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Research article

Comparing likely effectiveness of urban Nature-based Solutions worldwide: The example of riparian tree planting and water quality

Michael Hutchins [a,b,*], Yueming Qu [a], Isabel Seifert-Dähnn [c], Gregor Levin [d]

[a] UK Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK
[b] Department of Earth Sciences, Royal Holloway University of London, Egham Hill, Egham, TW20 0EX, UK
[c] Norwegian Institute for Water Research, Økernveien 94, 0579, Oslo, Norway
[d] Department of Environmental Science, Aarhus University, 4000, Roskilde, Denmark

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ABSTRACT

Amongst a spectrum of benefits, Nature-based Solutions (NBS) are increasingly being advocated as improving the quality of aquatic environments in urban areas. Of these, a widely adopted measure is tree planting. Yet, because of the local complexities and spatial variability of urban hydrological response, it is difficult to predict to what extent improvements in water quality will arise. To overcome this barrier, a standardised approach to process-based model simulation of urban river quality is described (QUESTOR-YARDSTICK (QUESTOR-YS)). The approach eliminates the influence of point sources of pollution and harmonises the way in which river hydrodynamics and contributory catchment size are represented. Thereby, it focuses on differences in water quality between cities due solely to climate, river discharge and urban diffuse nutrient pollution factors. The relative sensitivity to NBS establishment between urban water bodies in different cities anywhere across the world can also potentially be quantified. The method can be readily extended to include wastewater effluents. The validity of the approach is demonstrated for a small river in Birmingham, UK; and thence demonstrated for the case of 10 km of riparian tree planting in Birmingham, Oslo (Norway) and Aarhus (Denmark). Modelling suggests that riparian tree planting can substantially improve water quality in each example city for three key indicators of water quality in sensitive summer conditions (water temperature, chlorophyll-a and dissolved oxygen). Results show the level of benefit achievable in response to a fixed amount of planting will depend on the existing level of riparian tree occupancy.

1. Introduction

The need for sustainable urban environmental management to counteract the deleterious effects of urbanisation on rivers has long been recognised (Walsh et al., 2005). In this context, growing awareness of the shortcomings of engineering solutions and the value of urban areas in delivering ecosystem services to support human and environmental wellbeing makes for an increasing need to assess the various environmental benefits of Nature-based Solutions (NBS) (Palmer et al., 2015). NBS come in a variety of forms (Jones et al., 2022), some are highly engineered, but among the most prevalent are urban forests and parks, roadside vegetation including street trees, and riverbank vegetation (Almassy et al., 2018). Urban trees are known to have substantial, albeit uncertain, beneficial effects for many water-related ecosystem functions (Baker et al., 2021; Hutchins et al., 2023). Riparian woodland in particular can beneficially reduce stream water temperature (Bowler et al., 2012) and may improve other metrics of urban water quality (Hutchins et al., 2023) and freshwater biodiversity (Gwinn et al., 2018). Despite uncertainties, this evidence supports management for optimising provision of ecosystem function (Dowtin et al., 2023). The uncertainty in estimating urban water quality benefits is a consequence of many factors, but most notably relates to the importance of local context. Complexities of urban hydrological pathways and how these mobilise pollutant sources to determine water quality in urban streams hamper assessments (McGrane, 2016). Water quality response can vary markedly across small geographic areas within an urban area (Shupe, 2017; Hasenmueller et al., 2016).

With the burgeoning adoption of NBS across cities worldwide, water resource managers can potentially profit greatly from information on the efficacy of schemes implemented outside of their locality. Can

* Corresponding author. UK Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK.
E-mail address: mihu@ceh.ac.uk (M. Hutchins).

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knowledge, for example of the benefits of tree planting, be transferred effectively in a well-informed manner to support decision-making? Because of the complexity and uniqueness of urban localities this question is challenging to answer. The Urban Stream Syndrome is heterogeneous (Booth et al., 2016; Hale et al., 2016). Water quality modelling can potentially help overcome the challenge in that it allows scenarios to be trialled, but the often-encountered limitations of data availability and accessibility, coupled with the effort needed to set up and test model applications, present especially significant obstacles in urban settings. Unsurprisingly given these difficulties, a recent review found few water quality modelling studies assessing urban NBS, and a lack of effective standardisation of how simulated benefits are quantified (Matos and Roebeling, 2022).

While tailored models increase the accuracy and precision of predictions, they are of little use to decision makers in data-deficient cities. One solution is to develop a generic or standard model, that allows the incorporation of some key readily-obtainable local information but can run in the absence of detailed information. Therefore, rather than adopt the conventional approach to applying a model, whereby a specific river of interest and its contributing influences are characterised, we outline an approach based around standardising a conceptual representation of urban rivers which is theoretically applicable worldwide. Whilst the method cannot give an absolute indication of water quality response in a specific location, it can provide acceptably accurate general information for managers to make informed judgements which would otherwise rely on guesswork. Hence, barriers to knowledge exchange can be circumvented through this refocused perspective on water quality modelling.

The objectives of the present paper are to demonstrate the validity and usefulness of a standardised modelling approach. Hereby, we describe an example for assessing benefits of tree planting for urban water quality using the QUESTOR model (Pathak et al., 2021). In Section 2 we describe the model and its use for generating standard urban river applications. In Section 3, we first demonstrate the viability of standardisation by showing results from the city of Birmingham (UK) in which a standard application is compared to a model application populated with specific local information. Then, we present an example set of standard river model applications in three cities (Birmingham (UK), Aarhus (Denmark) and Oslo (Norway)). This illustrates the level to which water quality benefits are likely to arise from riparian tree planting in different climatic and land use settings. The primary purpose is to make comparisons between cities of typical benefits likely to arise from a standard tree planting regime, not to evaluate model outputs in the context of specific rivers in those cities. Presentation of results is followed by discussion (Section 4) of wider implications and global applicability of the approach for a range of NBS types.

2. Methodology

2.1. QUESTOR model overview

The process-based river eutrophication model, QUESTOR, simulates hourly time series of temperature, nutrient and sediment concentrations, chlorophyll (algal biomass), and dissolved oxygen; using long-established mechanistic theory summarised by Chapra (2008). Validity of the model to simulate these variables has been extensively demonstrated at daily resolution (e.g., Hutchins et al., 2016, 2020) and more recently at an hourly time-step (Pathak et al., 2021; Hutchins et al., 2021a). Equations are described elsewhere (Pathak et al., 2021). Thereby, QUESTOR quantifies ecosystem metabolism (Pathak et al., 2022), which represents the balance between photosynthesis and respiration, and how this might change under different scenarios. In this way it provides an integrated measure of aquatic ecosystem health; as well as information about pollutant concentrations which can be related directly to regulatory standards. QUESTOR is a 1-D model of river networks, consisting of a set of reaches bounded by influences related to hydrological flows (abstractions, effluents, tributary rivers) and hydrodynamics (weirs). The model computes river discharge and resolves errors in network mass balance by modifying assumptions about influences. To determine flow routing, the reaches are defined by constant-width and variable-depth, with travel time, water depth and discharge related using non-linear equations and information on riverbed condition. By linking flow routing to biochemical processes (as continuously stirred tank reactors, to represent the completely mixed environment typical of river channels) the reach structure represents advection and dispersion. Diffuse inputs can be represented by observations, process-based rainfall-runoff (and diffuse pollution) models or simple statistical models. The model uses solar radiation inputs to generate water temperature as part of an energy balance approach. Water temperature and related light inputs control the simulation of primary production.

2.2. Rationale for a standard approach and parameterisation

Fig. 1 summarises the QUESTOR model domain and its use in the present study. We have specified a standard urban catchment and river channel morphology which can be readily applied in any city worldwide with a minimum data requirement: the standard urban river model, termed hereafter QUESTOR-YARDSTICK (QUESTOR-YS) or “basic model”. The approach covers characterising two main elements: standardised attributes and data specific to the urban area.

2.2.1. Standardised attributes

The catchment size, river width, hydrodynamics and rate constants of in-river biogeochemical transformations were assumed constant between city applications. This then allowed isolation and identification of how sensitive river water quality is to local conditions of river discharge, climate and diffuse nutrient pollution (nitrogen, phosphorus, and carbon). The standard comprises a 10 km stretch of river draining a catchment of 30 km^2, comprising 10 km^2 of upstream catchment and the remaining area contributing incrementally and homogeneously along the 10 km stretch. The intention was to represent small rivers subject to local diffuse urban nutrient pollution. In-river biogeochemical transformation fluxes heavily depend on residence time in the channel. Residence time is defined by flow velocity (V), which can be estimated from readily available river discharge (Q) measurements. Therefore, in each application, three alternative hydraulic conditions were covered: (1) slow flowing (hereafter denoted “slow”) (2) moderately flowing (“medium”) (3) fast flowing (“fast”). The slow flowing case is likely typical of regulated rivers, for example as controlled by dams. Whether rivers are medium or fast flowing will largely be controlled by topography. The inclusion of these alternative hydraulic characteristics is to help managers best relate the model outputs to their local setting. In each case, river widths were defined, and channel hydrodynamics specified using non-linear relationships between discharge and velocity (Leopold and Maddock, 1953), as represented by two empirical parameters (a, b: Table 1, Fig. A1). Biogeochemical process rate constants were taken from detailed modelling studies in the Thames basin and elsewhere in England covering a range of hydrodynamic situations (Pathak et al., 2021; Hutchins et al., 2016) (thus defined at 20 °C (/h): deamination 0.01, nitrification 0.0775, denitrification 0.0055, BOD decay 0.035, benthic oxygen demand 0.002, P mineralisation 0.01, maximum algal growth rate 0.095, algal respiration proportional multiplier 0.15, algal death proportional multiplier 0.15). In the present study, urban diffuse inputs alone were represented. Abstractions, weirs and point source influences were not included. The effects of urban diffuse pollution are the initial focus of QUESTOR-YS; responses which reflect land cover and local climate drivers. Effluents are a ubiquitous feature of the overall urban environmental footprint and can easily be incorporated in the QUESTOR-YS approach to place effects of riparian planting in a wider context.

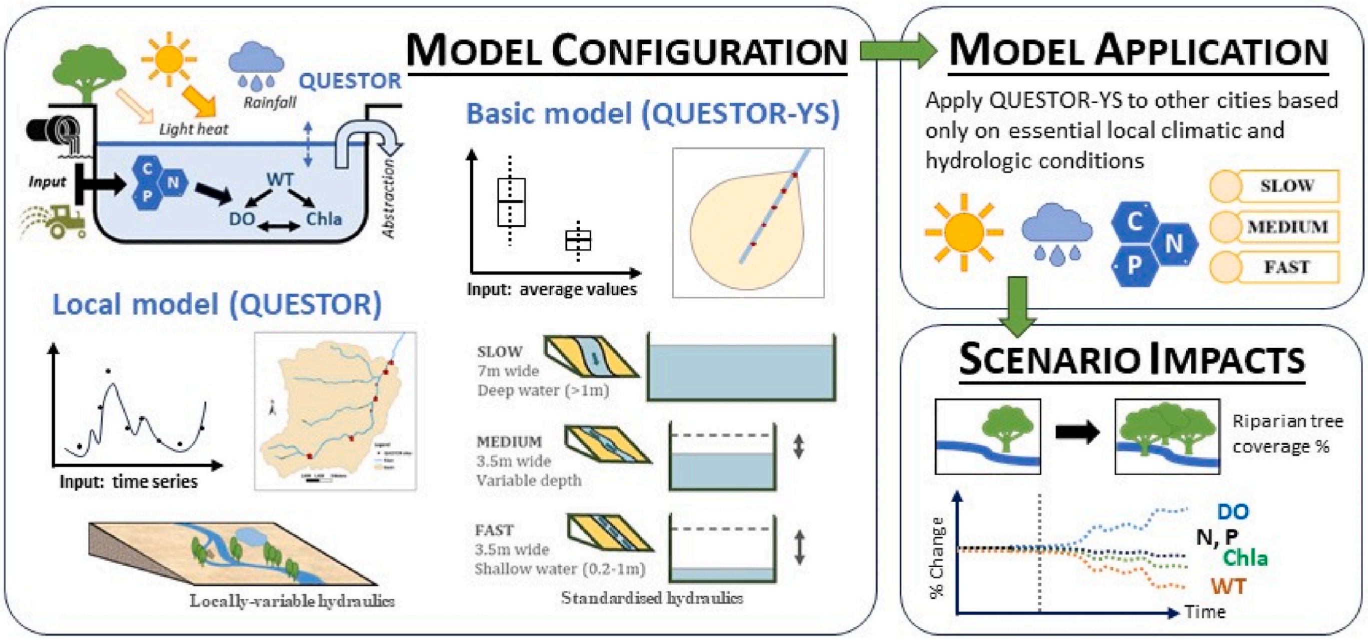

Fig. 1. A diagram of the QUESTOR model domain simplified for overview purposes (i.e. not all determinants are included; and hydrological inputs, although ultimately rainfall-controlled, are in practice provided as river discharge and runoff). Model configuration represents the development from the original "local model" of the "basic model (QUESTOR-YS)"; which differs in having less detailed input data demands and standardised attributes describing the catchment, channel hydraulics and in-channel transformation rates. The basic and local models were compared in Birmingham; and the basic model applied in Birmingham, Aarhus and Oslo (Model application), and thenceforth used for analysing scenarios of riparian canopy establishment (Scenario impacts). Scenarios were evaluated by assessing change in summary metrics of dissolved oxygen (DO), phytoplankton (chlorophyll-a: Chla) and water temperature (WT). Nutrients (N, P) were also included as these are taken up and released by biotic processes controlled by WT and light.

Table 1
Hydraulic parameters used under three flow scenarios (slow, medium, high) by the basic model to describe the relationship between velocity and discharge. where observations of river discharge (Q: $m^3 s^{-1}$) define estimates of velocity (V: $m s^{-1}$) (Leopold and Maddock, 1953) using parameters a and b: $V = aQ^b$. Channel width is provided to relate discharge to water level.

hydraulic parameters	slow	medium	fast
Width (m)	7.0	3.5	3.5
a	0.05	0.1	0.3
b	0.75	0.5	0.4

2.2.2. Data characterising hydrology, climate, and nutrient pollution

For application of the approach by practitioners, data specific to the urban area are necessary. Time-series data of at least one year are required, covering: (1) river discharge from an urban river, (2) solar radiation (or sunshine hours if unavailable), (3) water temperature (or air temperature if unavailable), and (4) water quality data describing nitrogen, phosphorus, organic carbon, and dissolved oxygen concentrations from one or more urban rivers. The data need not be from specific rivers and can be a representative sample of multiple rivers. The key requirement is that they should reflect typical summer conditions in the city. The intention is that data should be chosen in consultation with local stakeholders to identify typical rivers, using qualitative or quantitative criteria as desired. A summary of local driving data used, and their source derivation, is presented in Table A1.

2.3. Model applications

To demonstrate the viability of the approach we compared results from a standardised Birmingham application (denoted "basic model"; intended to represent a typical river in the city) to that derived from a model set up to specifically represent local conditions as fully as possible (denoted "local model"). For this purpose, we studied the River Rea (a 74 km^2 basin covering the southwest part of the city). The Rea comprises a narrow (<5 m variable width) 12 km river with 6 reaches, some bounded by weirs and tributary influences, and with varying amounts of riparian tree cover within 20 m of the channel (mean: 45%). It is characterised by periodic water quality observations at 5 sites (3 for input from tributaries, 2 for model testing) over 2 years (2013–14). Water quality from this "local model" was compared to that of a river specified using the "basic model" setup as described in Section 2.2.1. In both the local and basic models, hydraulic parameter values for a fast flow were used (Table 1). In both cases, hypothetical establishment of NBS involved a 4% increase in the land cover share of woodland, with a tenth of the tree planting focused along riverbanks and the remainder in headwater catchment areas. Local authority targets for achieving net zero emissions informed the 4% increase in tree cover. In practice, other emerging considerations might in time result in minor changes to these targets. The level of benefit of headwater planting for reducing total nitrogen and total phosphorus concentrations in runoff was derived from literature review meta-analysis (Hutchins et al., 2023). For the local model, the riparian planting was prescribed to raise bankside tree occupancy to 100%. This was based on expert judgment giving priority to planting in riparian locations wherever possible. In translating this amount of planting to the basic model, this equated to an increase from 0% to 26% in tree bankside occupancy.

Applications of the basic model (QUESTOR-YS) then enable between-city comparisons of their baseline water quality and their relative potential for delivering restoration benefits of diverse types associated with NBS. Capability to consider NBS includes: (1) daylighting, (2) riparian shade, (3) restoring meanders, (4) catchment tree planting in headwaters or nearby. Evaluating other catchment NBS may be possible (e.g., grass swales, wetlands). The downstream spatial evolution of beneficial effects can be quantified. In the present paper we considered the benefits in turn of planting riparian trees to achieve 25%, 50%, 75% and 100% bankside occupancy along a 10 km stretch of river. The water quality at the downstream end of the 10 km stretch was compared to a baseline condition where riparian trees were absent. It was assumed that increasing riparian tree occupancy equates to increased shading and has a linear effect on light penetration to the water surface. Full riparian shade reduces light penetration to 32% (Bachiller-Jareno et al., 2019). The basic model was applied in three cities: Birmingham, Aarhus, and Oslo. In each case, three models were run representing three hydraulic scenarios (slow, moderate, and fast flowing). It was assumed that a range of rivers spanning the three types will be present in each city, and this would be typical of any city. By repeating the application three times as described, the approach covered the spectrum of hydraulic situations to be found in each city and evaluated the likely range of arising water quality conditions.

3. Results

3.1. Model testing in Birmingham

The local and basic models were in agreement, simulating beneficial water quality response to the tree planting NBS scenario. Results for five summary metrics of water quality are shown: water temperature (WT, 90th percentile), chlorophyll-a (Chla, 90th percentile), dissolved oxygen (DO, 10th percentile), nitrate-N (NO_3–N, mean) and soluble reactive phosphorus (SRP, mean) (Fig. 2). The metrics relate to EU Water Framework Directive application and summarise river state when most vulnerable to ecological deterioration (e.g., during warm and slow flowing summer conditions). Although availability of observations was sparse (for each determinant: n = 16), the local model simulated a close fit to the data. Percentage bias in the mean (PBIAS) was −2.1, −0.6, −19.8 and 19.0 for DO, WT, NO3–N and SRP respectively. Nash-Sutcliffe Efficiency values (Nash and Sutcliffe, 1970) obtained were 0.71, 0.88, −1.22 and 0.05 respectively for DO, WT, NO3–N and SRP. The local model simulated a beneficial water quality response to NBS establishment for all five of the metrics. The model predicts if and how implementation of different combinations of riparian planting and planting away from watercourses can meet local authority targets for water quality. The combinations of planting strategy are predicted to be effective. Likewise, the basic model also predicted a universally beneficial effect of NBS. For the two approaches, predicted benefits due to NBS were in fairly close accordance, in particular for water temperature and DO metrics, indicating that the simplification has potential to yield reliable and robust information about the value of NBS for water quality (Fig. 3).

Some differences arising from the simplification are apparent, however. Simulated present day 90th percentile water temperature is approximately 2 °C lower in the local model. This is probably due to the influence of a few unusually low summer water temperature observations in the headwater tributary. Also, the differences between the two models in 10th percentile DO levels can likely be largely attributed to this. Similarly, differences in present day simulations of nutrient concentrations are likely a manifestation of the observations used to describe headwater model inputs. For suppression of algal biomass (Chl-a), the benefit is underestimated by the basic model relative to the local model. This is likely due to differences in present-day level of riparian shade between the two applications. For the basic model it is assumed

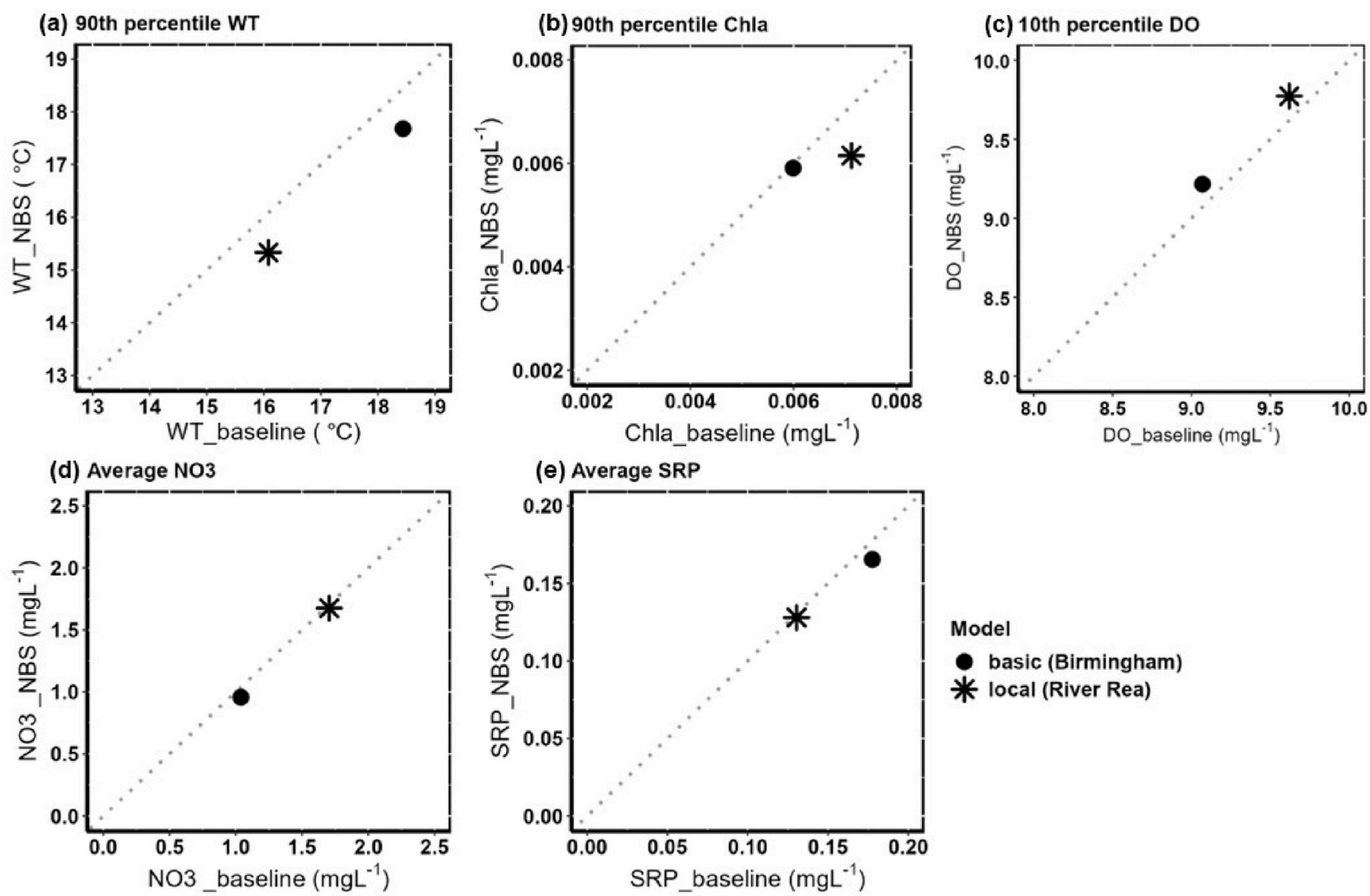

Fig. 2. Comparison between basic and local model outcomes for water quality at the downstream outlet reach. The tested nature-based solutions (NBS) scenario here is a 4% tree planting increment (the increased tree coverage comprising 10% in riparian zone and 90% in the headwater catchment). Water quality, illustrated with 5 parameters, included: (a) water temperature (WT), (b) chlorophyll-a (Chla), (c) dissolved oxygen (DO), (d) nitrate-N (NO3), (e) ortho-phosphate (measured by soluble reactive phosphorus, SRP). The dashed lines represents where the water quality metrics under the tree planting scenario are identical to the baseline. Points plotting far from the line show where tree planting has a substantial effect.

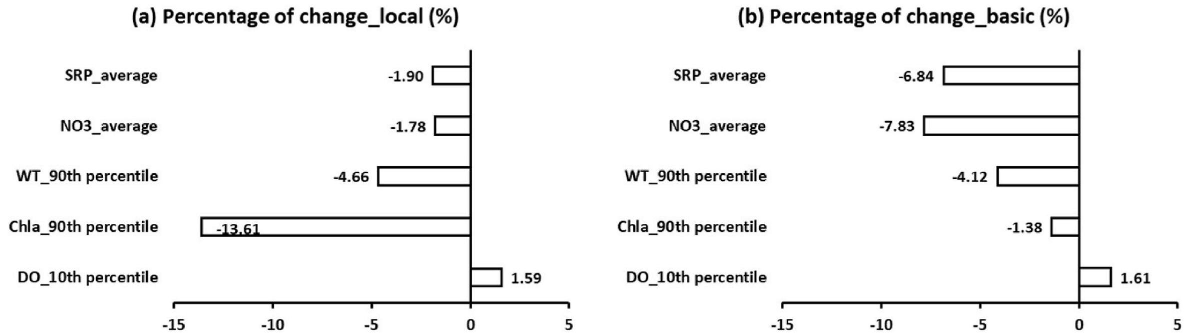

Fig. 3. Percentage change in water quality metrics from present day baseline to the NBS scenario for (a) local (River Rea) model and (b) basic (Birmingham) model approach.

there is no present-day shade. Differences are propagated through to differences in nutrient concentration benefits. Nutrient concentrations are largely controlled by two processes (runoff inputs from the land and biotic uptake in the channel). The basic model simulates larger nutrient reductions than the local model because the reduced nutrient load in input runoff (due to increased uptake by trees in the catchment) is minimally offset by reduction in biotic uptake by algal biomass in channel. In the local model, as there is considerable reduction in biotic uptake under the NBS scenario, the two processes are closer to being in balance. Although differences between results from the basic and local models are apparent, NBS benefits are consistently predicted for all determinants, and the predicted magnitudes of benefit are very similar for WT and DO metrics.

3.2. Between-city comparisons

Models were applied for a duration of one year (Aarhus, 2019) or two years (Birmingham, 2013-14 and Oslo, 2017–18). For summary metrics of five indicators, comparison of baseline conditions and levels of benefit due to riparian tree planting are shown at outlet reach locations 10 km downstream (Fig. 4). In all cities and for all hydraulic conditions, benefits are omnipresent for WT (reductions of up to 6.8 °C at 90th percentile level) and Chl-a (up to 0.01 mg L^{-1} at 90th percentile level). Changes due to NBS are predicted to be minimal for nitrate-N and SRP.

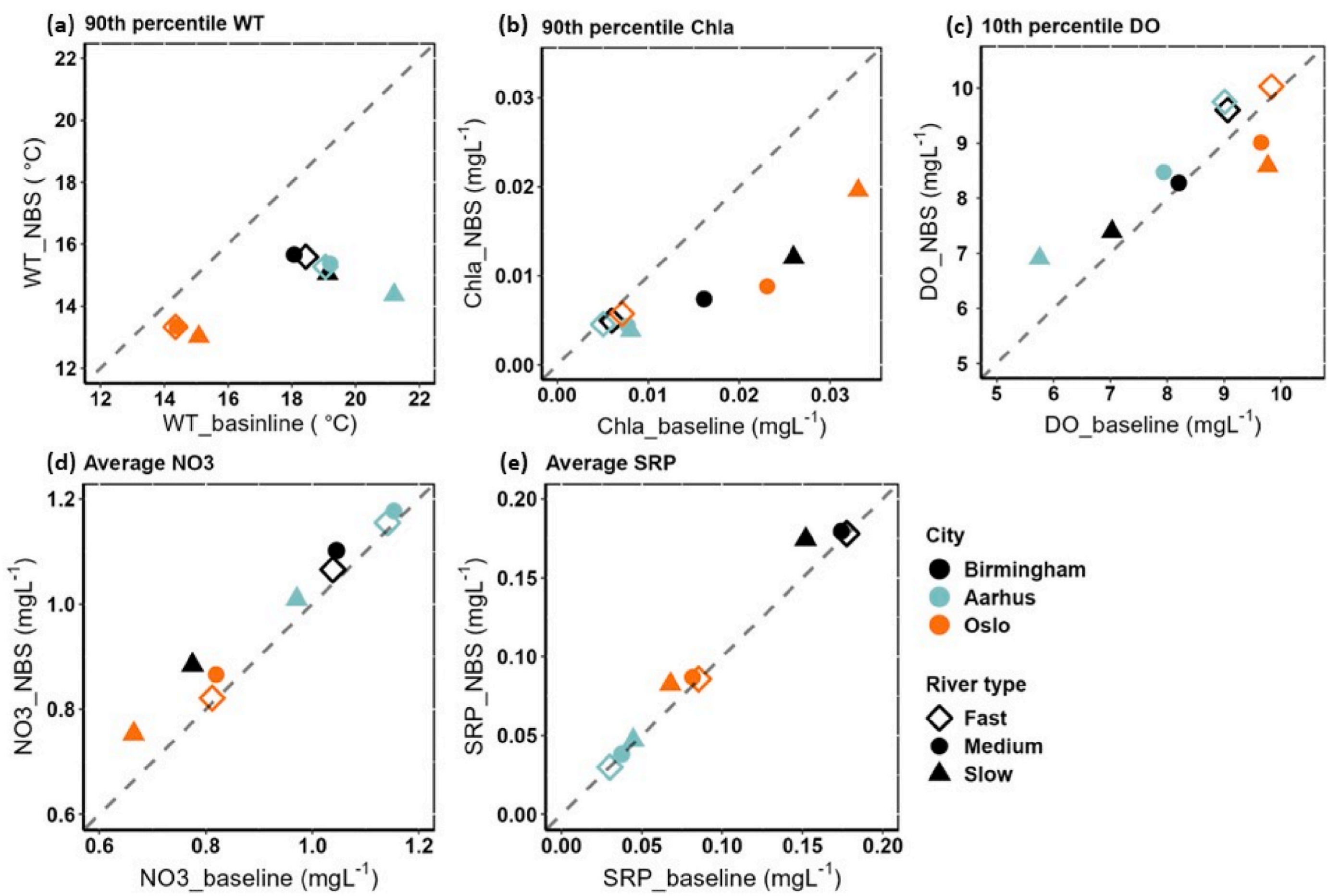

Fig. 4. Comparison across three cities of predictions of 10 km 100% riparian tree planting NBS benefits for five water quality indicators of (a) water temperature (WT), (b) chlorophyll-a (Chla), (c) dissolved oxygen (DO), (d) nitrate-N (NO3), (e) ortho-phosphate (SRP). The dashed lines represent where the water quality metrics under the riparian planting scenario are identical to the baseline. Points plotting far from the line show where riparian planting has a substantial effect.

Mean nutrient concentrations may slightly increase because of lower algal uptake in shaded rivers. Effects of NBS on DO are mostly beneficial (increase in 10th percentile level of up to 1.1 mg L^{-1}) except in Oslo.

Some of the summary indicators show large differences between cities (e.g., SRP, Chl-a). Simulated algal growth is more substantial in Oslo than elsewhere (>0.03 mg L^{-1} under slow hydraulics). For each city, hydraulic conditions substantially affect all indicators, except SRP. Large differences both between cities and between hydraulic conditions are apparent for nitrate-N. For all summary indicators the level of benefit (or disbenefit) depends on hydraulic conditions, with slow flowing rivers showing much greater sensitivity to change. The effect of hydraulics on benefit is most apparent for WT and Chl-a (Fig. 4).

3.3. Relationships between water quality benefit and canopy penetration

The response of water quality at the downstream end of a 10 km reach to change in level of canopy penetration arising from changes in riparian tree occupancy differs between summary indicators (Fig. 5). Differences are also apparent between cities. Relationships are non-linear. With increasing levels of shade, suppression of phytoplankton (Chl-a) accelerates (Fig. 5b). This bears out the differences simulated in Birmingham between local and basic configurations (Fig. 3). In contrast, incremental water temperature benefits with increasing shade are most marked at low levels of shade (Fig. 5a). Similarly, DO benefits tail off with increasing shade; and in Oslo, and at highest levels, deteriorations are simulated (Fig. 5c). These relationships can form the basis of benefit functions. The level of benefit arising from riparian shade is greatest in rivers with slow hydraulics, as indicated by the stronger slopes (Fig. 5). Relative differences in the benefit functions between slow, medium, and fast rivers are broadly to be expected, but lack consistency somewhat, either between indicator or between cities.

4. Discussion

Evidence presented in Section 3.1 indicates that an increase in riparian shading delivers benefits to physical water quality (WT and DO) that can be recognised and quantified by a simplified standard urban river model. This is encouraging as it indicates that differences between cities are identifiable. These differences are apparent in Fig. 4 and are due to the interactions between baseline regimes of water quality, water temperature, incident sunlight and river flow. All these qualities are controlled by land use, geographic and climatic attributes. Complex effects of local morphology and hydrological setting are successfully isolated and removed from comparisons. Therefore, the approach enables municipal planners to ask whether riparian planting effective elsewhere might also be successful in their city.

4.1. Differences between cities

In Oslo, despite its more northerly location, higher Chl-a concentrations are simulated than in the other cities. This is due to those temperature, light and river flow conditions that are maximally beneficial for growth occurring coincidentally only in Oslo and not in the other cities. The phytoplankton model assumes cool water centric diatoms to dominate the community. These have a maximum growth rate at 14 °C. In Oslo, 14 °C is typical of mid-summer conditions when river flow is at its lowest and bright sunshine most prevalent. Elsewhere, the driest and sunniest mid-summer conditions coincide with warmer waters that are sub-optimal for diatom growth. There are also differences in Chl-a between Birmingham and Aarhus. As nutrient concentrations are lower and likely to become limiting more readily, accelerated growth is less prevalent in Aarhus than in Birmingham. Due to higher present-day Chl-a, the benefits of tree planting are more marked in Birmingham than in Aarhus. Benefits in Birmingham approach those in Oslo.

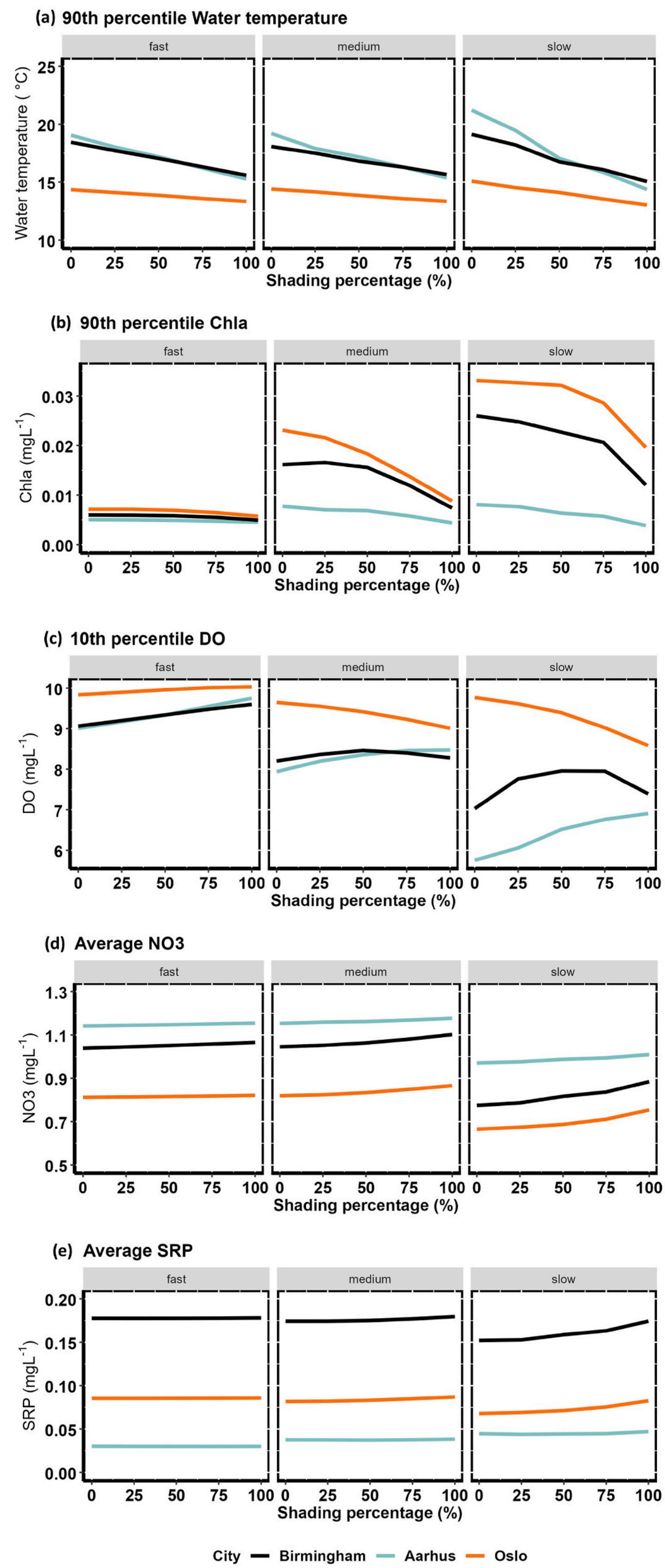

Fig. 5. Water quality responses in Birmingham, Aarhus, and Oslo under fast, medium, and slow hydraulic conditions to change in riparian tree occupancy for indicators of (a) water temperature (WT), (b) chlorophyll *a* (Chla), (c) dissolved oxygen (DO), (d) nitrate-N (NO3), (e) ortho-phosphate (SRP).

4.1.1. Current limitations of the approach and future requirements

To further scrutinise the differences identified between cities and to improve the validation of the standardised modelling approach more generally, additional testing of the model is strongly recommended. Due to shortfalls in data availability in Aarhus and Oslo, undertaking of model testing (reported in Section 3.1) was possible only in Birmingham. This testing only covered a relatively fast flowing system. Additional data collection for ground-truthing in the existing cities and extension of the approach to other cities are important priorities. When extending applications of the standard model to other cities, testing against observations will be important, particularly in slow flowing cases. The slower the velocity, and thereby the longer the river residence time, the more sensitive the water quality is to rates of in-channel transformations. As stated in Section 2.2.1, the model has previously been validated in slow flowing rivers, but not in environments as predominantly urban as those covered in the present study.

4.2. Effect of residence time on level of NBS benefit

As residence times are directly related to the different hydraulic conditions covered in the standard applications, their effects on simulated water quality are very apparent (Fig. 4). The magnitude of channel biogeochemical transformation fluxes is very sensitive to time of travel along the 10 km river stretch. As longer contact with streambed sediment promotes denitrification, effects of increasing residence times beneficially reduce nitrate concentrations. In contrast, the effects of increasing residence time are detrimental for WT, Chl-a and DO. The detrimental effects are due to slower flowing water being more exposed to solar heating. Similarly, longer residence times foster more opportunity for accelerated primary productivity.

The overall influence of residence time on DO is complex, with a set of competing processes operating. Negative consequences are likely. Whilst primary productivity elevates DO in the daytime, carrying capacity is reduced in warmer water and longer residence time promotes larger heterotrophic respiration fluxes. These detrimental in-channel effects are mitigated in all cases by establishing riparian shade. The slower flowing the river, the larger the benefit of riparian NBS. An exception is DO in Oslo. In the higher latitude Norwegian city, stream water in summer is notably cooler and of larger river discharge than in the other cities under baseline conditions (Table A1). As competing in-channel processes are all influenced differently by temperature, colder and faster flowing conditions are a likely cause for the distinct response in Oslo.

4.3. Potential for wider application of QUESTOR-YS

The data requirements behind the QUESTOR-YS approach are flexible and undemanding. As illustrated (Table A1), seasonal frequency of water quality inputs is sufficient. Allied to realistic assumptions, proxy information can be used (e.g., to derive DO from WT). Ultimately, meteorological information can act as the source for required variables. Water temperature and solar radiation can be derived from air temperature and sunshine hours duration respectively. Alternatively, simulated time-series of light inputs can be applied. Scarcity of flow observations in small rivers is a potential constraint, although this can be overcome globally with the advent of high-resolution simulated data (Lin et al., 2019). Inclusion in the approach of repeating model applications under multiple hydrodynamic parameterisations allows the effects of river modification to be accounted for, including the establishment of dams and other artificial structures common in urban rivers.

The results presented for Birmingham, Aarhus and Oslo demonstrate how direct comparisons can be made between any cities in the world based solely on climate. The comparison should be repeated for a range of river hydrodynamic situations encountered in urban environments. Doing so isolates and quantifies the influence climate and geographic location have on the vulnerability of typical urban rivers to poor water quality, and the potential for benefits from NBS. The approach provides a framework for putting urban NBS assessments in a worldwide context and can substantially enhance knowledge exchange. Whilst the cities studied fall in similar Koppen-Geiger climate classifications (Geiger, 1954) along relatively shallow gradients from oceanic (Cfb) through humid continental (Dfb) towards sub-arctic (Dfc), quantifying to what extent the responses contrast with those in markedly different climates with hotter summers will unlock much value.

In addition to assessing tree planting, future work should characterise functional responses to establishment of other NBS types, such as daylighting or river re-naturalisation. Daylighting is often undertaken to suppress pathogens emanating from wastewater, but the consequential trade-off, of warmer waters, can be balanced by riparian planting. As far as possible, QUESTOR-YS applications should be extended geographically to cover urban areas falling within the range of climate and levels of pollution encountered throughout the world. For planners, it will also be helpful to consider how future climate trajectories may affect sensitivity to NBS. For example, Oslo climate may become more like that currently experienced in Aarhus or Birmingham. When working towards planting targets within specific cities, planners will also find value in the response functions relating level of benefit to amount of riparian woodland NBS, and how these vary with hydraulic characteristics (Fig. 5). These can help plan optimal cost-beneficial levels of additional riparian tree planting depending on the current level of shade in specific rivers. By using multiple model applications to assess a range of tree placement scenarios (both next to and distant from watercourses), the approach (1) highlights the importance of size and spatial location of NBS in determining benefit, and (2) contributes to the optimisation of multiple benefits to maximise a range of ecosystem services in addition to that of water purification (Hutchins et al., 2021b).

5. Conclusion

The paper describes the development of an approach for standardising model assessments of water quality between cities. Data from three cities (Aarhus, Birmingham, and Oslo) were collated and propagated through the QUESTOR-YS river water quality model; and typical variations in river hydrodynamics accounted for by re-running model applications. The potential viability of the approach was tested against additional data from an urban river in Birmingham. Further corroboration is strongly recommended. Nevertheless, the approach pinpoints climatic and land use influence on the level of water quality benefit achievable by establishing NBS (e.g., riparian tree planting). This allows appraisal of the inherent vulnerability of urban water quality at a city-specific level. In so doing, knowledge transfer between cities can be more effective, through levels of benefit being quantified in a novel systematic way, and through direct between-city comparisons of management interventions. More generally, the standardised QUESTOR-YS approach, whereby spatial variability in the sensitivity of river channel systems is quantified in response to environmental change, can be applied beyond urban environments and for a variety of pressures or interventions.

CRediT authorship contribution statement

Michael Hutchins: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing, Project administration. **Yueming Qu:** Conceptualization, Formal analysis, Visualization. **Isabel Seifert-Dähnn:** Resources, Funding acquisition, Project administration. **Gregor Levin:** Project administration, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Input data are available at websites listed in Appendix Table A1. Modelled output data available on request.

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Appendix A. Supplementary data

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References

Almassy, D., Pinter, L., Rocha, S., Naumann, S., Davis, M., Abhold, K., Bulkeley, H., 2018. Urban Nature Atlas: a Database of Nature-Based Solutions across 100 European Cities. https://naturvation.eu/atlas.

Bachiller-Jareno, N., Hutchins, M., Bowes, M., Charlton, M., Orr, H., 2019. A novel application of remote sensing for modelling impacts of tree shading on water quality. J. Environ. Manag. 230, 33–42.

Baker, H.J., Hutchins, M.G., Miller, J.D., 2021. How robust is the evidence for beneficial hydrological effects of urban tree planting? Hydrol. Sci. J. 66, 1306–1320. https://doi.org/10.1080/02626667.2021.1922692.

Booth, D.B., Roy, A.H., Smith, B., Capps, K.A., 2016. Global perspectives on the urban stream syndrome. Freshw. Sci. 35 (1), 412–420.

Bowler, D.E., Mant, R., Orr, H., Hannah, D., Pullin, A., 2012. What are the effects of wooded riparian zones on stream temperature? Environ. Evid. 1, 3. https://doi.org/10.1186/2047-2382-1-3.

Chapra, S., 2008. Surface Water Quality Modelling. Waveland Press, 1478608307, 9781478608301.

Dowtin, A., Cregg, B., Nowak, D., Levia, D., 2023. Towards optimised runoff reduction by urban tree cover: a review of key physical tree traits, site conditions and management strategies. Landsc. Urban Plann. 239, 104849.

Geiger, R., 1954. Klassifikation der Klimate nach W. Köppen. In: Geiger, R. (Ed.), Landolt-Börnstein–Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik (alte Serie), vol. 3. Springer, Berlin, Germany, pp. 603–607.

Gwinn, D.C., Middleton, J.A., Beesley, L., Close, P., Quinton, B., Storer, T., Davies, P.M., 2018. Hierarchical multi-taxa models inform riparian vs. hydrologic restoration of urban streams in a permeable landscape. Ecol. Appl. 28, 385–397.

Hale, R.L., Scoggins, M., Smucker, N.J., Suchy, A., 2016. Effects of climate on the expression of the urban stream syndrome. Freshw. Sci. 35 (1), 421–428.

Hasenmueller, E., Criss, R., Winston, W., Shaughnessy, A., 2016. Stream hydrology and geochemistry along a rural to urban land use gradient. Appl. Geochem. 83, 136–149.

Hutchins, M.G., Williams, R.J., Prudhomme, C., Bowes, M.J., Brown, H., Waylett, A.J., Loewenthal, M., 2016. Projections of future deteriorations in UK river quality are hampered by climatic uncertainty under extreme conditions. Hydrol. Sci. J. 61, 2818–2833.

Hutchins, M.G., Harding, G., Jarvie, H., Marsh, T., Bowes, M., Loewenthal, M., 2020. Intense summer floods may induce prolonged increases in benthic respiration rates of more than one year leading to low river dissolved oxygen. J. Hydrol. X 8, 100056.

Hutchins, M.G., Qu, Y., Charlton, M., 2021a. Successful modelling of river dissolved oxygen dynamics requires knowledge of stream channel environments. J. Hydrol. 603, 126991.

Hutchins, M.G., Fletcher, D., Hagen-Zanker, A., Jia, H.F., Jones, L., Li, H., Loiselle, S., Miller, J., Reis, S., Seifert-Dähnn, I., Wilde, V., Xu, C.-Y., Yang, D.W., Yu, J., Yu, S., 2021b. Why scale is vital to plan optimal Nature-Based Solutions for resilient cities. Environ. Res. Lett. 16, 044008.

Hutchins, M.G., Qu, Y., Baker, H.J., 2023. Woodland establishment reduces nutrient losses to waterbodies in urban catchments: a review of the evidence. Water Resour. Res. 59 (6), e2022WR032626.

Jones, L., Anderson, S., Læssøe, J., Banzhaf, E., Jensen, A., Bird, D.N., Miller, J., Hutchins, M., Yang, J., Garrett, J., Taylor, T., Wheeler, B., Lovell, R., Fletcher, D., Qu, Y., Vieno, M., Zandersen, M., 2022. A typology for urban green infrastructure to guide multifunctional planning of nature-based solutions. Nature-Based Solutions 2, 100041. https://doi.org/10.1016/j.nbsj.2022.100041.

Leopold, L.B., Maddock, T., 1953. The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. USGS Professional Paper No. 252, pp. 1–57.

Lin, P., Pan, M., Beck, H.E., Yang, Y., Yamazaki, D., Frasson, R., et al., 2019. Global reconstruction of naturalized river flows at 2.94 million reaches. Water Resour. Res. 55, 6499–6516.

Matos, F., Roebeling, P., 2022. Modelling impacts of nature-based solutions on surface water quality: a rapid review. Sustainability 14, 7381.

McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrol. Sci. J. 61, 2295–2311.

Nash, J., Sutcliffe, J., 1970. River flow forecasting through conceptual models: part 1 – a discussion of principles. J. Hydrol. 10, 282–290.

Palmer, M., Liu, G., Matthews, J., Mumba, M., D'Odorico, P., 2015. Manage water in a green way. Science 349, 584–585.

Pathak, D., Hutchins, M., Brown, L., Loewenthal, M., Scarlett, P., Armstrong, L., et al., 2021. Hourly prediction of phytoplankton biomass and its environmental controls in lowland rivers. Water Resour. Res. 57 (3), 2020WR028773.

Pathak, D., Hutchins, M., Brown, L.E., Loewenthal, M., Scarlett, P., Armstrong, L., et al., 2022. High-resolution water-quality and ecosystem-metabolism modeling in lowland rivers. Limnol. Oceanogr. 67, 1313–1327.

Shupe, S.M., 2017. High resolution stream water quality assessment in the Vancouver, British Columbia region: a citizen science study. Sci. Total Environ. 603–604, 745–759.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan, R.P., 2005. The urban stream syndrome: current knowledge and the search for a cure. J. North Am. Benthol. Soc. 24, 706–723.