and its perturbations is crucial for successful modelling studies. The human alteration of the nitrogen cycle is immense (Vitousek et al. 1997). The creation of reactive nitrogen increases every year predominantly due to agricultural activities and demands (Galloway et al. 2008). Naturally nitrogen is fixed by *Rhizobium* associated with legumes, and sometimes by lightening, although the industrial Haber-Bosch process now produces the majority of reactive nitrogen for agriculture (Galloway et al. 2004, Galloway et al. 2008). The most commonly applied nitrogen species in fertilizer are, nitrate and ammonium as they are most readily available for crop uptake. Nitrate is usually
the focus of nitrogen based water quality studies as it is highly soluble and can therefore be transported by regular hydrological processes such as leaching, throughflow or percolation (see figure 1) (Mehdi et al. 2015). Ammonium, in contrast, is not very mobile as when soil temperatures exceed 5°C it is readily adsorbed onto clay minerals or used by microorganism and plants. Excess nitrogen that is not taken up by crops either becomes a source for transfer to aquatic environments, or is removed from the soil to the atmosphere via denitrification or volatilization (Gassman et al. 2007, Neitsch et al. 2011).

Figure 1: Inputs, outputs and transport processes of N and P from agricultural land (Source: Carpenter et al 1998)

1.3 Significance of Climate Change

In the northern hemisphere the period between 1982-2012 represented the warmest thirty year period for 1400 years (IPCC 2013). With global greenhouse gas emissions continuing to rise these trends seem set to continue (IPCC 213). This warming results in increasing precipitation and evapotranspiration, due to roughly exponential increase in water holding capacity of the atmosphere with temperature rise (Min et al. 2011). Furthermore the warming will increase winter rainfall because a greater proportion of precipitation will fall as rain instead of snow.

The observed global temperature increase over several decades has been linked to significant changes in the hydrological cycle and associated impacts on water quality (Bates et al. 2008). Changes to nutrient loads are correlated with surface runoff and sediment transport rates (McElroy et al 1976), both of which are impacted by climate change (Marshall and Randhir 2008, Tong et al. 2007). Therefore, whilst the processes involved in nitrogen pollution and transmission to waterbodies are understood, the response of water quality to future climate changes remains uncertain, and spatially variable (Wilson and Wong 2011). The use of climate model scenarios provide the best information to address these
uncertainties associated with climate change and investigate the impact on hydrology and water quality at regional scales (Whitehead et al. 2009).

1.4 Relevant policy

Since the Second World War there has been a shift towards increasingly mechanised agriculture, the changing agricultural practices have potential for adverse impacts on waterbodies (O'connell et al. 2007).

Nitrogen, especially in its reactive nitrate form, is a key pollutant in aquatic ecosystems. Increased concentrations in watercourses can be damaging to human and environmental wellbeing and have financial implications terms of water management and treatment costs (Ahmadi et al. 2014). There is existing legislation in place such as the EUs Nitrogen directive and Water Framework Directive (European Parliament 2000) which set maximum acceptable levels for nitrate concentration in water bodies. Regulation is necessary as agricultural sources provide the largest transport of excess N to waterways (Foley et al. 2005). The degradation of both surface and groundwater is a documented problem throughout Europe with nutrient enrichment causing waterbodies to breach EU regulation (Outram et al. 2014). In England and Wales 17% of the 7,300 river monitoring points exceeded the 50 mg/l nitrate drinking water limit at least once during the winter months of 2005 (Defra 2008).

Quantifying potential future changes to nitrate pollution in the Wensum catchment should be of importance to various stakeholders within the catchment and could prove useful to the long term management plans of the Wensum river basin. Many of the issues discussed above are exacerbated by the fact that the Wensum catchment has a significant amount agricultural land use. The dominance of high intensity agriculture is associated with decreased water quality (Green et al. 2014, Mehdi et al. 2015). The main channel is adjudged to be of poor ecological status according to water framework directive indictors. Therefore the impact of climate change in this region is of particular concern. The small scale nature of the study offers the opportunity to reveal more detail than regional or national analysis of water quality.
1.5 Aims and objectives

Aim:

To model the impacts of climate change on nitrate load in the Blackwater sub-catchment and compare results with the baseline data.

Objectives:

- Evaluate the accuracy and uncertainties involved in both hydrological and climate models.
- Quantify the export of nitrogen into the River Wensum from the Blackwater sub-catchment.
- Investigate the processes involved in nitrogen pollution and how they are impacted by climate change.

2. Literature Review

The impact of climate change on the hydrological cycle has been a heavily researched topic however much of the effort has concentrated on direct impacts such as water resource availability and flooding (Dunn et al. 2012, Charlton and Arnell 2014). Relatively less attention has been paid to the indirect effects of climate change on water quality (Whitehead et al. 2009, Dunn et al. 2012). It is understood that changes in rainfall and temperature, and increases in extreme event frequency associated with climate change will have impacts on the hydrological cycle (Whitehead et al. 2009, Charlton and Arnell 2014). Changes to the hydrological cycle have the potential to damage water quality standards and have ramifications for human and ecosystem health (Murdoch et al 2000, Wilby et al. 2006, Ahmadi et al. 2014).

However despite awareness of possible impacts to water quality there is debate about the processes involved and whether nutrient loading will increase or decrease. A crucial cause of this uncertainty is due to the challenge involved in predicting changing rainfall patterns in future climate scenarios. The UKCP09 (United Kingdom Climate Projections 2009) projections suggest an increase in winter precipitation whilst a decrease in summer precipitation for south east England (Defra 2009) with the frequency of extreme events also predicted to rise (Whitehead et al. 2009). These changing patterns of precipitation are linked to river flow and thus have associated impacts on nutrient loads and water quality (Arnell 2003, Whitehead et al. 2009).
Higher precipitation and associated increases in runoff will be linked with greater nitrate pollution. A study by Donner et al. (2002) attributed ~25% of the nitrate export to the Gulf of Mexico to increased runoff alone. Observational studies have also shown an increase in nitrate pollution during wetter years with greater nitrogen retention in dry years (Kaushal et al. 2008). The processes by which runoff increases nitrate pollution is partly caused by the increased erosion and mobilization of fine sediments and an increase in the flushing of diffuse pollution into the river channel and along the river system (Wilby et al. 2006, Whitehead et al. 2009, Solheim et al. 2010). In contrast, there will likely to be periods of lower river flows in the future, predicted during dryer summer months (Defra 2009). The higher temperature increases potential evapo-transpiration, which may lead to decreased soil moisture and runoff (Stone et al., 2001, Jeppesen et al., 2009). The decrease in precipitation may lead to lower diffuse pollution due to reduced runoff, and therefore a decrease in the quantity of sediments transmitted from the soil profile to rivers. On the other hand the lower flows would reduce the volume of water available for the dilution of pollutants and thus lead to higher concentrations (Murdoch et al. 2000, Whitehead et al 2009).

Increased temperatures could also lead to increased soil nitrogen mineralization leading to higher nitrate concentrations when the build up of nitrogen is washed out during storm events (Wilby et al. 2006, Whitehead et al. 2009). Another factor to consider with higher temperatures is that dissolved nitrates are more likely to cause eutrophication as lower dissolved oxygen levels are associated with warmer air temperatures (Murdoch et al. 2000).

The lack of consensus on the pattern of future nitrogen pollution amongst several studies is due to the differences in methods adopted between them. There are a range of variables including the choice of: study area, hydrological model, water quality variable and climate scenario (Dunn et al. 2012, El-Khoury et al. 2015). This lack of agreement highlights the importance of further research, especially on smaller scales as there is no larger uniform pattern to changes in nitrogen transport.

### 2.1 Water quality studies in the Wensum

Several other water quality studies have been undertaken in the Wensum catchment. A range of pollutants have been studied including Nitrogen (Evans 2012, Outram et al. 2014), Phosphorous (Demars et al. 2005, Outram et al. 2014, Whitehead et al. 2015), and fine grained sediment (Collins et al 2013).

Concentrating on the studies concerning nitrogen. Acute storm induced N transfer was highlighted in the blackwater sub catchment. The 2011/12 drought caused desiccation and soil wetting resulting in increased rates of mineralization. The outcome led to high nitrate
concentrations in the Wensum (Outram et al 2014). In addition it has been shown that there is abundant nitrate supply in the Blackwater sub catchment and that supply was transport limited rather than supply limited (Outram et al. 2014). Evans (2014) has also carried out a less detailed reconnaissance survey to identify sources of diffuse pollution. Features such as eroded fields and tracks were recorded in parts of the Wensum catchment to identify high risk areas.

However despite these investigations into water quality that have occurred in the Wensum, no study appears to have considered the impact that climate change could have on water quality in the region. In other regions in the world, however, there are several other studies. Several use the same SWAT model although other modelling methods are used. Relevant information from these studies is discussed below.

### 2.2 Similar studies in other catchments

Several SWAT based modelling studies have been carried out. The use of the hydrological model has often been paired with climate models or land use models (Tong et al 2012). There are authors investigating the impact of climate change on water quality in other catchments around the world using SWAT: Bouraoui et al (2002) modelled nutrient loading in the River Ouse Catchment and predicted an increase in N loss due to processes of soil mineralization and increased leaching. Ahmadi et al. (2014) undertook a similar study in midwestern United States in an agricultural catchment. Marshall and Randhir (2008) paired SWAT with IPCC high and low scenarios climate in New England. There is also a wide range of literature in which other hydrological models and transport models have been used other than SWAT. For example, Jeppsen et al (2011)’s approach investigating N transport in cultivated catchments in Northern Europe for different climate scenarios used a combination of three different models; a statistical N-model, the MIKE11-TRANS model and the INCA-N model. As another example Dupas et al (2015) used a mass balance model, Nutting, to estimate N loss.

Whilst the majority show that N dynamics are impacted either directly or indirectly by changes to climate the magnitude and direction of change show differences. The majority of studies using a climate scenario which predicts increased rainfall show an increase in nutrient transfer to surface water (Bouraoui et al. 2002, Jeppsen et al. 2011, Tong et al. 2012, El-Khoury et al. 2015). For example, Tong et al. (2012) modelled the wettest climate scenario predicted N to increase by 11% compared to driest scenario. However, Chang (2004) found most catchments forecast to have decreased N loads under future climate scenarios. Denitrification and mineralization processes can be directly impacted by
temperature rises. Weyhenmeyer et al. (2007) found warmer water increases the rate of denitrification processes, thus reducing the N concentration in warmer months. Enhanced biological uptake of nitrogen in a warmer climate is also a documented process (George et al. 2004). Nitrate uptake from the soil is undertaken by two mechanisms; Nitrate uptake by vascular plants dominates in summer months whereas bacterial denitrification occurs when soil temperatures are low. Therefore a range of studies have found that depending on the temperature to increased nutrient uptake by crops can lead to reduced N transport to water courses or reduced mineralization my microbes (Fan and Shibata 2015). It is the poorly drained, wet soils that are likely to have high denitrification potential due to prevalence of low oxygen conditions (Galloway et al. 2004).

Several studies have found that there is not just a change in total N transfer to the river network but also changes in timing, in terms of seasonal distribution. Fin and Shibata (2015) recorded increased surface runoff and nutrient runoff in winter months, driven by precipitation changes but exacerbated by a decrease snowfall and increase rainfall in winter months due to the higher predicted temperatures. Maximum monthly sediment yield shifted from May to April, and therefore these months saw greater proportions of total annual nutrient load under the future climate scenarios (Fan and Shibata 2015). Tu (2009) investigated the impact of both climate and land use change on streamflow and nitrogen in Eastern Massachusetts. In this case it was found that the total annual volume of streamflow and nitrogen loads were not significantly altered, rather, the timing of both were significantly affected by climate change. Nitrogen loading and streamflow again increased in winter months and fell in summer months due to differences in temperature and precipitation under climate scenarios.

Land use change introduces more complex factors into joint studies of climate change and nutrient loss which are harder to predict and account for as there are a wide range of direct and indirect impacts that climate change has on land use and vice-versa (Vitousek et al. 1997). In China, Wu et al. (2012) found that climate change had the greater impact on increasing N loads compared to changing land use to increase livestock densities. Tong et al (2012) also found that climate change had more impact on N concentration than land use change, which alone was responsible for just a 3% in N concentrations. While El-Khoury et al. (2015) determined that the increase in organic N levels was both a consequence of climate change and land use change to similar degrees. In any case it is clear there have been a variety of studies investigating the complex interaction of land use and climate change and find different relative importance of each of them on nutrient pollution of watercourses.
2.3 Use of climate models and hydrological models

There are a range of both climate and hydrological models used in the literature. Global or regional climate models can be applied directly but a more common approach when applying climate impacts to hydrological models is to downscale, global climate models to an appropriate scale for the river basin, using either statistical to dynamic method (Dunn et al. 2012, Fiseha et al. 2014, El-Khoury et al. 2015). For example Marshall and Randhir (2008) and Jeppsen et al. (2011) both used IPCC based global climate models in conjunction with SWAT in their studies of water quality in the Connecticut River and European catchments respectively. Dunn et al. 2012 used the UKCP09 projections in their investigation into future water quality in Scotland. In this study a projections the UKCP09 database will also be applied to investigate possible future changes to water quality caused by climate change.

The hydrological models used in the literature range from water balance models to more complex catchment models that can model water flow and simulate point source and diffuse pollution, at regional and national scales (El-Khoury et al. 2015). The SWAT model used in this project has been used extensively in the literature (Gassman 2007), often for similar studies investigating climate change and nutrient transport (Bouraoui et al. 2002, Donner et al. 2002, El-Khoury et al. 2015). It is important to consider how each model represents nutrient transport and how key hydrological, ecological and bio-geochemical processes interact (Bouwman et al. 2013). This is difficult as key concepts of nutrient delivery, supply and transport are not fully understood and can only be reduced to simplified equations. Attempting to include ecology into the system is a current goal to attempt to better simulate hydrological process to closer match reality. However, it adds another layer of complexity, especially considering the differences in spatial and temporal scales operating between the terrestrial and aquatic ecosystems. Other models use different approaches of describing nutrient transport, often in response to different spatial scales of study location (Bouwman et al. 2013). For example; regression based models, with nutrient inputs and measured river outputs, are often used for extrapolation when there are limited measurements of nutrient export or over large river basin scale studies (Maybeck 1982, Mayorga et al., 2010, Wilby et al. 2006). As mentioned earlier SWAT has occasionally been used in conjunction with the UKCP09 database. More detail on the two tools will be provided in the Methods section.
3. Methodology

3.1 Study Site

The River Wensum is a 78 km long, enriched, lowland calcareous river in Norfolk, East Anglia. The Wensum drains a 593 km$^2$ area containing Site of Special scientific Interest (SSSI) and European Special Area of Conservation (SAC) designated sites. The entire catchment is underlain by Cretaceous Chalk with the eastern side overlain by Pleistocene Crag sands and gravel while the western side has glacial till overlain by chalky boulder clay (Outram et al. 2014, Wensum alliance 2015). The Wensum Catchment is monitored as part of the Demonstration Test Catchment project (DTC) which aims to investigate how to cost-effectively control diffuse agricultural diffuse pollution in order to improve water quality in rural river catchments (Demonstrating Catchment Management, 2015). Of the 20 sub-catchments in the Wensum it is the 20km$^2$ Blackwater sub catchment which is intensively monitored as part of the DTC project. The Blackwater sub-catchment is further subdivided in 6 mini-catchments. Data recorded including pH, turbidity, temperature, stage, flow, ammonium, chlorophyll, dissolved oxygen and electrical conductivity at 30-minute resolution. Nitrate and Phosphorous measurements are also recorded (Cooper et al.2015b).
Predominantly subsurface N transport pathways are more common due to the permeable nature of the Blackwater sub-catchment.

Intensive arable farming is the dominant land use in the Blackwater sub-catchment with N fertiliser application rates of around 220 kg N ha\(^{-1}\) on cereal crops. It is therefore expected for water quality to be lower in catchments because of the dominant agricultural land use. (Green et al 2014). Indeed, the ecological status of the Blackwater tributary is compromised, with 99.4% of its protected habitat in an unfavourable and declining state, largely because of high rural N, P and sediment inputs. (Sear et al. 2006, Outram et al. 2014, Wensum Alliance 2015). Furthermore, the Blackwater sub-catchment has long recession periods after storm events, the nitrate concentration on the descending limb of a storm can stay elevated for several days during periods of high concentration. Although the very low relief and flat topography of the Wensum catchment may offer some natural protection from pollution as nitrogen lost through runoff should be lower in comparison to catchments with greater relief (Liu et al. 2014)

3.1.1 Climate
The Wensum catchment has a temperate maritime climate with a mean annual temperature of 10.1 °C and mean annual precipitation total of 674 mm over the 1981–2010 period. (Cooper et al 2015b)

3.2 Model description - Soil and Water Assessment Tool
The water quality modelling will be carried out using SWAT software (Arnold et al. 1998), a sophisticated, process-based hydrological and water quality model with a range of soil, hydrological, weather and nutrient components (Santhi et al. 2001). SWAT has been chosen, in preference to other software such as Farmscoper or SPARROW, as it is suited to this study for a number of reasons. Firstly, it is a freely available ArcGis extension, it is able to simulate water yield and quality across long timescales and is suited to agricultural river basins (Borak and Bera 2003, Tong et al. 2007). SWAT divides the catchment into Hydrological Response Units (HRUs) based on land use, soil type and elevation differences that influence hydrological conditions. The flexible nature of SWAT allows simulation of fertilizer application rate and timing with simple parameter changes. Furthermore, SWAT and similar models offer improvements on other tools by linking ecology, biogeochemistry and the physical habitat with water quality (Bouwman et al. 2013).
The way SWAT tracks the movement and transformation of several forms of Nitrogen is described. Surface runoff volume is used by the Modified Universal Soil Loss Equation (MUSLE) to calculate soil erosion and sediment yield (Marshall and Randhir 2008, Panagopoulos et al. 2011). The assimilation of nitrogen by plants is calculated using a supply and demand approach. The amount of nitrate removal from soil in runoff, lateral flow and percolation are estimated in terms of water volume and average nitrogen concentration in the soil layer. (Neitsch et al. 2011). Organic N transport is calculated using a loading function adapted from McElroy et al. (1976) which is based on organic N in the top soil layer and sediment yield. Denitrification rates are calculated in relation to nitrate levels, water content, temperature and carbon source presence (Neitsch et al. 2011). The potential evapotranspiration rate is calculated using the Hargreaves equation which is a function of air temperature and maximum solar radiation (Neitsch et al. 2011). Therefore, to summarize, the model considers the removal of nitrogen via the following processes: plant uptake, leaching, denitrification, volatilization, runoff and soil erosion (Ahmadi et al. 2014). See figure 3. For a schematic.

**Figure 3: Diagram showing how nitrogen is represented in SWAT. (Source: Neitsch et al. 2011).**

SWAT is considered a robust, interdisciplinary tool with hundreds of related papers published (e.g. Jha et al. 2004, Santhi et al. 2006, Gassman et al. 2007, Panagopoulos et al, 2011, Niraula et al. 2013, El-Khoury et al. 2015, Fan and Shibata 2015, Mehdi et al. 2015). It has therefore been demonstrated on numerous occasions that the SWAT model is capable of carrying out this study. Although it is worth recognizing that the complexity of deterministic models, such as SWAT, often creates intensive data and calibration requirements, which generally limits their application in large watersheds (Bouwman et al. 2013). In this case SWAT was used with the ARCGIS 10.2 interface.
3.3 Model Inputs

Data requirements are high due to SWAT being a process based model. Much of the data is available on the Wensum Alliance database containing data from the DTC. Nitrogen data is collected every 30 minutes within the Blackwater sub catchment.

- Meteorological data – Wensum Alliance Server
- N and P loads – Wensum Alliance Server
- River Discharge - Wensum Alliance Server
- Water abstraction – Environment Agency
- Soil data - Wensum Alliance Server
- Land Use – Wensum Alliance Server
- Topography – LandMap database

To setup the model hydrological response units were delineated according to elevation, soil data, and land use, along with defining stream network and inputs and outputs. The SWAT model was calibrated using data collected by the Wensum Alliance since January 2009 to the present day. SWAT-CUP is a computer program that was calibration of the model. There is lots more information on input files available from Neitsch et al. (2005).

Climate change simulations were based on the UKCP 09 simulations as explained later. Once the model has been run with the climate simulation the differences in nitrogen concentration can be compared with the baseline data.

3.4 Model Calibration

The model was calibrated until an acceptable Nash Sutchcliffe efficiency ($E_{NS}$) was reached. The model was run for 5 year 6month time period from 1st January 2009 to April 30th 2014. Changes were made to relevant parameters based on SWAT guidance (Arnold et al. 2011) and other studies discussing SWAT calibration (Santhi et al. 2001, Reungsang et al. 2005).

The main amendments were to the runoff curve parameter.

The results achieved for the calibration for daily flow and total N are shown below. Both $E_{NS}$ and $R^2$ values.
Table 1: SWAT calibration statistics comparing observed values and baseline predictions

<table>
<thead>
<tr>
<th></th>
<th>Regression statistics</th>
<th>Calibration score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Flow</td>
<td>$E_{NS}$</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.52</td>
</tr>
<tr>
<td>Total N</td>
<td>$E_{NS}$</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Both the $E_{NS}$ and $R^2$ were above the minimum statistical requirements, so the baseline simulation was accepted. It should be noted that it is far from optimal.

3.5 Incorporating climate change

The climate change applied to model were based on techniques utilized by Bouraoui et al. (2004), Tong et al. (2007) and Dunn et al. (2012). The aim of this study is not to accurately predict future climate change but rather to assess the hydrological and nitrogen transport response to possible future climate change. Therefore the scenarios used reflect a range of possible conditions, they will give an indication of a possible set of impacts that will provide decision makers with information to make adaptive and flexible choices (Tong et al. 2007). In order to make the study more manageable the simplified assumption was made that the type and range of crops did not change over time and that the same management processes were applied. This study did was not focusing on changing land use.

The climate change scenarios in this study are based on the UKCP09 climate projections. The new 2009 UK Climate Projections provide a more complete picture for climate change assessments than previous scenarios because they provide future data based upon a more systematic characterisation of uncertainty across several climate models and different emission estimates (Street et al. 2009, Dunn et al. 2012). ‘Mid-term change’ was set for the year 2050 and ‘long term change’ for 2080, both under the A1B (medium) emissions scenario (Nakicenovic et al. 2000). Precipitation and temperature were the variables adjusted; both of them are important variables in the SWAT model as they are included in several equations involved in the simulation of nutrient transport to rivers including, evapotranspiration, surface runoff, baseflow and soil erosion (Panagopoulos et al. 2011). The annual average changes in temperature and precipitation are shown in the table below based on the central estimates for each scenario. The climate change variables are shown...
as percentage change for precipitation and degrees Celsius for temperature. To calculate the deviation from the baseline the parameters were edited using a simple method employed by Bouraoui et al. (2002). The projected change in temperature (°C) for each month was added to the baseline temperature for each day of the corresponding month. The estimated percentage change in precipitation for each month was multiplied with the daily baseline values for that month to calculate the precipitation amendments.

Table 2: Change of precipitation (%) and temperature (°C) from baseline as predicted for each scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>P (%)</th>
<th>T Change (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2050 Scenario</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter mean</td>
<td>6%</td>
<td>2.2</td>
</tr>
<tr>
<td>Summer mean</td>
<td>-8%</td>
<td>2.8</td>
</tr>
<tr>
<td>Annual Average</td>
<td>2%</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>2080 Scenario</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter mean</td>
<td>22%</td>
<td>3</td>
</tr>
<tr>
<td>Summer mean</td>
<td>-23%</td>
<td>2.9</td>
</tr>
<tr>
<td>Annual Average</td>
<td>4.45%</td>
<td>2.95</td>
</tr>
</tbody>
</table>
4. Results

Table 3: Changes to temperature (°C), precipitation (mm) and total nitrogen (kg/ha) for UKCP09 2050 and 2080 central estimates assuming a medium emissions scenario (A1B)

<table>
<thead>
<tr>
<th>Month</th>
<th>Baseline Scenario</th>
<th>Mid-term 2050</th>
<th>Long-term 2080</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (°C)</td>
<td>P (mm)</td>
<td>TN (kg/ha)</td>
</tr>
<tr>
<td>Jan</td>
<td>4.5</td>
<td>43.2</td>
<td>5.43</td>
</tr>
<tr>
<td>Feb</td>
<td>5</td>
<td>41.2</td>
<td>3.26</td>
</tr>
<tr>
<td>Mar</td>
<td>7</td>
<td>45.7</td>
<td>3.36</td>
</tr>
<tr>
<td>Apr</td>
<td>8.5</td>
<td>40.5</td>
<td>1.98</td>
</tr>
<tr>
<td>May</td>
<td>11.5</td>
<td>35.6</td>
<td>1.25</td>
</tr>
<tr>
<td>Jun</td>
<td>14</td>
<td>53.1</td>
<td>1.34</td>
</tr>
<tr>
<td>Jul</td>
<td>16.5</td>
<td>47.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Aug</td>
<td>17</td>
<td>53</td>
<td>0.65</td>
</tr>
<tr>
<td>Sep</td>
<td>14.5</td>
<td>66.3</td>
<td>0.35</td>
</tr>
<tr>
<td>Oct</td>
<td>11</td>
<td>60.4</td>
<td>2.03</td>
</tr>
<tr>
<td>Nov</td>
<td>7.5</td>
<td>67.8</td>
<td>3.96</td>
</tr>
<tr>
<td>Dec</td>
<td>5</td>
<td>62.1</td>
<td>4.23</td>
</tr>
<tr>
<td></td>
<td>10.2</td>
<td>616</td>
<td>2.51</td>
</tr>
<tr>
<td>Annual Average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage change</td>
<td>-</td>
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</tr>
</tbody>
</table>
The table above shows the results of the models for the years 2050 and 2080. The annual average changes from the baseline of TN are shown as well as monthly variation.

The result show a 14.3% decrease in N in response to a 2% increase in precipitation and a 2.5°C increase average annual in temperature for the 2050 simulation. The 2080 simulation showed a 20.7% decrease in N from the baseline, a 4.45% increase in precipitation and a 2.95°C increase in average annual temperature. In future climates, according to the UKCP09 projections, the pronounced rainfall maximum in winter combined with higher summer temperatures and evaporation will lead to high winter flows and low river flows, amplifying the existing flow regime.

![Figure 4: Graph showing average monthly temperature (°C) for the baseline, 2050 and 2080 time frames](image-url)
The decrease in precipitation was not massive in terms of changes to annual totals but there was significant alteration in terms of seasonal variability. As displayed in figure 5 winter rainfall increased while summer rainfall fell markedly. The decreases in precipitation led to increases in both annual water yield and surface runoff despite increases from the baseline in the winter months.
The temperature increase was fairly even across seasons in both mid and long-term simulations, with an average temperature increase of 2.95°C compared to the baseline in 2080.

Both the models outputs showed increase in TN annually. The monthly trend also has similarities. In both cases the overall TN to increases during the winter months and fall drastically during the summer months. January exhibits the greatest N concentration in all scenarios with TN values of 6.97 kg/ha as an average for January 2080. In every month although there are differences in magnitude of changes to TN between time frames, the direction of changes from the baseline are always identical.

5. Discussion

The results of this study suggest that nitrogen loading to the River Wensum will decrease in the Blackwater sub-catchment, under future climate conditions predicted by UKCP09 assuming a medium emissions scenario. Although there are bound to be several drivers of changes to nutrient loading it is clear that changes to precipitation, both intensity and duration, and temperature have significant impacts on the timing and magnitude of nitrogen transport. Several trend in the results can be explained.

5.1 Temporal variation

5.1.1 Increasing winter TN levels

The winter months of November, December and predominantly January all showed elevated TN concentration in both long-term and mid-term simulations. This corresponds with the expected trend as reported in the literature. The main driver of the higher nitrogen concentrations would seem to be the increase in winter precipitation. As explained previously, an increase in number and intensity of precipitation events brings an associated increase in surface runoff, N leaching and erosion all of which increase the loading of nitrogen to both surface water and groundwater (Jeppsen et al. 2009). Indeed Panagopoulos et al. (2011) attributed 40% of total annual N loss to processes in winter months and numerous other studies show that show that nitrate pollution is more pronounced during wet years, especially in intensively farmed catchments (Kaushal et al. 2008). Freezing soils in the winter months also have an impact as a change flow pathways from subsurface to surface flow dominant has potential to increase N transport (Panagopoulos et al. 2011). This would probably only be an relevant during the baseline
period as it was the only scenario that had several days with subzero temperatures, but could contribute in colder periods.

Another explanation for the high, and increasing, winter nitrogen loads is due to flushing nitrate from soils. A number of factors are at play in this process. The greater summer temperatures, combined with the decreased summer rainfall, results in less transport of nitrogen in the summer months also due to accelerated mineralization processes there is higher concentrations remaining in the soil before the winter. The more frequent winter rainfalls then wash out the nitrogen that has accumulated over the summer. This flushing process would help contribute to the high winter nitrogen levels. Whitehead et al., 2006; Wilby et al., 2006).

What makes these results slightly unusual is that in most studies that predict an increase in rainfall under future climate scenarios, an increase rather than a decrease in N loading is observed. (E.g. Bouraoui et al. 2002, Jeppsen et al. 2011, Tong et al. 2012, El-Khoury et al. 2015). The next section offers further suggestions on why this has not been the case in the Blackwater sub-catchment.

5.1.2. Decreasing summer TN levels

Whilst the increases in nitrogen levels in the winter is notable it is clear the severe decrease in N loading in the summer months outweighs the winter increase and is responsible for the overall fall in N concentration.

One might expect the lower summer rainfall and lower daily flow to lead to an increase in nitrogen concentration due less water available in the river to dilute the nitrates. (Whitehead et al 2009b). Especially in agricultural catchments in the lower course of a river, like the Wenusm, as here there is extra nitrate input from fertilizer application. Therefore, the reduced dilution effect in summer would be more pronounced. This scenario would explain why the baseline model had higher TN levels that both future scenarios. To understand why the TN levels fell in the summer compared to the baseline the effect of temperature on the rate of denitrification should be examined. The rate of denitrification has been shown to increase under certain climate change scenarios (Marshall and Rhandir 2008). Warmer summers can be linked to accelerated denitrification, and removal of N from the soil to the atmosphere, thereby reducing the potential source to waterbodies. A study focusing on the River Tamar by Whitehead et al. (2009b) found that by 2050 the denitrification effect began having a greater impact on nitrate concentration compared to the lack of dilution explaining, thus lowering the nitrate concentration. This shift therefore could explain why summer TN
levels decreased so drastically in the summer months after 2050 and highlight that while the rates of both processes are accelerated by increasing temperature, it would seem that the denitrification process increases at a faster rate relative to the impact caused by less dilution of nitrates. It has already been shown how marked the impact of this denitrification effect in low summer flows can be, in a study by Whitehead and Williams (1982) the River Thames lost up 70% of nitrate through the process. In agricultural catchments a typical amount of denitrification is expected to account for between 10-20% of fertilization rate (Neitsch et al 2005). A study on Connecticut River Watershed for the period 2060-2100 predicted an average annual decrease in nitrogen. The decrease was not only related to increased denitrification as described above but also reduced annual runoff due to increased evapotranspiration (Marshall and Randhir 2008).

An example of a response of the agricultural ecosystem to climate change that has indirect effects on the flows of nitrogen to freshwater is the increased growth rate of crops (Patil et al. 2010). An increase in CO2 and temperature is associated with processes that lead to more N efficient crops, which in turn means reduced transpiration and increases N uptake and thus removal from the soil (Jeppesen et al. 2011). This therefore leads to a decreased risk of N leaching. Since the highest rates of plant growth occur during the growing season in the spring and summer this would agree with the lower predicted N levels during these periods in the Blackwater sub-catchment. Indeed it is another variable that has been shown to offset an increase in N concentration caused by to increased rainfall (Patil et al. 2010). This phenomenon would also account for the seasonal variation that shows August is consistently the month with the lowest N concentration. Faster crop growth in the previous months would have taken up and depleted the nutrients in the soil profile (Bouraioui et al.2002). Increases in the rates of decomposition and mineralization also occur with increases in temperature (Ahmadi et al. 2014, Fan and Shibata 2015). These alter the ratio of nitrogen species as mineralization is shown to decrease the amount of organic nitrogen in the soil but is also linked with increasing nitrate levels. (Wilby et al. 2006, Whitehead et al. 2009, Ahmadi et al. 2014)
5.3 Limitations

5.3.1 Data limitations
In every modelling study there will always be inherent epistemic uncertainty involved in the input data (Apel et al. 2009). In this case there can always be finer elevation grids or improved delineations of land use, improved resolution of flow or nitrate measurements; all of which would improve the precision of the model. There must be some trade of in terms of accuracy to allow time to carry out the study with the available computational power.

Another inherent flaw with the data is that the results obtained will only be accurate under climate projection and emissions scenario chosen, in this case the central estimates of the UKCP09 climate projection and A1B emissions scenario. A broad spectrum of future climate projections would ensure the best results, (Nakicenovic et al. 2000) however there were time limitations to consider in this study.

5.3.2 Assumptions within model
As with all modelling studies these results represent a simplification of the reality of a highly complex catchment system (El-Khoury et al. 2015, Whitehead et al. 2015). In this study the incorporation of climate change was simplified down to two parameters; precipitation and temperature. In reality solar radiation, humidity and a range of other variables would also have had an impact (El-Khoury et al. 2015).

Simplifying of the climate change applied to the model because only precipitation and temperature parameters where changed to simulate climate change impacts. In reality both solar radiation and humidity parameters would have also been impacted (El-Khoury et al. 2015). Prediction of regional precipitation is notoriously difficult, especially intensity, and represents a major uncertainty in this study as storm events represent one of the major controls on nitrogen mobilization (Rozemeijer and Broers 2007, Jepsen et al. 2011). Thus, any change in future precipitation could lead to rather different results, especially as change to rainfall tend to be amplified in runoff projections (Chiew and McMhan 2002). Additionally SWAT only considers certain variables that may be impacted by climate, certain biological and ecological variables are neglected in order to focus on physical and chemical changes.

5.3.3. Variables not considered
Land use change is one of the major variables that is likely to change with climate, either directly or indirectly. For example the diversification or expansion of crops is likely to see warm season crops such as maize and sunflower encroach on areas currently used for small-grained cereals, etc. (Olsen
and Bindi 2002). This in itself will impact nitrogen dynamics but the larger change will come from how farmers change their farming practices in response to climate change. Changing management practices not taken into account including those that would have been capable of being modelled by SWAT, such as planting, tillage, irrigation and fertilization practices (Panagopoulos et al. 2011). Changes to the duration of farming or timings of fertilizer application will all have major impacts on the transfer of nutrients to waterbodies. Increased period of bare soil in Autumn will occur if crops are harvested earlier and winter crop planted later, increase the risk of N loss especially under wetter climates (Olsen et al. 2004, Patil et al. 2004), but were out of the scope of this study. This is justified due the complexity that changes in land use introduce; There are direct human changes which impact biological, chemical and physical process as well as possible subsequent feedbacks involved with these human alterations (Murdoch et al.2000).

6. Conclusion

Climate change can potentially have important consequences on regional water resources. This study evaluates the impacts of UKCP09 climate change predictions on nitrogen dynamics in the Blackwater sub-catchment of the River Wensum catchment, Norwich. Evaluation at this regional scale is important to help understand changes in hydrology (Marshal and Randhir 2008).

Although this study is based on hypothetical scenarios that are far from certain, changes in runoff and nutrient loading are shown to be a distinct possibility in the future that will require a management response (Tong et al. 2007). The results although insight to be gained concerning the relative importance of different processes involved in the nitrogen cycle under different climate pressures. For example, in this case increasing temperatures and increasing seasonality of rainfall towards a pronounced winter maxima seem to increase nitrogen loss through plant uptake and denitrification so that it outweighs the nitrate increase through the processes of surface runoff and leaching. The overall 14.3% and 20.7% decrease in total nitrogen loading in 2050 and 2080 respectively in the Blackwater sub-catchment is attributed the processes impacted by increased temperature more so than increased precipitation.

In summary, climate change had significant impacts on water quantity and quality in the Blackwater sub catchment of the River Wensum. The simulated impacts on nitrogen transport varied between seasons and time frames and could have important implications on future water management in the Wensum Catchment.
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