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Green infrastructure and climate change impacts on the flows and water quality of urban catchments: Salmons Brook and Pymmes Brook in north-east London

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ABSTRACT

Poor water quality is a widespread issue in urban rivers and streams in London. Localised pollution can have impacts on local communities, from health issues to environmental degradation and restricted recreational use of water. The Salmons and Pymmes Brooks, located in the London Borough of Enfield, flow into the River Lee, and in this paper, the impacts of misconnected sewers, urban runoff and atmospheric pollution have been evaluated. The first step towards finding a sustainable and effective solution to these issues is to identify sources and paths of pollutants and to understand their cycle through catchments and rivers. The INCA water quality model has been applied to the Salmons and Pymmes urban catchments in north-east London, with the aim of providing local communities and community action groups such as Thames21 with a tool they can use to assess the water quality issue. INCA is a process-based, dynamic flow and quality model, and so it can account for daily changes in temperature, flow, water velocity and residence time that all affect reaction kinetics and hence chemical flux. As INCA is process-based, a set of mitigation strategies have been evaluated including constructed wetland across the catchment to assess pollution control. The constructed wetlands can make a significant difference reducing sediment transport and improving nutrient control for nitrogen and phosphorus. The results of this paper show that a substantial reduction in nitrate, ammonium and phosphorus concentrations can be achieved if a proper catchment-scale wetland implementation strategy is put in place. Furthermore, the paper shows how the nutrient reduction efficiency of the wetlands should not be affected by climate change.

Key words: catchment management, green infrastructure, modelling, urban rivers, water quality, wetlands

HIGHLIGHTS

- Modelling urban flows and water quality in London streams is demonstrated.
- Impacts of pollution, deposition and urban runoff are illustrated under future climate change.
- The paper uses a dynamic process-based water quality model to assess impacts of wetlands.
- Constructed wetlands can make a significant difference improving nutrient control.
- Mitigation measures significantly reduce nitrate, ammonium and phosphorus.

GRAPHICAL ABSTRACT

1. INTRODUCTION

Poor water quality in urban streams and rivers is a major global issue, with localised pollution causing severe impacts on local communities creating health problems, limited recreational use of water and reduced livelihoods (e.g., fisheries) resulting from degraded water systems. Pollution arises from urban discharges, often via misconnected and mismanaged sewerage systems, runoff from roads and hard surfaces, as well as diffuse runoff from industrial sites and contaminated soils.

In many cities, such as London, there is also an old infrastructure system with misconnected sewers and urban sources of pollution from dense housing, road runoff and atmospheric deposition of pollutants (Bell & Paskins 2013). In urban areas served by sewerage consisting of separate 'clean' surface rainwater and 'dirty' sewer pipe systems, it is not uncommon for misconnections to be made either accidentally or deliberately, whereby the sewerage effluent discharge is connected to the 'clean' water drainage (Ellis & Butler 2015; Johnstone *et al.* 2019) and discharged into local streams. Other potential illicit wastewater sources to the surface water network include septic tanks, spillages, vehicle wash water and contaminated groundwater (Ellis & Butler 2015).

Such misconnections have become a significant water management issue in London, with the national environmental regulatory agencies estimating that as many as one in five properties may have misconnections discharging wastewater effluent directly to receiving waters via separate sewer systems. National estimates of the total numbers of properties in the UK possessing offending misconnections vary between 130,000 and 1.25 million and the illicit wastewater discharges from misconnected properties can directly impact on receiving water quality potentially prejudicing the achievement of relevant environmental quality standards (Revitt & Ellis 2016). Growing population and urbanisation are likely to exacerbate these impacts in the future (Vorosmarty *et al.* 2000; McDonald *et al.* 2011, 2014).

One of the possible strategies to be employed for mitigating water quality issues in urban rivers is catchment-based green infrastructure (Everard & Moggridge 2012; Gaffin *et al.* 2012; Demuzere *et al.* 2014). Green infrastructure has the potential of reducing water quality impacts of urbanisation and at the same time providing solutions that are sustainable and resilient to climate change (Tzoulas *et al.* 2007; Foster *et al.* 2011). Green infrastructure can provide multiple benefits to an environment including increased biodiversity, reduced flood risk, improved water quality and social cohesion (Wright & Wheelwright

2017). Applying nature-based measures is an alternative solution for environmental improvements. Green infrastructure can take a variety of forms, for example, constructed wetlands, green roofs or sustainable drainage systems (SuDS). Also, the conversion of arable land into woodland and pasture can relieve the nutrient loads on streams and also mitigate flood peaks. Such mitigation measures can either be used as a retrofitting strategy, so that wetlands are constructed in an already urbanised area to slow flows, reduce sediments and reduce nutrient loads, or as an urban planning tool for new urbanisations. In this paper, the focus is on the former of the two options.

Superimposed on the urban pollution is the prospect of a changing climate, altering rainfall events, resulting in enhanced flooding or extended periods of drought (Bussi & Whitehead 2020). This is likely to worsen pollution incidents alongside the expected economic growth of cities and the associated increase in population. In addition, relationships between the natural environment and urban water infrastructure are highly complex, comprising several elements – from hydrological to social and political – and their respective stakeholders. Typically, researchers, practitioners and water agencies need to identify sources and paths of pollutants and to understand their transport and transformation through catchments and rivers in order to find a sustainable and effective solution to these issues. Water quality models are often used by water companies, public bodies and practitioners as a tool to assess this issue and have the potential to be used by community groups to understand the complex interactions (which is just beginning to be explored).

In this study, the Integrated Catchments (INCA) water quality model was implemented for two urban catchments located in north-east London (Figure 1), with the aim of providing local communities with a tool they can use to assess the water quality issue, supported by environmental NGOs (The Rivers Trust; Thames21, Landström *et al.* 2019). The urban catchment

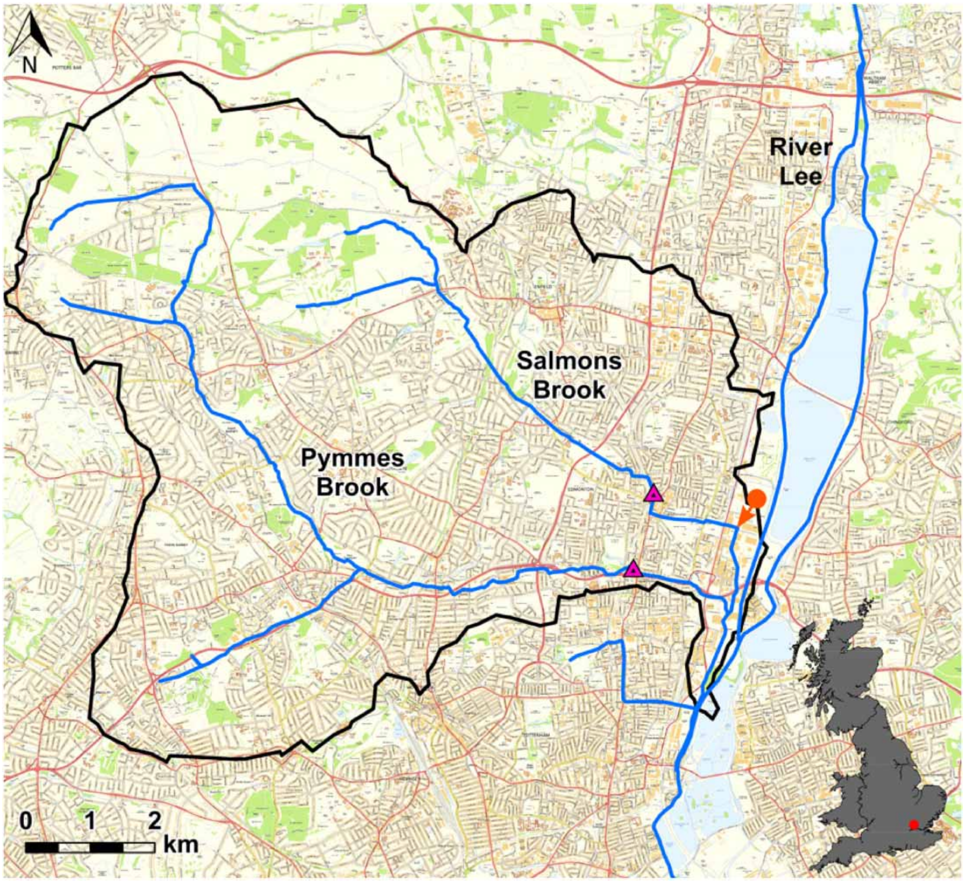

Figure 1 | Location of the catchments of study. Catchment boundaries are indicated in black and the main river network in blue. The two pink triangles at the outflow of the rivers show the locations of flow gauging stations and the orange arrow shows the discharge point of Deephams STWs. Contains Ordnance Survey data © Crown Copyright and database right 2021. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2022.013.

includes the Salmons and Pymmes Brooks, located in the London Boroughs of Enfield, Haringey and Barnet, which flow into the River Lee. The Salmons Brook is the recipient of effluent wastewater from one of the largest sewage treatment works (STW) in London, the Deephams STW, which treats wastewater from approximately a one million-population equivalent. These catchments show heavy signs of pollution, mainly due to road runoff, air pollution, pipe misconnections from properties and occasionally combined sewer overflows.

2. STUDY AREA

The Salmons and Pymmes catchments, located in north-east London, within the borough of Enfield, both drain into the River Lee (Figure 1). The lower Salmons Brook, just above its confluence with the River Lee, is the recipient of effluent from Deephams STW. The size of the catchment is 41.37 km^2 for the Pymmes Brook and 23.58 km^2 for the Salmons Brook. The area occupied by the two catchments is rather flat, with elevations ranging from 10 to 130 m above sea level.

The catchments are heavily urbanised, particularly the southern part of the area. The central part dominated by sub-urban areas, and the northern areas are covered by arable land. The population density (CIESIN 2016) varies between 300 inhabitants/km^2 in the upper Salmons Brook and 11,500 inhabitants/km^2 in the lower Pymmes Brook. The total population in 2010 was around 320,000, with an average density slightly below 2,000 inhabitants/km^2.

3. METHODOLOGY

3.1. INCA model

INCA is a process-based model which simulates the main processes related to rainfall–runoff transformation and the cycle and fate of several compounds, such as nitrate, ammonium and phosphorus. Several publications can be found in the literature, regarding both the model conceptualisation and the model application. The main papers describing the model structure are Whitehead *et al.* (1998a, 1998b), who presented the INCA-N model structure, Wade *et al.* (2002a), who described some modifications to the INCA-N structure, Wade *et al.* (2002b), who presented the INCA-P model structure and Lázár *et al.* (2010), who described the INCA-Sediment model structure.

The hydrological and water quality sub-models of INCA have been applied to several basins around the world (Bussi *et al.* 2021a, 2021b; Whitehead *et al.* 2021b) and in England (Crossman *et al.* 2021), and, in particular, to the River Thames catchment (Jin *et al.* 2012; Crossman *et al.* 2013; Whitehead *et al.* 2013, 2016, 2021a; Bussi *et al.* 2016a, 2016b, 2017; Lu *et al.* 2016; Nizzetto *et al.* 2016) and the River Lee catchment (Flynn *et al.* 2002; Snook & Whitehead 2004). The inputs to INCA are daily time series of precipitation, temperature, hydrologically effective rainfall and soil moisture deficit (SMD). The latter two are estimated using another semi-distributed hydrological model, called PERSiST (Futter *et al.* 2014). PERSiST is a semi-distributed catchment-scale rainfall–runoff model which is specifically designed to provide input series for the INCA family of models. It is based on a user-specified number of linear reservoirs which can be used to represent different hydrological processes, such as snowmelt, direct runoff generation, soil storage, aquifer storage and stream network movement. The description of its application to the River Thames can be found in Futter *et al.* (2014).

The nitrogen sub-model of INCA (Whitehead *et al.* 1998a, 1998b; Wade *et al.* 2002a) reproduces the cycle of nitrogen from its main sources (atmospheric deposition, fertilisers, wastewater, etc.) to the river. Two forms of nitrogen are considered as state variables: nitrate and ammonium. The most important soil processes are included, such as denitrification, nitrification, immobilisation, mineralisation and leaching towards the aquifer. Nitrification and denitrification processes in the streams are also taken into account. The phosphorus sub-model of INCA (Wade *et al.* 2002b) incorporates the main sources of phosphorus, both diffuse (fertilisers) and point (wastewater), as well as the main processes involving phosphorus, such as sorption/desorption. The phosphorus sub-model of INCA also includes a sediment sub-model, which computes the detachment of soil particles from the hillslopes and their transport towards the catchment outlet. It is important to realise that INCA is a process-based model and that hydrological and bio-chemical reactions are modelled by a set of differential equations. Each equation has a set of reaction rates, such as the denitrification rate or the nitrification rates, and these are all temperature dependant so that day-to-day changes in mass chemical transfer will occur. Other factors that affect the chemical response are the residence time and INCA simulates the flows, velocities and residence times taking account of reach (or wetland) characteristics. This means that the chemical transfers will also depend on residence times and these will also vary on a day-to-day basis over the whole period of the simulation run.

3.2. Sources of information

The INCA model requires precipitation and temperature data as driving meteorological inputs, as well as hydrological effective rainfall (HER) and SMD time series. Precipitation and temperature data were derived from UK Met Office station measurements. Several stations exist within the Lee catchment, measuring daily precipitation, minimum temperature and maximum temperature among other variables. The mean temperature was calculated as the average between minimum and maximum temperatures. The Met Office station meteorological data were obtained from the Centre for Environmental Data Analysis (CEDA) Archive.

Other parameters of the INCA model were obtained from the Ordnance Survey digital elevation model at a 50 m resolution, the MERIT-Hydro digital elevation model (Yamazaki *et al.* 2019) and the Centre for Ecology and Hydrology's digital river network of Great Britain (Moore *et al.* 2000), which were used to identify the river network and the catchment extension. The UK 2007 land-cover map (Smith *et al.* 2007) was used to identify fractions of land uses in each catchment, and population density data from the Gridded Population of the World dataset (CIESIN 2016) was used to estimate effluent discharges from misconnections.

Observations of flows and nutrient concentrations are required in order to adjust the INCA model parameters to reproduce correctly the system (i.e., for calibration and validation purposes). Water discharge data were retrieved from the National River Flow Archive (NRFA). Two active river flow gauging stations are located in the study catchments, one close to the outlet of the Salmons Brook and another close to the outlet of the Pymmes Brook. Data on the concentration of nutrients in rivers, in particular, nitrates (NO_3), ammonium (NH_4), orthophosphate (PO_4) and soluble reactive phosphorus (SRP), were obtained from the Water Quality Data Archive of the Environment Agency, again for two stations located close to the outlet of the two rivers.

Data on the efficiency of constructed wetlands for nutrient removal were collected by the organisation Thames21 and its volunteers (Gilbert 2016a, 2016b). In particular, a sampling campaign was carried out in 2015 to obtain measurements of nitrate, ammonium and phosphorus concentration upstream and downstream of four wetlands constructed in 2014 and 2015 (Firs Farm and Pymmes Park, implemented on small tributaries of the Pymmes Brook; Groveland Park and Glenbrook, implemented on small tributaries of the Salmons Brook). For the Salmons Brook, samples were collected approximately twice monthly between April and November 2015 (9–12 occasions) from the same sampling locations in each of the constructed wetlands. For the Pymmes Brooks, water samples were collected once per month between January and December 2016 (total of 12 samples). In particular, the Thames21 study found reductions in nitrate concentration between 28 and 67%, reductions in ammonium concentration between 66 and 80% and reductions in orthophosphate concentration between 33 and 72%. These reductions are from average annual concentrations of 3.8 mg/L of N, 0.7 mg/L of ammonia and 0.6 mg/L of phosphorous.

A list of constructed and potential future wetlands was compiled based on information from local communities (Table 1).

3.3. Modelling strategy – catchment set-up and climate change

For the baseline set-up, the two catchments were divided into sub-catchments based on the location of data stations, the presence of relevant tributaries, the extent of the sub-catchments and the length of the river reach. The Salmons Brook was divided into 16 sub-catchments and the Pymmes Brook into 12 sub-catchments. For each sub-catchment, the land-use map (Smith *et al.* 2007) was reclassified into six categories: Woodland; Grassland; Arable; Urban; Sub-urban and Water. Significant fractions of arable land only exist in the headwaters of the Salmons Brook (around 15% in the upstream part of the catchment). Grassland fractions gradually decrease from 30% in the headwaters to almost none in the downstream part of the two catchments. Woodland has normally rather small fractions, typically linked to urban forests and parks. Urban and sub-urban fractions are usually predominant, and increase from headwaters towards downstream, with the most downstream parts of the catchments showing up to 100% of urban and sub-urban land use. Given the limited relevance of diffuse sources from agriculture, with only 15% of the uppermost catchment in the Salmons Brook, misconnections and outfalls are the main sources of nutrients in the catchments (at least upstream of the wastewater flow inlet of Deephams (see Figure 1), and these were introduced in the model as fixed flows proportional to the population living in each sub-catchment (CIESIN 2016), with fixed nutrient concentrations. Both the 'misconnected' flow rate per inhabitant (i.e., the amount of water per day per person discharged into the river network instead of being collected and directed to the nearest wastewater treatment plant) and its concentration of nutrients were calibrated based on observed nutrient concentration data. In particular, initial values of raw effluent concentrations were taken from the literature (e.g., from Pescod 2013) and used in the INCA parametrisation, and

Table 1 | Location of existing constructed wetlands and sites for planned wetlands

ID	Location	Year of construction or planned	ID	Location	Year of construction or planned
1	Glenbrook	2014	18	Ferny Hill	Planned
2	Grovelands	2014	19	Firs Farm Wetland Extension	Planned
3	Firs Farm	2015	20	Grange Park	Planned
4	Pymmes Park	2015	21	Green Brook	Planned
5	Bury Lodge	2016	22	Grovelands Lake	Planned
6	Town Park	2018	23	Hazelbury School	Planned
7	Broomfield Park	2019	24	Hazelwood Sports Ground	Planned
8	Angel Gardens	Planned	25	Kenninghall Open Space	Planned
9	Arnos Park	Planned	26	King George's Gardens	Planned
10	Boxers Lake	Planned	27	Monken Hadley Common	Planned
11	Bramley Sports Ground	Planned	28	Oakwood Park	Planned
12	Brooks Park	Planned	29	Riverside Park	Planned
13	Bush Hill Park Golf Club	Planned	30	Tatem Park	Planned
14	Bush Hill Gardens	Planned	31	Tike Kiln Lane	Planned
15	Cheyne Walk Open Space	Planned	32	Wilbury Way Open Space	Planned
16	Churchfield Recreation Ground	Planned	33	Edmonton Green	Planned
17	Enfield Golf Club	Planned	34	Edmonton County School	Planned

then adjusted together with other model parameters to obtain a better fit between observed and simulated concentrations at the outlet.

The INCA models were calibrated over the time period 1/1/2010–31/12/2012, with a daily time step, and validated over the time period 1/1/2013–31/12/2018. The model parameters were adjusted to reproduce observed values of hydrological and water quality variables, using a Monte Carlo approach in which the parameters are varied randomly within a range of feasibility, and the model performance is evaluated based on the monthly Kling and Gupta efficiency (KGE) goodness-of-fit index (Gupta *et al.* 2009). The same calibration strategy has been employed successfully with the INCA model in previous applications (Bussi & Whitehead 2020; Crossman *et al.* 2021).

The baseline set-up does not account for the impact of wetlands on the water quality of the Salmons and Pymmes Brooks. While it is true that wetlands were constructed in 2014 (Gilbert 2016a, 2016b), these wetlands drain a very small portion of the total catchment (around 1 km^2), and their effect is hardly noticeable at the catchment outlet, where reference data for calibration are available. Thus, for the baseline set-up, no potential mitigating effect of wetland or green infrastructure was accounted for.

To represent the impact of wetlands on the water quality (as used in the scenario analysis described below), the model parameters were adjusted to reproduce the nutrient removal efficiency calculated by Thames21 (Gilbert 2016a, 2016b). Several parameters in the model control the removal rate, such as denitrification and nitrification rates for ammonia and nitrate and P adsorption and sedimentation, with many rates being kinetic, then temperature plays a key role, increasing daily rates as daily temperature increases. Also, water velocity and residence times are crucial as these determine the length of the contact time with the sediments in the wetlands and the plants. The longer the residence time, the more time there is for a biochemical reaction to occur. Velocity and residences times can also be changed via the velocity flow equation parameters. This was achieved in INCA by reducing the value of the key velocity parameter in the reaches (Whitehead *et al.* 1998a, 1998b), thereby increasing the residence time of the water. This extra residence time allows more time for kinetic processes to occur such as nitrification of ammonia and denitrification of nitrate, as well as facilitating sediment deposition and enhancing phosphorous adsorption.

By introducing wetlands (and their nutrient removal effect) into the INCA model, scenarios of wetland implementation could be created, and their overall impact on the nutrient load at the catchment outlet analysed. The resulting model and scenarios provide a tool for the design of a multi-faceted nutrient removal strategy at the catchment level, in which wetlands and, in general, green infrastructure can have a significant role in mitigating pollution. In this paper, two theoretical scenarios were considered (Figure 2):

A. *Existing and planned wetlands*: In this scenario, wetlands are implemented in all the locations of Table 1, i.e., where actual wetlands exist and where they might potentially be constructed in the future. Such wetlands drain 72% of the total catchment. All the wetlands are assumed to have the same average nutrient removal efficiency as the ones already implemented in 2014 (Gilbert 2016a, 2016b).
B. *Wetlands on all the sub-catchments of the Salmons and Pymmes Brooks*: In this scenario, wetlands are implemented in all reaches. This is a theoretical scenario, in which the wetlands do not correspond to actual existing or planned wetlands, but are just hypothetical wetlands. The aim of this scenario is to assess the effect of a spatially distributed system of nutrient-removing wetlands and its benefits, compared to the benefits of simply implementing the wetlands that are planned at the moment. All the wetlands are assumed to have the same average nutrient removal efficiency as the ones already implemented in 2014 (Gilbert 2016a, 2016b).

The results of the model under the two scenarios are compared to the baseline, and their efficiency in reducing nutrient loads at the catchment outlet is evaluated in this paper.

The effect of future climate change was modelled using the UKCP18 climate projection dataset (Lowe *et al.* 2018). UKCP18 provides probabilistic projections of climate change at a range of spatial and temporal scales over the 21st century, for a number of future greenhouse gas concentration pathways. Depending on geographical extent, and spatial and temporal

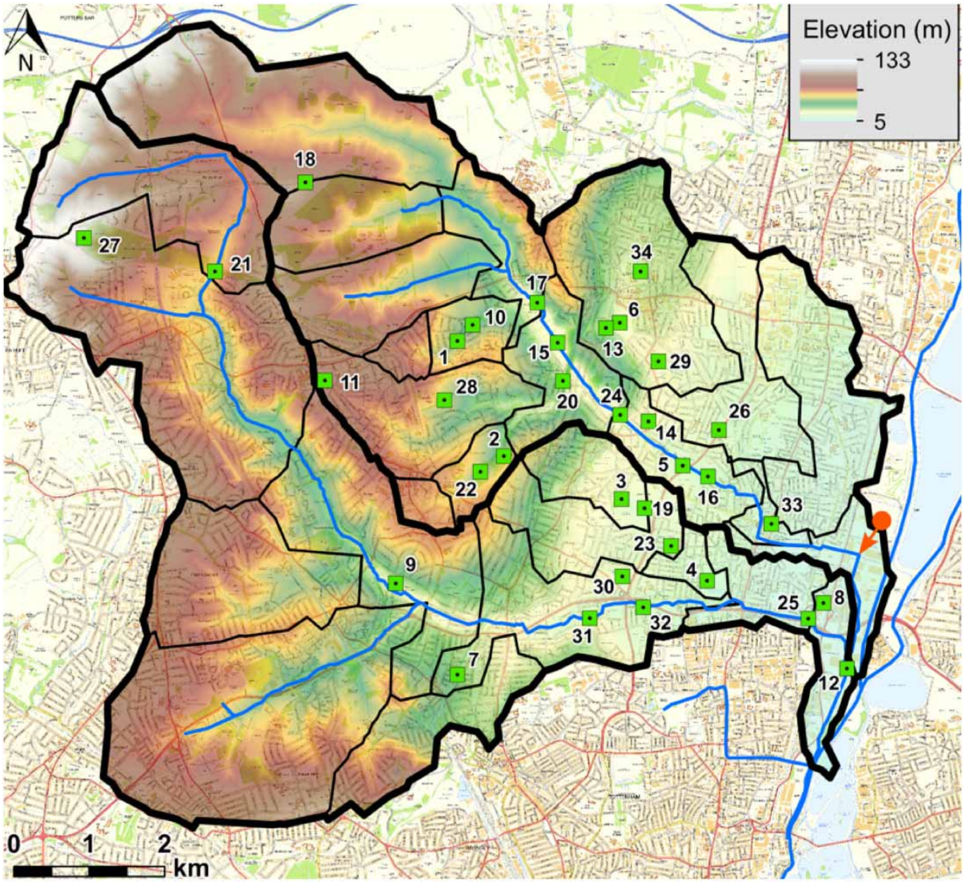

Figure 2 | Wetland scenarios. Wetlands are implemented in the hatched sub-catchments in Scenario A and in all sub-catchments in Scenario B. The digital terrain map illustrates the connectivity between the sub-catchments. The red arrow shows the location of Deepens STWs. The green squares denote the locations of actual or planned wetlands (see Table 1). Contains Ordnance Survey data © Crown Copyright and database right 2021. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2022.013.

resolution, projections are available for different future time slices compared to a historical baseline, or as continuous time series. In this study, we generated time series of future daily precipitation and temperature by perturbing the historical (2010–2018) daily time series of these variables. This was done using the gridded 25 km probabilistic projections of monthly precipitation and temperature anomalies, which describe changes between two 30-year time slices; in our case 1980–2009 and 2040–2069 (the '2050s'). The 25 m grid is a significant improvement on previous climate datasets, so this has enabled good coverage of the two catchments. One hundred sets of monthly anomalies were randomly sampled from the 3,000-member ensemble for the 25 km grid square containing the catchment, and for two representative greenhouse gas concentration pathways (RCPs): RCP4.5 and RCP6.0 (IPCC 2014). Figure 3 shows the median and ranges of variation of the two climate change projections used for precipitation and temperature. These show significant variations at the 90 percentile levels, with temperatures rising by above 3 °C and precipitation falling by 20–40% but with some significant summer storms. Each of these 100 pairs of future precipitation and temperature time series was applied to the model to obtain an ensemble of nitrate, ammonium and phosphorus concentration time series. These simulations were repeated for the baseline wetland scenarios and the two wetland scenarios A and B.

4. RESULTS

4.1. Model calibration

The model was calibrated using a Monte Carlo approach, in which multiple parameter sets were tested and the best performing model was retained and used throughout the study. The Monte Carlo calibration/validation procedure is very similar to the one employed in other INCA applications, as illustrated in Bussi *et al.* (2021a, 2021b), Bussi & Whitehead (2020), Crossman *et al.* (2021) and Whitehead *et al.* (2021b). The feasible ranges of the parameter values were taken from previous studies; Bussi *et al.* (2021a) report the feasible ranges of the hydrological and sediment parameters of the model, while Crossman *et al.* (2021) report values for phosphorus parameters. The prior distribution used in this calibration was the uniform distribution for all the parameters. The best performing set was chosen based on the performances of the model in terms of goodness-of-fit, using as a metric of the KGS index on daily discharge, nitrate concentration and phosphorus concentration.

The results of the best model are shown in Table 2, where the daily KGE (for flow) and the monthly KGE (for water quality variables) for the Pymmes and Salmons Brooks are listed. Given the intermittency of the water quality observations, no daily KGE could be computed on the water quality variables. The results show a very good fit for flow in both rivers. In terms of water quality, the results are also good in general for both nitrate and phosphorus, while the model underestimates ammonium concentrations, especially in the Salmons Brook, as can also be seen in Figure 4. However, ammonia data is notoriously unreliable as levels are generally very low and suffer from transport from the field sites to the laboratory.

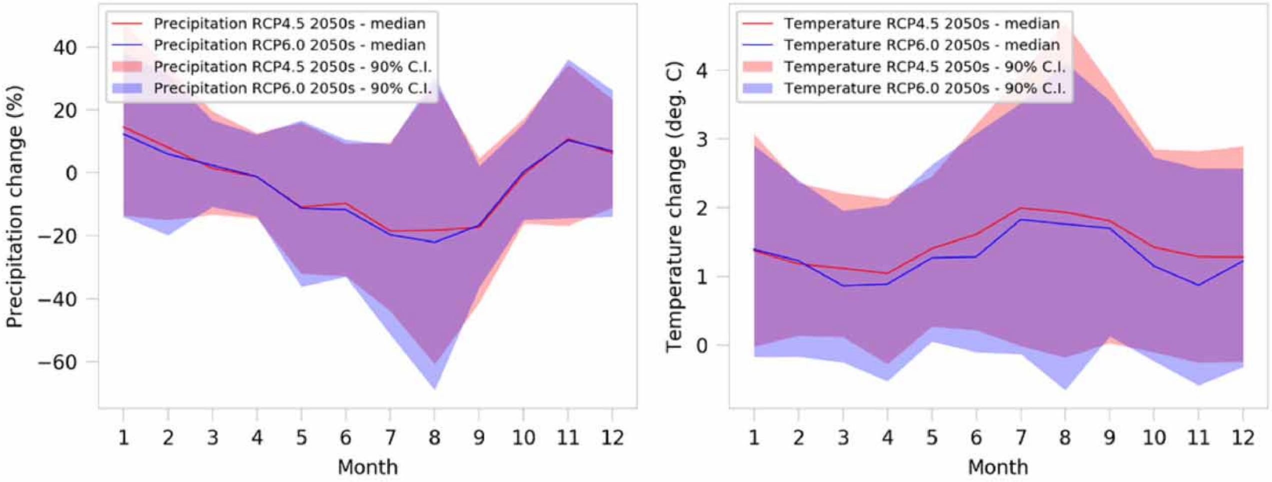

Figure 3 | Projected changes (median and confidence interval – C.I.) for the Salmons Brook and Pymmes Brook catchments for the 2050s under RCP4.5 and RCP6.0 scenarios, according to UKCP18 (Lowe *et al.* 2018).

Table 2 | Model goodness-of-fit index (Gupta *et al.* 2009)

		Time period 2010–2021	Time period 2010–2021
Variable	**Index**	**Pymmes Brook**	**Salmons Brook**
Flow	Daily KGE	0.78	0.71
Nitrate	Monthly KGE	0.44	0.38
Phosphorus	Monthly KGE	0.53	0.69

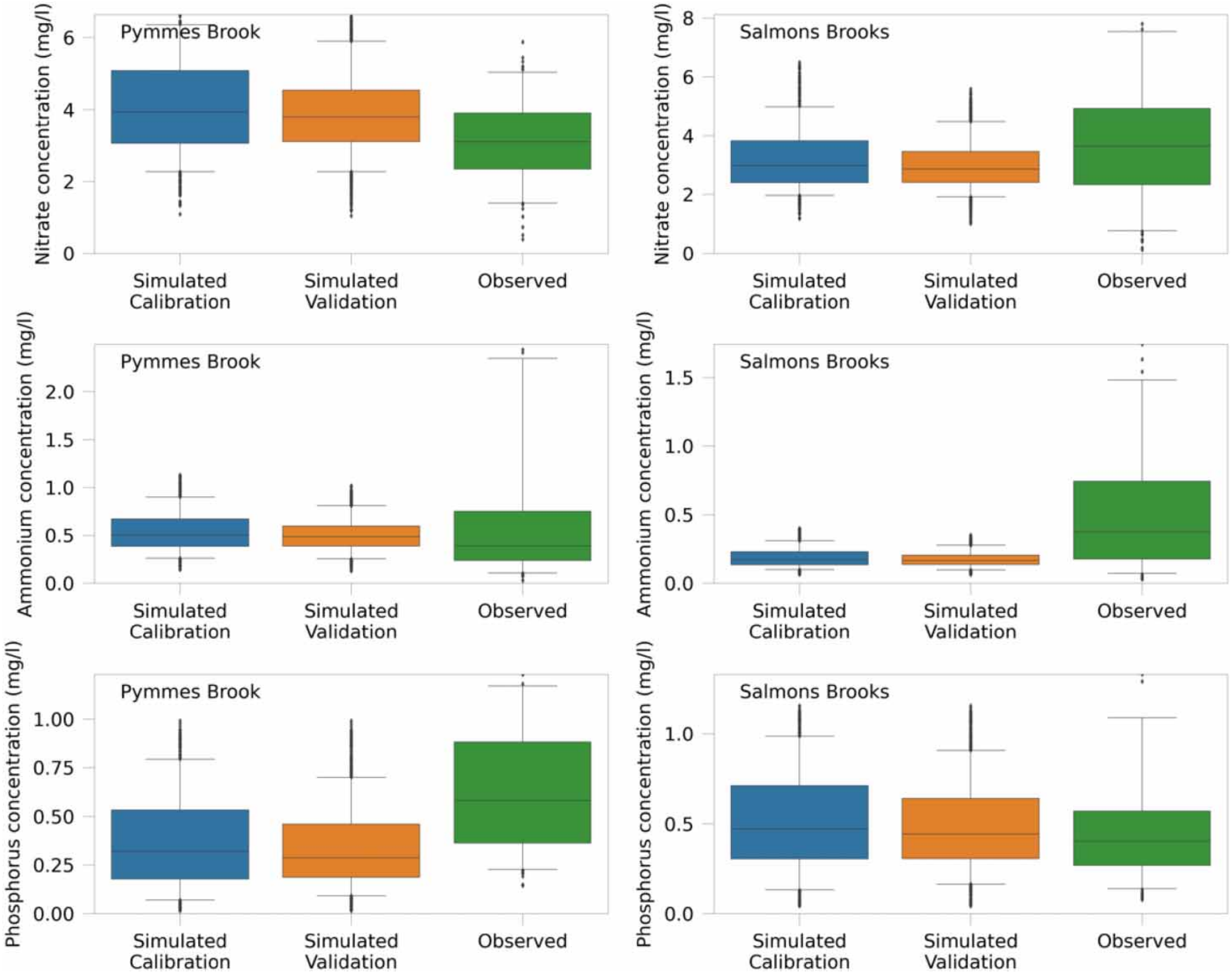

Figure 4 | Model calibration and validation (water quality).

4.2. Wetland nutrient removal scenarios under baseline climate

After calibration/validation of the INCA model against observations of flow and nutrient concentrations at the catchment outlets, the following step of the modelling process was to reproduce the nutrient removal efficiency of existing wetlands in the two catchments. As described above, four existing wetlands were used as reference (Firs Farm and Pymmes Park in the Pymmes Brook catchment; Groveland Park and Glenbrook in the Salmons Brook catchment). The velocity parameter in the INCA flow routing equation (Whitehead *et al.* 1998b) was adjusted to enhance the residence time, as explained above, and hence achieve a nitrogen removal efficiency similar to the observed one (Gilbert 2016a), while the sorption coefficient and the sorption scaling factor for the water column (Wade *et al.* 2002b) were adjusted to obtain a phosphorus removal efficiency similar to that observed. The results are shown in Figure 5, where the ranges of variation of nitrate, ammonium and phosphorus concentrations are shown for the model reach corresponding to the four wetlands, upstream and downstream the wetlands.

Figure 5 shows that the range of reductions is similar to the one reported by the monitoring programme carried out in 2014 (Gilbert 2016a). For example, the average nitrate concentration reduction ranges between 66 and 69%, reducing the average nitrate concentration from 9.7 to 3.3 mg/l at Firs Farm (#3 in Figure 2), from 8.6 to 2.7 mg/l at Pymmes Park (#4 in Figure 2), from 4.0 to 1.3 mg/l at Groveland Park (#2 in Figure 2) and from 4.8 to 1.5 mg/l at Glenbrook (#1 in Figure 2). Average phosphorus concentrations were reduced by 28 to 40%, i.e., from 0.46 to 0.33 mg/l at Firs Farm, from 0.4 to 0.24 mg/l at Pymmes Park, from 0.83 to 0.58 mg/l at Groveland Park and from 0.7 to 0.45 mg/l at Glenbrook.

The model parameters adjusted to account for the impact of wetlands on nutrient concentrations were used to set up the scenarios ‘A’ and ‘B’ described above, i.e., (A) wetlands on all the locations of existing and potential future wetlands; (B) wetlands on all the reaches of the Salmons and Pymmes Brooks. Their efficiency in reducing nutrient concentrations was assessed at the catchment outlets. Figure 6 represents the range of variation of the nutrient concentrations under the ‘baseline’ scenario (i.e., current wetlands) and the A (existing and planned wetlands) and B (wetlands on all reaches) scenarios. It can be seen that both scenarios have a very good nitrate reduction efficiency (65 and 67% nitrate reduction on the Pymmes Brooks; 73 and 74% nitrate reduction on the Salmons Brooks). The ammonium reduction efficiency is similar for both

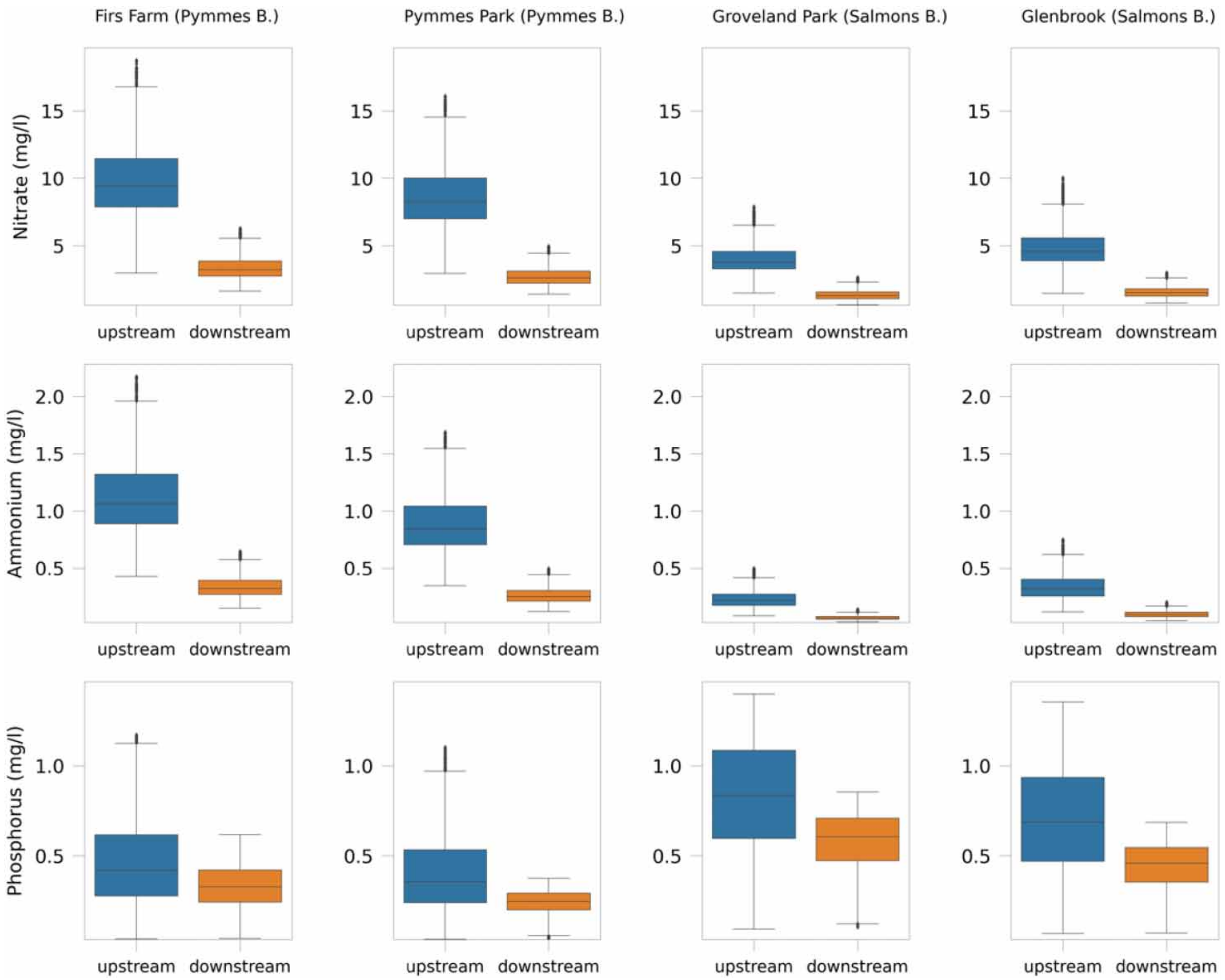

Figure 5 | Removal efficiency at the four locations of the existing wetlands (Firs Farm and Pymmes Park, in the Pymmes Brook catchment; Groveland Park and Glenbrook, in the Salmons Brook catchment).

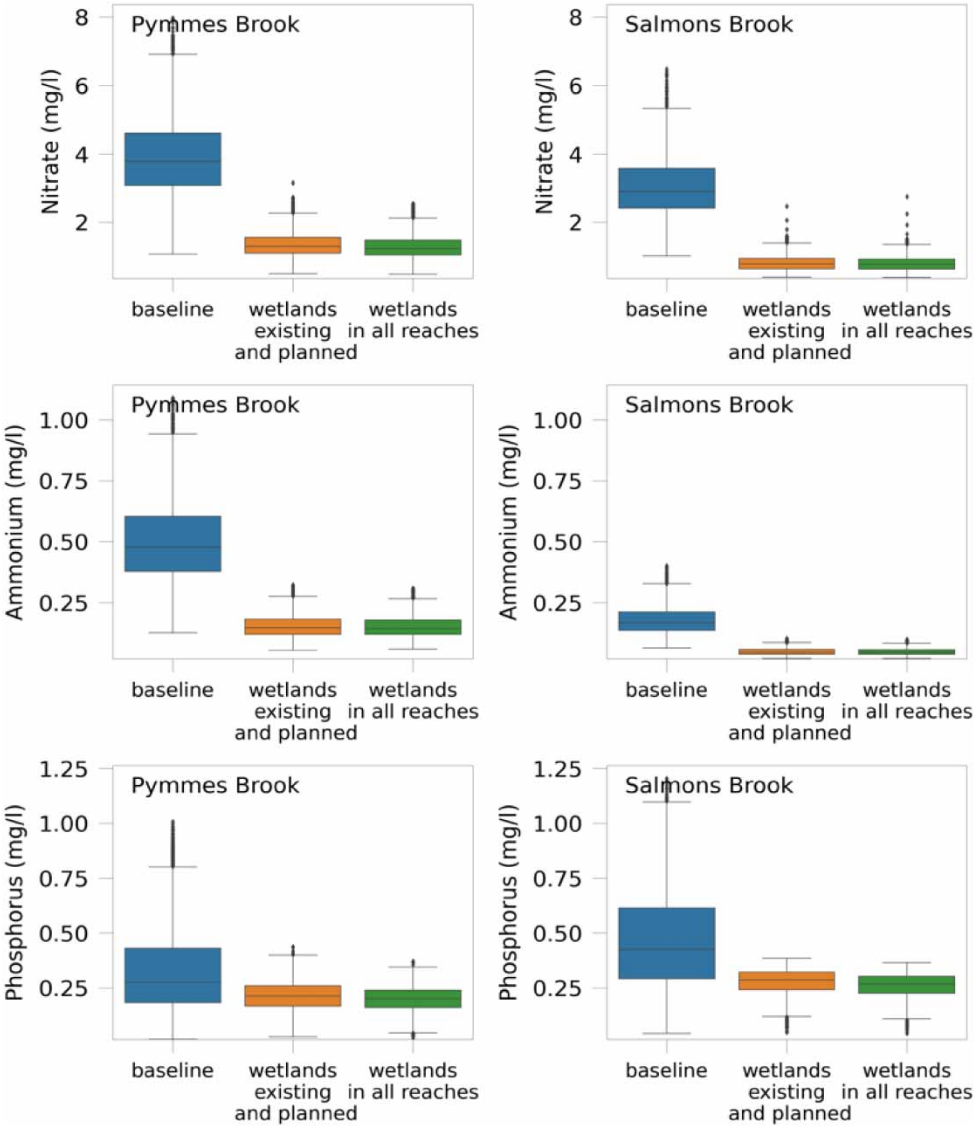

Figure 6 | Removal efficiency at the catchment outlets for the two scenarios considered.

scenarios (70% for the Pymmes Brooks and 72% for the Salmons Brook). The efficiency in reducing phosphorus concentration is lower but still significant (34 and 38% for the Pymmes Brook, 40 and 45% for the Salmons Brooks). It is also interesting to note that the wetlands are particularly efficient in reducing peak concentrations. The reduction of the 95th quantile of nitrate concentration is 66% in the Pymmes Brook and 75% in the Salmons Brook under scenario A, while for ammonium it is 70 and 76%, respectively. The reduction of phosphorus peak concentrations is more pronounced than the reduction in its average value: under scenario A, the 95th percentile of phosphorus concentration is reduced by 54% for the Pymmes Brook and 62% for the Salmons Brook.

While the specific removal efficiency of a single wetland is the same in both scenarios, clearly scenario B has more wetlands than scenario A and thus a greater removal efficiency. However, the removal efficiency of scenario B is only marginally greater than the removal efficiency of scenario A: 65 and 67% nitrate reduction on the Pymmes Brooks, respectively, 73 and 74% nitrate reduction on the Salmons Brooks, respectively, 34 and 38% phosphorus reduction for the Pymmes Brook, and 40 and 45% phosphorus reduction for the Salmons Brooks. The small difference can be explained by the fact that wetland efficiency is greater when the nutrient concentration is larger, and that the benefits of wetlands decrease when the nutrient concentration is incrementally smaller. Therefore, wetlands located just downstream other wetlands do not

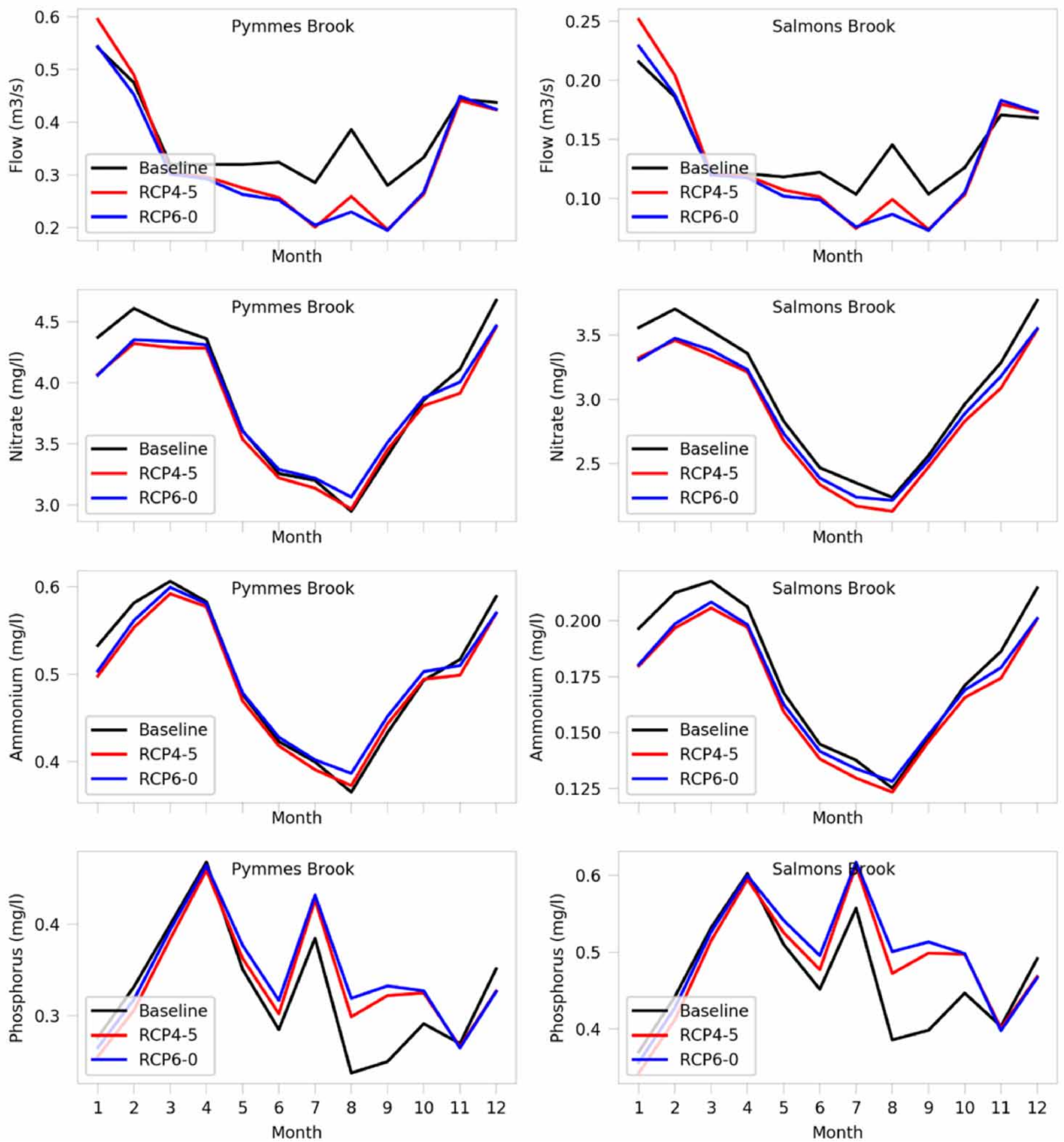

Figure 7 | Flow and nutrient concentration monthly averages under different climate scenarios.

add a significant removal capacity, as the nutrient concentration is already relatively low. It is interesting to note that the findings of this study suggest that a significant total removal efficiency can be achieved by constructing wetlands on the main tributaries, in the headwaters of the catchment and in just a few sections of the main river, rather than scattering wetlands all over the catchment. While these conclusions are important in generic terms, because they point to the need for designing a catchment-specific wetland construction strategy, their transferability to other locations is yet to be determined, as clearly the optimal position of the wetlands depends on the location of the sources of the pollution, which changes in every catchment.

4.3. Wetland nutrient removal scenarios under future climate

The same exercise of nutrient removal efficiency at the catchment outlets was repeated using the future climatic projections as input for the model, allowing the assessment of climate change impacts over nutrient concentrations and removal efficiency. Figure 7 shows the impact of the two climate change scenarios considered on flow, nitrate concentration, ammonium concentration and phosphorus concentration at the outlets of the Salmons Brook and the Pymmes Brook. Winter flows are not projected to vary, while summer flows are forecasted to decrease significantly. No large variations of nitrate and ammonium concentrations are simulated, while phosphorus concentration is forecasted to increase in summer and autumn months.

Figure 8 shows the impact of climate change on nutrient concentrations and removal efficiencies. It can be noticed how only small changes in average nutrient concentrations are expected under the two climate change scenarios. For nitrate, the expected changes are +3% in the Pymmes Brooks and +6% in the Salmons Brook under RCP4.5 and +1 and +4%

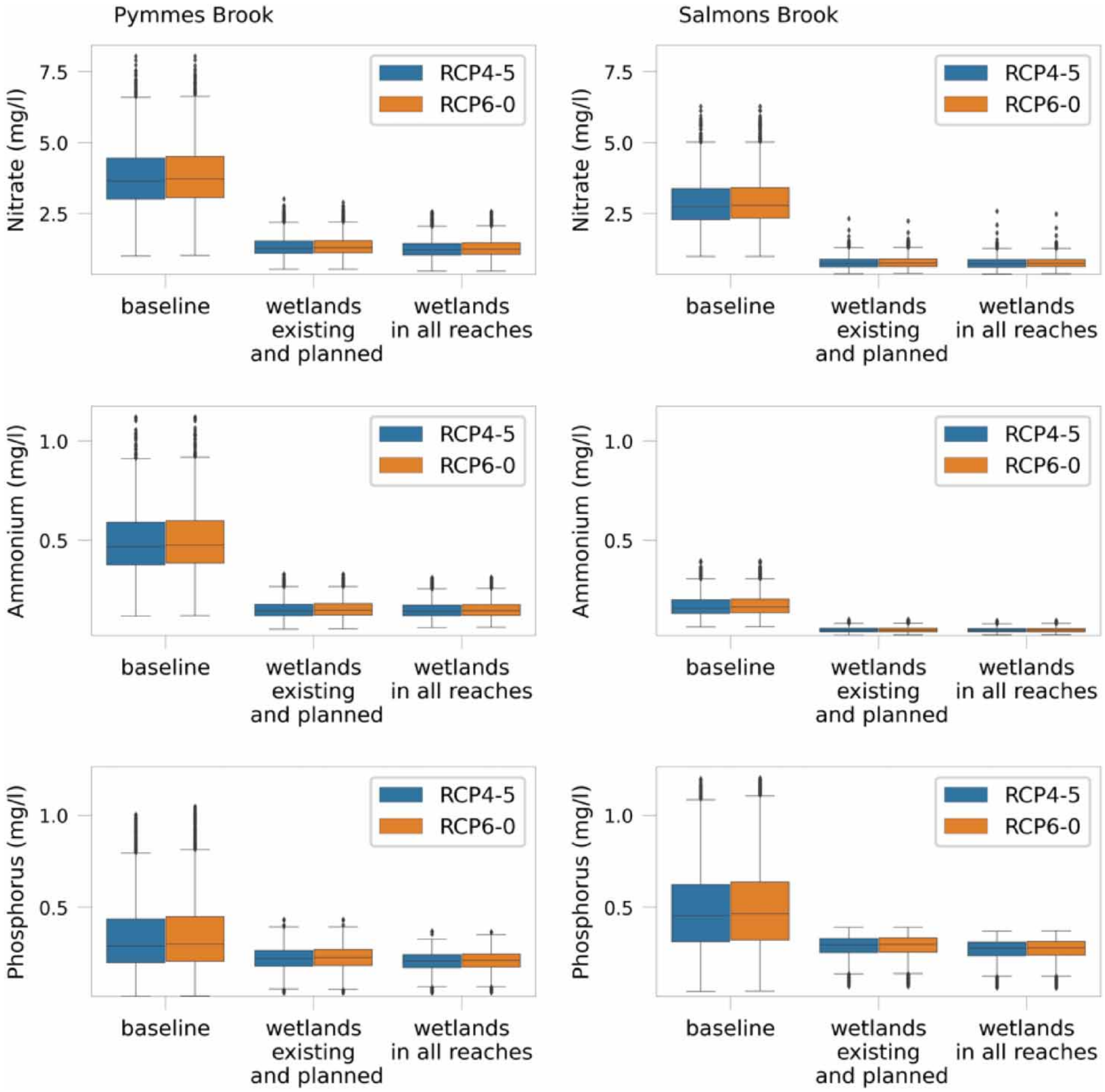

Figure 8 | Climate change impact on nutrient concentrations and removal efficiencies.

under RCP6.0 if no further wetlands are considered (i.e., the 'baseline' scenario). For ammonium, these values are 2 and 6% for the Pymmes and Salmons Brooks, respectively, under RCP4.5 and 0 and 6% for the Pymmes and Salmons Brook, respectively, under RCP6.0. Phosphorus is expected to vary by −6% in the Pymmes Brooks and −4% in the Salmons Brook under RCP4.5 and by −9 and −6% under RCP6.0. Very similar changes are forecasted by the model also for the peak concentrations of nutrients. Within this context, the efficiency of the wetland is not expected to be altered by changing climate, with nutrient reduction ratios that are very much in line with the ones estimated under current climatic conditions.

5. DISCUSSION

In this study, the INCA model was used to assess the impact of wetlands as a measure for nutrient load reduction in urban catchments, where sources of nutrients are dominated by raw and treated sewage discharges. As shown in Figures 4 and 9 and Table 2, the model is able to reproduce very well the observed flows, while for nutrients the model is able to reproduce well the mean observed concentrations (although with some underestimation of ammonium concentrations in the Salmons Brook, probably due to an underestimation of the effluent sources in that catchment) and the spread of values (i.e., low-flow peaks and low concentration during high-flow spells). The model provides overall nutrient loads that are generally in line with the available observations from the Environment Agency. Based on these and other observations, the Environment Agency classified both rivers as having a 'moderate' ecological status (Environment Agency 2019a, 2019b) and 'bad' invertebrates index status. In both catchments, misconnections from properties are mentioned as confirmed sources of phosphorus and

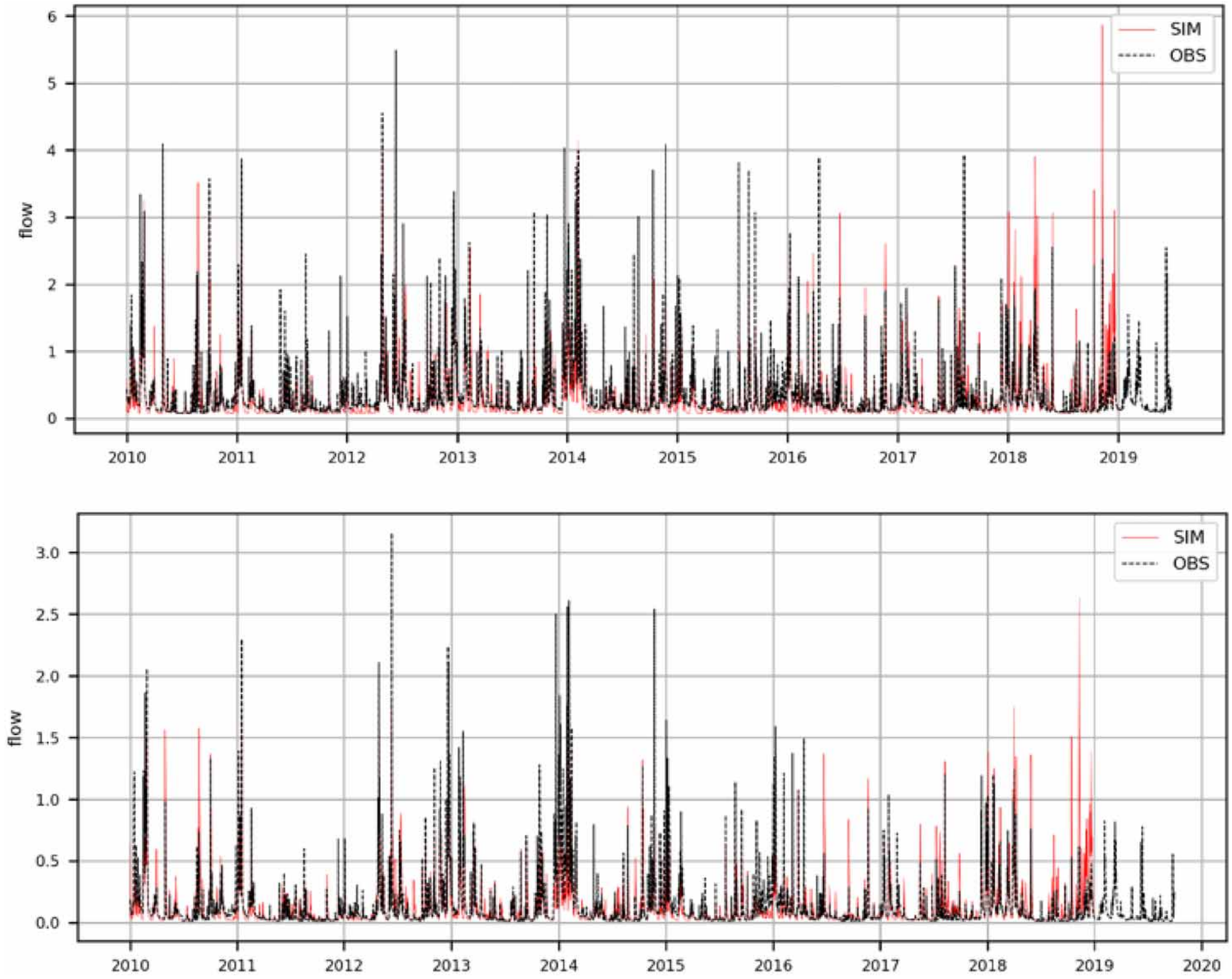

Figure 9 | Model simulated and observed flows (m^3/s) 2010–2020.

ammonium and identified as one of the main issues causing low dissolved oxygen levels and having an impact on invertebrates in the rivers.

Wetlands are often suggested as an effective way to reduce nutrient loads in urban catchments (Fisher & Acreman 2004; Braskerud *et al.* 2005). In particular, swamps and marshes have been indicated as the most effective type of wetlands in nutrient reduction (Fisher & Acreman 2004). In this paper, wetland efficiency data (Gilbert 2016a, 2016b) were employed to introduce the effect of wetlands over nutrient loads into the INCA model. This was done by modifying some of the INCA parameters, in particular those controlling nutrient cycles in the river channel. While this is standard practice in water quality modelling (Fennessy & Mitsch 1989; Mitsch & Wise 1998; Kazezyılmaz-Alhan *et al.* 2007; Samsó & Garcia 2013), it introduces a necessary simplification, which can increase the uncertainty of the final results and should certainly be highlighted. For this reason, the calibration of such parameter modifications against reference data of measured nutrient removal efficiency is paramount.

In this study, the INCA model results indicated that nutrient removal efficiency by constructed wetlands is reasonably well reproduced, with percentage reductions from model results well in line with the measurements. Previous studies also indicate comparable nutrient reduction efficiencies for constructed wetlands similar to the ones in the Pymmes and Salmons Brooks. For example, a review of 43 wetlands all over the world (Fisher & Acreman 2004) showed that the average reduction for nitrogen species was 67% and for phosphorus species 58%. Another scientific review (Tournebize *et al.* 2017a) found a reduction of 20–90% of nitrogen in stream caused by wetlands. Knox *et al.* (2008) measured a retention of total nitrogen, total phosphorus and soluble reactive phosphorus between 35 and 42% of loads entering a wetland in Northern California (US), while Reinhardt *et al.* (2006) estimated a nutrient reduction of 27% for a wetland in Central Switzerland. As can be noticed, the spread of nutrient reduction rates is rather wide, strongly depending on the characteristics of the wetland and corroborating the need for wetland-specific data to inform the modelling approach, as done in this study.

One of the aims of this paper is to evaluate whether a catchment-scale wetland implementation strategy would reduce significantly the nutrient loads at the catchment outlets. For this reason, two scenarios were analysed: (A) existing constructed wetlands plus planned constructed wetlands, which would receive water from 72% of the total catchment area, and (B) wetlands on all the sub-catchments, thus receiving 100% of the water flowing within the catchment. According to the model results, both scenarios seem to attain similar levels of nutrient reduction and are particularly efficient in reducing nitrate and ammonium loads, thus supporting the case for the completion and implementation of the wetlands that are already intended to be built within the catchments. These results are encouraging, as they show the potential for wetlands to be used on a much larger scale than they currently are for the reduction of nutrient loads in urban rivers where misconnected raw sewage deteriorates the overall status of the water and the aquatic communities.

On the other hand, they also point to the need for more intensive research on the efficiency of wetlands in reducing nutrient concentrations, especially at larger scales. A significant body of literature is available for the assessment of the impact of wetlands at the scale of small catchments (Fisher & Acreman 2004; Tournebize *et al.* 2017b). However, the analysis of the impact of a full set of wetlands distributed homogeneously over a medium or large catchment is still hampered by the lack of data, also because wetland construction is rarely undertaken at the scale of medium and large catchments. The outcomes of this paper suggest that such an approach would be highly beneficial for the water quality of urban rivers but requires further validation with data from catchments where this strategy has actually been implemented, especially to verify the assumption that the nutrient reduction efficiency of a few existing wetlands can be extrapolated to other potential wetlands located in different areas of the catchment.

An interesting point of discussion is the fate of the removed nutrients. The model results suggest that, while nitrate-nitrogen is mainly transformed via denitrification processes, phosphorus is mainly retained by sediments through sorption. Johnes *et al.* (2020) review a range of processes of N and P in wetlands and illustrate via experimental techniques that loss of P from sediments can be significant. Thus phosphorus can be flushed out during wet conditions, and when tied to sediments can be remobilised under high flow conditions floods and reintroduced into the aquatic system, with potentially negative effects. Also, there can be significant mobilisation of the organic components of N and P (Johnes *et al.* 2020) but in densely urbanised catchments, such as the Salmon and Pymmes Brooks, the organic components are likely to be less significant than in predominantly agricultural or grassland catchments with large animal populations.

This paper has also analysed the impact of climate change on flows, water quality and wetland efficiency, employing scenarios from the UKCP18 dataset (Lowe *et al.* 2018). The results show that, while flows are expected to be slightly reduced in summer, the average water quality of the rivers is not expected to change significantly, probably because the increase of nutrient concentrations triggered by the reduction in the dilution potential of the rivers is partially compensated by the reduction in nutrients from diffuse sources caused by lower summer rainfall. Nevertheless, the model results point to some increase in phosphorus concentrations in August, September and October, consistently with other studies in the area (Bussi *et al.* 2016b, 2017). At the same time, the model results seem to suggest that climate change should not have a relevant impact on the nutrient removal efficiency of wetlands, thus confirming the strong potential of this green infrastructure for nutrient load control and reduction in urban catchments. While the assumptions made within the framework of the modelling approach used in this paper are reasonable and should be framed within the context of a catchment-scale study, more experimental data are needed to understand how wetlands respond to changes in flows triggered by raising temperature and altered precipitation patterns.

Finally, some consideration on the model uncertainty and its impacts on the outcomes of this paper are given. While flow records used for model calibration are considered reliable and directly comparable to the model results (i.e., they are daily averages), the same cannot be said for the nutrient concentration records, which are intermittent, instantaneous and do not represent the water quality of a river section or reach but simply the water quality at the sampling point. These factors make model calibration complex, and the use of a physically based model can only partially fill this gap. From a qualitative point of view, ammonium results are more uncertain than nitrate and phosphorus results, because ammonium typically varies more abruptly than the other two water quality variables, and the intermittent and instantaneous record might have missed many of these variations or might have selected a non-representative sample of the average behaviour of the ammonium in the river system. Thus, we recommend that more ammonium data are collected with a greater frequency, so that future decisions can be based on more reliable model results.

6. CONCLUSIONS

In this paper, the results of a modelling experiment for the assessment of the nutrient load capacity of wetlands in urban areas are presented. Rivers in urban areas are often polluted by raw sewage and outfalls, as is the case of the Salmons and Pymmes Brook in north London, UK. The INCA water quality model was implemented in these two catchments, leveraging available measurements of nutrients upstream and downstream of four existing wetlands. The model was then applied at the whole catchment scale, exploring the effectiveness of two wetland construction scenarios and under current and future climate conditions. The results suggest that if a set of wetlands are constructed in a way that a substantial part of the runoff is drained by one or more wetlands (in the case of this study, 72% of the total catchment was drained by potential wetlands), such a strategy can have great potential for significantly reducing loads of nitrate, ammonium and phosphorus (by 73, 76 and 36%, respectively, according to the results of the model). Climate change is expected to reduce summer flows, although its impact on water quality will be limited. The strategy of implementing a large number of wetlands distributed over the catchment shows good potential for providing a large nutrient load reduction also under a changing climate. These results are encouraging in that they show a catchment-scale wetland construction strategy has a very good potential for improving the overall water quality of urban rivers.

Limitations of the study are that the model is only a representation of reality and hence is subject to uncertainties such as the limitations of that data availability, such as water quality data for the system, and the variability of the parameters across a complex catchment and multiple wetland sites. Also, longer term changes driven by climate change are a potential issue as the climate models themselves are subject to considerable uncertainty as well as the downscale simulation methods. Nevertheless, this is a valuable study in addressing issues of installing green infrastructure in urban catchments.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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