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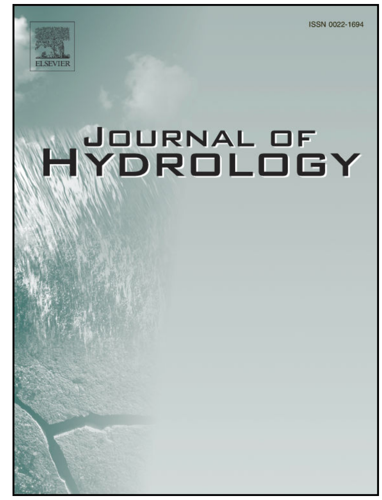

Research papers

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Balancing Upland Green Infrastructure and Stream Restoration to Recover Urban Stormwater and Nitrate Load Retention

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Abstract

Urban watersheds have experienced ecosystem degradation due to land cover change from vegetation to impervious areas. This transformation results in increased stormwater runoff, stream channel erosion and sedimentation, and both increased inputs and reduced ecosystem retention of nutrients. Ecosystem restoration practices, including terrestrial and aquatic low impact development (LID), are becoming widely implemented in urban watersheds globally. A major question is how "green" and "grey" infrastructure can be optimally balanced to shift ecohydrological behavior towards pre-urbanization conditions. Traditional stormwater engineering typically controls runoff by temporary storage (detention) and release of stormwater, while LID designs are developed to reduce runoff by a combination of infiltrating precipitation and evapotranspiration, while promoting biogeochemical retention of nutrients. These practices are often combined with stream and riparian restoration that increases nutrient retention and reduces in-stream loads. In this study, we simulated the potential impact of three types of terrestrial LID and green infrastructure (GI) on watershed runoff and nitrate (NO_3^-) loading to local streams, independent of detention storage effects. The treatments included increased tree canopy, vegetated roadside bioswales, and permeable pavement. We then evaluated the individual and interactive impacts of these practices on the effectiveness of NO_3^- load reduction provided by stream restoration, which is affected by the altered runoff and nutrient loading caused by the LID and GI. Urban reforestation provided the highest effectiveness in terms of reducing stormflow and nutrient export, while bioswales and permeable pavement unexpectedly increased in-stream NO_3^- loads. Retrofit of the previously developed watershed by LID/GI alone may not provide sufficient mitigation in stormwater and nutrient loads, and should be balanced with additional grey infrastructure, such as detention ponds, rain cisterns, and sewer system upgrades.

Keywords

Green infrastructure; low impact development; urban ecosystem restoration; stream restoration; terrestrial nitrogen cycle; water quality; stormflow mitigation; Baltimore

1. Introduction

Urbanization increases impervious area and drainage infrastructure (stormwater and sanitary systems), replacing vegetation and natural streams within watersheds. This development has brought economic growth and reduced water-borne disease, but has elevated stormwater runoff and downstream impacts of flash flooding and stream nutrient loading (Booth et al., 2002; Walsh et al., 2005). In addition, climate change has increased the frequency of intense precipitation (Mishra et al., 2015; Trenberth, 2011), elevating urban watershed vulnerability to stormwater hazards (Ashley et al., 2005; Zhou et al., 2012). Standard stormwater engineering solutions includes installation of temporary detention storage (e.g., wet/dry detention ponds) to capture and slowly release stormwater to reduce peak flows. This detention storage does not reduce flow volume, and there is an interest to use low impact development or green infrastructure (LID/GI) to infiltrate and evapotranspire stormwater. However, there is increasing evidence that increased infiltration and groundwater recharge associated with efforts to reduce surface runoff may mobilize subsurface sources from sanitary sewer leakage and septic systems (Delesantro et al., 2022).

Coupled with impervious surface and engineered drainage expansion, vegetation canopy loss is one of the most impactful land cover changes. Trees are a main source of transpiration and a major influence on urban and peri-urban water, carbon, nutrient end energy balance. Increased tree canopy cover has the potential to mitigate peak flow during storm events by promoting infiltration and water storage capacity of soils (Bartens et al., 2008). Trees also bring co-benefits such as abatement of urban heat islands (Wang et al., 2015), provision of green spaces which can improve quality of life for urban residents (Roe & Sachs, 2022; Wolch et al., 2014), and uptake of carbon dioxide and available nitrogen (Livesley et al., 2016). Other terrestrial LID approaches utilizing vegetation (e.g., rain garden, roadside swale, green roof, etc.) have also been widely used in many metropolitan regions to mitigate stormwater (Davis et al., 2009; Hopkins et al., 2020) and to provide other environmental and socioeconomic co-benefits (Breed et al., 2015; Jones et al., 2017; Wise et al., 2010).

Nitrogen (N) export from urban watersheds occurs across the range of stream discharges from baseflow to stormflow. There is great concern about this export in coastal watersheds where this element is a key driver of eutrophication (Conley et al., 2009), and the target of total maximum daily load (TMDL) regulations (Wainger, 2012). In-stream retention processes can reduce these loads, but these processes are only effective at lower flows (Lin et al., 2021; Shields et al., 2008). Therefore, stormflow reduction may improve aquatic nutrient retention, especially where streams have been restored to increase retention processes (Craig et al., 2008). LID/GI promotes increased soil water storage and infiltration to reduce surface stormwater peaks, along with increased evapotranspiration to reduce total outflow. Repartitioning flows from surface to subsurface flows by enhanced infiltration may reduce surface sources of nutrients, but increase baseflows and nutrient loading from subsurface sources (Delesantro et al., 2022; Kaushal et al., 2011). Higher soil moisture and groundwater levels, with enhanced vegetation cover may impact ecosystem retention processes (e.g., plant N uptake and denitrification) both in “on-site” areas (i.e., where treatments are implemented) of infiltration-based practices and potentially downslope in “off-site” areas (i.e., downslope, downstream, and riparian areas). Therefore, there is an interaction between upland LID/GI and stream restoration in whole watershed retention. Understanding the balance between upland, riparian, and channel restoration is a key gap that needs to be addressed. In addition, deconvolving the effects of increased (temporary) stormwater storage from practices that increase infiltration, evapotranspiration and biogeochemical retention also requires investigation to understand and optimize design.

Ecohydrological functions of LID/GI have been intensely examined at the scales of individual facilities. By comparing changes of water inflow and outflow from LID/GI facilities, studies have found various types of LID/GI can help reduce peak discharge and runoff ratio (Avellaneda et al., 2017; Damodaram et al., 2010; Giese et al., 2019; Hopkins et al., 2020; Li et al., 2017) and elevate baseflow levels (Bhaskar et al., 2016). Proper siting of LID/GI can also be crucial to maximize their effectiveness. For example, placing LID/GI downstream of impervious areas can disconnect runoff from adjacent impervious areas and store, evapotranspire, and delay surface runoff release to streams (Bell et al., 2016; Fiori & Volpi, 2020; Fry & Maxwell, 2017; Gilroy & McCuen, 2009; Walsh et al., 2005). Both the amount and spatial arrangement of LID/GI within a watershed influence streamflow and nutrient load mitigation, with more distributed implementation potentially providing greater efficiency (Hopkins et al., 2022). However, most studies of individual LID/GI facilities are limited to measurement of surface inflows and outflows, and the cumulative performance of LID/GI and corresponding impacts to baseflow at the watershed scale may be much less effective than at the individual LID/GI scales (Miller et al., 2021). This may be due to insufficient LID/GI volume to mitigate flashy flow regimes from the dominant impervious areas and piped drainage systems. In addition, infiltration-based LID/GI may shift surface impervious runoff to subsurface stormflow or saturation runoff from pervious areas receiving run-on (Miles & Band, 2015) depending on subsurface storage capacity and conductivity.

Stream restoration has gained in popularity as a method to reduce sediment and nutrient loads to downstream waterbodies (Bernhardt et al., 2005). Stream restoration projects reshape stream channels by reshaping steep, eroding banks to create gentle-slope near-stream areas to improve connectivity between riparian ecosystems and the stream channel. The re-engineered channel and riparian zone increases the residence time of water, promoting nutrient retention by plant uptake and denitrification (Craig et al., 2008; McMillan & Noe, 2017; Ward et al., 2011). The reestablished streamside vegetation can provide aesthetic and socioeconomic value for urban residents (Rosenberg et al., 2018). Stream restoration can increase stream-subsurface exchange and hyporheic processing by altering stream hydraulics (Kasahara & Hill, 2008), which is an additional sink for in-stream nutrients. The effectiveness of urban stream restoration is reduced if it is not accompanied by complementary catchment restoration to mitigate runoff and nutrient inputs that are the initial causes of aquatic degradation (Jahnig et al., 2010; Lorenz & Feld, 2013; Palmer et al., 2010). A limitation to evaluation of restoration performance is that most in-stream nutrient retention studies (Newcomer Johnson et al., 2014; Reisinger et al., 2019; Violin et al., 2011) have been conducted at low to moderate stream flow levels, when instream retention is highest, while nutrient loads may be dominated by high flows with minimal retention.

The effectiveness of terrestrial and stream restoration for urban runoff and nutrient regime mitigation has typically been separately studied. Much less is known about how catchment and in-stream restoration can be balanced to optimize long-term changes in terrestrial-aquatic loading at whole-watershed scales. In this study, we developed a spatially-explicit terrestrial-aquatic framework to evaluate the combined effects of upland and instream restoration. We used the Regional Hydro-Ecological Simulation System (RHESSys) to simulate changes in terrestrial ecohydrological processes, the Weighted Regressions on Time, Discharge, and Season (WRTDS) to estimate corresponding changes in nitrate (NO_3^-) flux for four different watershed restoration scenarios, and an aquatic metabolism model (Lin et al., 2021; Zhang et al., 2022) to estimate subsequent in-stream effects on retention. Though RHESSys is capable of estimating watershed N cycle and retention processes including vegetation uptake and denitrification, sanitary sewer inflow and infiltration (I&I) and effluent leakage are difficult to parameterize. The data-based WRTDS, on the other hand, implicitly includes the impacts of multiple sources of NO_3^- but cannot project the impacts of LID/GI implementation on ecosystem retention. Therefore, we used information from both approaches to estimate changes in runoff quantity and changes in water quality in streams after terrestrial restoration scenarios. The aquatic metabolism model was used to depict the effects of stream restoration on N retention in restored and unrestored downstream reaches (Lin et al., 2021; Zhang et al., 2022). In summary, the framework can provide estimates of hydro-biogeochemical cycling, retention, and export at patch, flowpath, and watershed scales, and the ability to allow stakeholders to evaluate efficiencies of different GI restoration plans on stormwater and nutrient load reductions at "on-site" and "off-site" locations. All numerical experiments were carried out using an urban watershed, Scotts Level Branch in Baltimore.

We addressed the following questions:

1. How do LID/GI practices produce "on-site" and "off-site" effects on hydrologic and biogeochemical processes, including biogeochemically critical offsite regions such as downstream restored stream and riparian areas?
2. What is the effectiveness of LID/GI restoration practices independent of storage detention (i.e., distributed tree canopy and green infrastructure implementation) on mitigating urban runoff

and NO_3^- export regimes towards pre-urbanization conditions and increasing N retention from stream restoration?

2. Methods

2.1. Study Area

We evaluated ecohydrological changes after implementing several types of LID/GI (see Method 2.2) using our modeling framework (Figure 2) at Scotts Level Branch (SLB) in Baltimore County, MD (Figure 1). SLB has a drainage area of 8.6 km^2, mean elevation of 166 m and mean annual precipitation of 1,153 mm. Residential land use and land cover (LULC) is dominated by single-family houses, driveways and roads, lawn, and tree canopy. According to the Chesapeake Bay 1-m LULC data (Hood et al., 2021), there are 2.4 km^2 of impervious area (structures, impervious surfaces, and roads), 3.3 km^2 of tree canopy, and 2.7 km^2 of lawn, covering 28.4%, 38.8%, and 30.7% of SLB, respectively. A set of stream restoration projects have been completed in the main stream and tributaries (example in Figure 3) by Baltimore County, and studies have measured and modeled the efficiency of nutrient reduction from these projects (Lin et al., 2021; Reisinger et al., 2019).

The United States Geological Survey (USGS) has gauged SLB (gage ID: 01589290, 39.36°N, 76.76°W) since Oct 2005. Average discharge from water year 2006 to 2021 is 0.13 m^3/s (1.3 mm/day). We delineated the stream network in SLB using the r.watershed tool from GRASS GIS with a threshold 0.62 km^2, which approximates the length of mapped streams from the NHD High resolution dataset (https://www.usgs.gov/national-hydrography/nhdplus-high-resolution). The delineated stream network was segmented into ~1000-ft reaches, from which we could estimate the projected N retention from stream restoration (Zhang et al., 2022). We approximated riparian areas extent as the areas less than 1.5 meter above nearest stream (as in Lin et al., 2015, 2019 & 2021), using the GIS algorithm HAND (Height Above Nearest Drainage, Nobre et al., 2011).

2.2. Terrestrial Restoration Scenarios

We considered three watershed terrestrial restoration scenarios (Figure 3) to compare to status quo (SQ) conditions to represent end-member restoration designs (Table 1): 1) replace all lawn more than 10-m from buildings with deciduous tree canopy (urban reforestation, URF), 2) introduce 2-meter shrub bioswale buffers along all roads (roadside bioswale, RBS), 3) retrofit current roads with permeable pavement (permeable road, PR), and 4) combine reforestation and roadside bioswales (URF+RBS). We note that these hypothetical scenarios may not be practical, particularly the extensive replacement of lawns and the use of permeable pavement on all roads. However, we use these to explore the limits of efforts to increase infiltration and transpiration, reduce road runoff volume and peak, and increase N retention. We deliberately did not include enhanced detention storage practices in these treatments in order to isolate the impacts of increased evapotranspiration, infiltration, and biogeochemical retention from detention practices. We evaluated impacts of these LID/GI scenarios on watershed-scale runoff and nutrient loading, N retention efficiency of stream restoration of local stream reaches, and N retention processes at LID/GI patches and riparian areas. Per unit efficiency of reducing runoff or NO_3^- load for three types of LID/GI (URF, RBS, and PR) was calculated as total change at the watershed outlet divided by the size of each LID. We noted that ecohydrological changes were reported for patches within which LID/GI are implementing (referred as LID/GI patches from this point), and the results were not normalized by the proportions of LID/GI in these patches as the effectiveness of LID/GI may be overestimated due to non-linearity between ecohydrological responses and the size of LID/GI in a patch.

2.3. Framework and model description

The framework (Figure 2) couples an ecohydrological model, the Regional Hydro-ecological Simulation System (RHESSys, Tague & Band, 2004) that simulates the effects of restoration on both on- and off-site changes in surface and subsurface water balance and key N cycling processes (i.e., vegetation uptake, nitrification, and denitrification) within the watershed. The streamflow simulation from each scenario is provided to the Weighted-Regression on Time, Discharge, and Season (WRTDS, Hirsch et al., 2010) that estimates the corresponding in-stream nutrient concentration and flux. We then estimate in-stream NO_3^- reduction expected for a restored stream compared to an unrestored stream using a stream ecosystem model from Lin et al. (2021) and Zhang et al. (2022).

2.3.1. Ecohydrological Modeling with RHESSys

RHESSys is a distributed ecohydrological model which simulates water balance (e.g., streamflow, evapotranspiration, soil moisture redistribution, and surface/subsurface flow), plant growth, and biogeochemical (N and C cycles) processes at patch to watershed levels. The model has been applied in many regions with different climates (e.g., semiarid California to humid eastern US) and LULC (e.g., forest and urban) conditions (Bart et al., 2016; Leonard et al., 2019; Lin et al., 2019; Ren et al., 2022). RHESSys can be set up to simulate at a range of spatial resolutions. The model can incorporate fractional sub-patch LULC as more fine-resolution LULC data are available. We use a computationally efficient resolution (15 m) with fractional land cover generated from a 1m land cover dataset (Hood et al., 2021). We used the calibrated RHESSys with SQ conditions as the baseline model against which other LID/GI scenarios were assessed. A set of model hydrological parameters governing subsurface moisture storage and flux (Table 2) were developed from SSURGO mapped soil properties, and further calibrated against USGS streamflow observations at Scotts Level Branch in the SQ baseline model. Vegetation parameters were acquired from previous empirical studies (summarized in White et al., 2000) and RHESSys studies (Hwang et al., 2012; Lin et al., 2015 & 2019) with similar soils and tree canopy communities. The parameter set generating highest Nash-Sutcliffe efficiency (NSE, Nash & Sutcliffe, 1970) value was used in this study.

We used a spin-up period of RHESSys from Jan 1, 1993 to Dec 31, 2005 to stabilize state variables, and then simulated watershed processes under different restoration scenarios from Jan 1, 2006, to Dec 31, 2016. Tree species composition was adapted from Lin et al. (2019 & 2021), which is a mix of red maple (*Acer rubrum*), oak (*Quercus spp*.), and tulip poplar (*Liriodendron tulipifera*) with proportions of 15%, 37%, and 48%, respectively. Specifically, drought resistant trees (e.g., oak) are placed more on the upland while higher water use trees (e.g., tulip poplar) in the riparian and near stream areas, with red maple evenly distributed in the watershed. Trees were assumed mature in our simulation, although RHESSys carbon budgets and allocation results in additional growth. Several "on-site" state, flux, and transformation variables (i.e., saturation deficit, transpiration, denitrification, vegetation uptake, and NO_3^- fertilization) governing water and N balance in the study watershed were simulated and used to characterize hydrological and ecosystem cycling and retention.

2.3.2. *Evaluation of Water Quality using WRTDS*

Streamflow regimes produced by the SQ model and LID/GI scenarios were combined with concentration-discharge-season (c-Q-s) relationships derived with the WRTDS model to produce estimates of daily stream nutrient concentrations and loads. WRTDS is a statistical model built with weekly stream chemistry data (collected by the Baltimore Ecosystem Study (BES) since 1998) for several watersheds gauged by the USGS in Baltimore City and County. Sources of N from the sanitary sewer system leakage may be significant (e.g., Kaushal et al., 2011), but are very difficult to accurately quantify. We therefore use the WRTDS estimates of NO_3^- concentration and load, based on discharge and time (seasonality) to encompass all N sources, including effluent sources (e.g., sanitary sewer leakage) which are not reliably simulated in RHESSys. This approach assumes that the relationships between stream N concentrations and flow and seasonality are not significantly impacted by alterations in the runoff regime.

As SLB was not monitored for stream chemistry by BES, the WRTDS estimated concentration-discharge-seasonality (c-Q-s) relations for a nearby section of the Gwynns Falls watershed (above the USGS Delight Gauge 01589197) with similar size and land cover, were used. Both Delight and SLB are dominated by residential LULC with similar proportions of impervious areas, lawn, and tree canopy. Long-term BES sampling indicates that while NO_3^- concentration increases with lower flows, there is a concentration reduction at the lowest flows (<0.1 mm/day). The WRTDS equations did not represent this phenomenon, and therefore, we capped all WRTDS estimated NO_3^- concentrations that were above the maximum observed concentration value to 8 mg NO_3-N/L in these lowest flows. We note the total loads derived from these very low flows are negligible. Uncertainty analysis of simulated NO_3^- concentration was performed through bootstrapping for 50 times.

2.3.3. Aquatic Restoration

Stream channel restoration can reduce NO_3^- loads by increasing stream water residence times, exchange rates with bed and bank sediments, and inadvertently by increasing solar radiation at the stream_surface by reduction of riparian vegetation cover (Reisinger et al., 2019). The latter increases algal nutrient uptake rates. The Lin et al. (2021) stream ecosystem metabolism model was used to simulate restored and unrestored stream reaches in SLB under scenarios with and without riparian vegetation cover, and with runoff regimes from several BES monitored streams with varying degrees of development (Zhang et al., 2022). We defined an exponential relationship between an index of the NO_3^--flow distribution, F75 (Shields et al., 2008), and the net stream ecosystem retention (g/m of restoration) of NO_3^- in restored and unrestored streams, with and without riparian cover (Zhang et al., 2022):

$$NO_3^-\ Reduction = \begin{cases} F75^{-0.302}e^{4.331}, & closed - canopy \\ F75^{-0.298}e^{5.023}, & open - canopy \end{cases} \qquad \text{(Equation 1)}$$

where F75 is the stream discharge level corresponding to the 75th percentile of the cumulative nitrate load, which is highly correlated ($R^2 = 0.89$) to the percent upstream impervious area. Eq. 1 was then used to estimate changes of in-stream nitrate retention following the different watershed LID treatments, based on the altered streamflow from RHESSys and nitrate load distributions from WRTDS that they produced, characterized by F75. The estimated nitrate reduction from stream restoration over all reaches in SLB was combined with streamflow and NO_3^- flux change from the SQ and each terrestrial restoration scenario to evaluate stream retention and the combined load reduction caused by both terrestrial (LID/GI) and aquatic (stream restoration) efforts.

2.4. Mass Balance of NO_3^- in Watershed

As WRTDS is data-based and does not estimate changes in watershed loads due to altered ecosystem N retention processes. Therefore, we used RHESSys to estimate daily changes in fixation, plant uptake, denitrification, immobilization, and fertilization in LID/GI scenarios, and aggerated to annual level. Specifically, in forested watersheds, N is accumulated through atmospheric deposition (ATM) and N fixation (FIX_{N_2}); In urban watersheds, additional N is added by human activities such lawn fertilization (FRT) and leakage from sanitary sewers (LKG_{sewer}). The input of N can then be used as vegetation uptake (UPT) and recycled through growing and dormant seasons. N leaves watersheds through denitrification (DNF) as nitrogen gas (N_2) or nitrous oxide (N_2O), is immobilized for long periods in stable soil compounds (IMM) and stored, or exported downstream through hydrological flow pathways ($Flux_{stream}$). The annual N in an urban watershed is thus balanced as:

$$\boldsymbol{\Delta}\mathrm{N} = ATM + FIX_{N_2} + LKG_{sewer} + FRT - UPT - Flux_{stream} - DNF - IMM$$

(Equation 2)

We assumed that N allocated for vegetation uptake does not directly leave the watershed unless leaf litter or mowed grass are collected and removed by landscaping practices, although it may mineralize and be transported at a later time. We also assume a fertilization rate (3 g NO_3^--N /m^2, twice during the growing season with 90 days interval, equivalent to 60 kg NO_3^--N/ha/year) for lawns in our study watershed, based on past household lawncare surveys (Law et al., 2004; Fraser et al., 2013) in the area. Watershed total fertilization (FRT) changed with the area of lawns in different scenarios, while the other three input sources, ATM, FIX_{N_2}, and LKG_{sewer},were assumed to be unaffected by restoration. For seasonal analysis, we defined Spring from March to May, Summer from June to August, Fall from September to November, and Winter from December to February.

3. Results

3.1. Model Accuracy

Calibrated parameters (Table 2) for SLB produced a best fit streamflow time-series of SQ conditions with a NSE of 0.79 to USGS observations (Figure 4a). Mean simulated streamflow for the SQ was 1.38 mm/day, which overestimated USGS measured flow by 12.8% (0.16 mm/day). Dormant season simulations produced higher baseflow than USGS observations, while growing season simulations underestimated streamflow, particularly in dry periods (Figure 4a). The calibrated WRTDS model predicted daily NO_3^- concentrations at Delight with NSE of 0.57 ± 0.01 (Figure 4b).

3.2. Changes in water quantity

Simulated mean daily streamflow (Table 3) for URF, RBS, URF+RBS, and PR, were 1.36, 1.40, 1.37, and 1.43, and mm/day, respectively. Two urban reforestation scenarios, URF and URF + RBS, showed small reductions in mean flow by 0.02 mm/day (-1.8%) and 0.01 mm/day (-1.1%), while other infiltration-based scenarios, RBS and PR, elevated the mean flow slightly by 0.01 mm/day (+0.8%) and 0.04 mm/day (+3.2%), compared to SQ scenario.

To quantify the effectiveness of restoration scenarios during different flow conditions, the SQ streamflow was classified into eight flow percentile groups (Table 3), and the mean streamflow produced by each restoration scenario for each percentile group was calculated. URF and URF+RBS scenarios resulted in lower streamflow for all flow groups compared to the SQ scenario, except for the 50-90% groups for URF+RBS. RBS and PR both increased streamflow for percentile groups below 95%. For stormflows above the 99% percentile, all restoration scenarios reduced stormwater quantity: URF+RBS had the highest effectiveness, while URF, RBS and PR scenarios had reduction of flows compared to SQ scenario (Table 3). From three scenarios with only one type of LID, reforestation, roadside bioswale, and permeable road, stormflows (> 99% percentile) were reduced by 3.9, 8.3, and 3.3 mm/day per unit treated area.

During dry, low-flow periods, the RBS and PR scenarios sustained higher streamflow while the URF and URF+RBS scenarios reduced flows compared to the SQ scenario. During wet periods, streamflow responded to our scenarios differently in different seasons. For example, in 2009 (Figure 5), all scenarios reduced high flows during the growing season, with the URF+RBS scenario having the highest reduction. In contrast, during the transition from dormant to growing season (e.g., April to May), the URF and URF+RBS scenarios increased streamflow during storm days, while the RBS and PR scenarios reduced streamflow during storm events.

The URF and URF+RBS scenarios decreased depth to water table in the dormant season and increased it in the growing season (Figure 6). The RBS and PR scenarios had much smaller effects on water table depth. Over the study period, water table dropped more than 50 mm in the URF and URF+RBS scenarios. PR only resulted in marginal drop of water table by 2.6 mm, and RBS was the only scenario that elevated water table by 5.7 mm.

3.3. Changes in NO_3^- export from terrestrial restoration

The c-Q relationships (Figure 7) for all restoration treatment scenarios had similar patterns, as expected using a consistent WRTDS model. Since our model yielded lower low flows in dry growing seasons than USGS gage observations at SLB, WRTDS simulated NO_3^- concentrations in these drought days were higher than the highest observed and simulated concentration of WRTDS using USGS streamflow records. Overestimated NO_3^- concentrations above 8 mg/L were therefore set to 8 mg NO_3^--N/L (see Method 2.3.2). The simulated mean NO_3^- flux (Figure 8) using USGS flows with WRTDS was 7.86 kg NO_3^--N/ha/year, and the simulated mean NO_3^- flux with the SQ scenario flows was 9.01 kg NO_3^--N/ha/year, which is 1.15 kg NO_3^--N/ha/year (15.6%) higher. The RBS and PR scenarios resulted in higher NO_3^- export than the SQ, with a mean flux of 9.12 (+1.2%) kg NO_3^--N/ha/year for RBS and 9.29 (+3.1%) kg NO_3^--N/ha/year for PR; The URF and URF+RBS scenarios reduced NO_3^- export to 8.89 (-1.3%) kg NO_3^--N/ha/year and 8.97 (-0.4%) kg NO_3^--N/ha/year. The cumulative NO_3^- export function (Figure 9), however, showed minor differences of NO_3^- export behavior after tree or LID implementation scenarios.

The per unit area efficiency of NO_3^- load modification varied among the three types of restoration treatment: one unit area of reforestation in URF reduced NO_3^- export by 0.86 kg NO_3^--N/ha/year while the two infiltration-promoting methods, roadside bioswale in RBS and permeable road in PR, increased NO_3^- export by 3.65 and 3.10 kg NO_3^--N/ha/year. The small areas affected by RBS and PR led to a small effect at the whole watershed scale.

3.4. N change in ecosystem retention processes

Restoration practices altered the biogeochemical processes underlying N retention. The infiltration-based practices (i.e., RBS and PR) increased denitrification rate (Figure 9), both at the LID sites as well as at off-site riparian areas. In contrast, denitrification rate decreased at reforested sites and riparian areas in the URF and URF+RBS scenarios. Results at LID/GI patches, riparian areas, and the watershed were summarized in Table 4. Simulated annual denitrification in SQ scenario was 18.2 kg NO_3^--N/ha/year, with the highest rate in spring (24.2 kg NO_3^--N/ha/year), followed by summer, fall, and winter (17.5, 17.2, and 14.0 kg NO_3^--N/ha/year, respectively). The URF and URF+RBS scenarios lowered annual denitrification to 12.1 (-6.1) and 13.5 (-4.7) kg NO_3^--N/ha/year, while the RBS and PR increased rates to 20.2 (+1.9) and 22.7 (+4.5) kg NO_3^--N/ha/year. In riparian areas, the RBS and PR scenarios increased denitrification rates significantly by 9% and 22%, respectively, while the URF and URF+RBS scenarios decreased by more than 30% compared to the SQ rate. At LID/GI patches with the RBS and PR treatments, mean denitrification rate also increased by 21% and 105% compared to the SQ rates, respectively (Figure 9). However, at LID/GI patches with the URF treatments, the rate decreased by 35% compared to the SQ rate (Figure 9).

Simulated annual vegetation N uptake (Table 4) in SQ scenario was 62.4 kg N/ha/year. Uptake varied seasonally, with the highest rates in summer (166.1 kg N/ha/year), followed by fall, spring, and winter (51.5, 30.0, and 2.1 kg N/ha/year, respectively). N uptake was highly correlated with deciduous tree canopy phenology. The URF and URF+RBS scenarios both increased annual uptake by about 13% for the whole watershed. The RBS and PR scenarios had negligible (< 0.5 kg N/ha/year) effects on N uptake. The 1.2-km^2 reforestation treatment in the URF and URF+RBS scenarios increased N uptake rates in all seasons except for winter. At the reforested patches, the seasonal rates increased to 199.7 (+60.2) and 55.1 (+4.9) kg N/ha/year in summer and fall compared to the SQ rates of 139.5 and 50.2 kg N/ha/year. These treatments decreased N uptake in spring and winter to 28.5 (-5.4) and 1.0 (-2.0) kg N/ha/year compared to 33.9 and 3.0 kg N/ha/year in the SQ scenario.

3.5. Cumulative NO_3^- export change through terrestrial and aquatic restoration

The altered flow regimes produced by the restoration scenarios shifted the NO_3^- export flow distribution (F75), which promoted or reduced estimated in-stream NO_3^- reduction efficiency from stream restoration, i.e., the efficiency of stream restoration increases if more NO_3^- is exported at lower flows (Figure 11). Compared to the F75 value of the SQ scenario (4.21 mm/day), the F75 of the URF (4.46 mm/day) and URF+RBS (4.30 mm/day) scenarios increased by 5.85% and 1.95%, while the RBS (4.13 mm/day) and PR (3.94 mm/day) scenarios had reduced F75 values by 2.11%, and 6.50%, respectively (Figure 12). If all stream reaches were restored with open-canopy design (Equation 1), projected NO_3^- reduction for the SQ scenario was 313.6 g/ha/year. By comparison, URF, RBS, URF+RBS, and PR scenarios resulted in NO_3^- reduction of 308.4, 315.5, 311.8, 320.0 g/ha/year, respectively (Figure 9). In addition, the reforestation of 1.2-km^2 of lawns reduced watershed level fertilization rates to 10.2 kg N/ha/year from the current rate of 18.3 kg N/ha/year (two applications in growing season).

A mass balance analysis of NO_3^- for SLB was performed to estimate NO_3^- load reduction from various input and sink processes. Results (Table 5) showed that the reforestation (i.e., URF and URF+RBS) scenarios reduced NO_3^- sources in the watershed by 31.54 and 30.67 kg N/ha/year. In contrast, the infiltration-based (i.e., RBS and PR) scenarios elevated NO_3^- sources by 0.98 and 2.33 kg N/ha/year, respectively. The URF and URF+RBS involved removal of lawns which reduced fertilization by 8.13 kg N/ha/year. For the infiltration-based scenarios, denitrification rates increased by 1.92 and 4.46 kg N/ha/year in the RBS and PR, but nitrification rates increased more strongly, by 3.28 and 7.27 kg N/ha/year. For URF and URF+RBS, denitrification rates decreased by 6.10 and 4.70 kg N/ha/year as well as nitrification which decreased more significantly by 21.40 and 18.91 kg N/ha/year. Vegetation uptake increased by 7.68, 0.17, 7.98 and 0.44 kg N/ha/year in the URF, RBS, URF+RBS, and PR scenarios. Instream NO_3^- flux estimated by WRTDS changed very little, with URF and URF+RBS reducing load by 0.12 and 0.04 kg N/ha/year and RBS and PR increasing load by 0.11 and 0.28 kg N/ha/year.

4. Discussion

4.1. Seasonal responses of hydrological processes to restoration

Our analysis focused on the efficiency of LID/GI practices in mitigating urban runoff and N regime. We note that each of LID/GI scenarios were modeled without additional built detention storage effects. The LID/GI practices we investigated included both terrestrial green infrastructure to increase infiltration and evapotranspiration, and stream restoration. Both individual and combined effects were considered. As expected, the URF and URF+RBS scenarios that replaced lawn area with tree cover reduced the water yield, especially during the growing season. Over the 11-year simulation period, once forest canopies started to transpire around mid-May, soil saturation deficits in the watershed increased rapidly (Figure 5). The drier soil enabled higher water storage capacity and increased the capacity of the watershed to store storm events, reducing stormflow and increasing baseflow in the growing season. However, our results also suggested that replacing lawns with trees in URF scenario created a short, higher soil moisture period prior to the growing season every year, suggesting altered antecedent conditions of soil could play a major role affecting the effectiveness of LID/GI to mitigate stormwater quantities. We found similar results as Hoghooghi et al. (2018), Fiori & Volpi (2020), and Miles & Band (2015). During this period of a year (e.g., late March to early May, Figure 5), trees start to transpire later than grass after reforestation, resulting in a larger dormant season increase in soil moisture and groundwater table height. However, we also note that our simulations are at daily steps, and may not fully capture peak flows from short but intense storms (e.g., the peak flow quantity would be reflected at daily scale in our model).

In addition, recent studies (Fry & Maxwell, 2017; Hoghooghi et al., 2018; Jarden et al., 2016; Speak et al., 2013) found the effectiveness of rain gardens to reduce peak flows tended to diminish when storm intensity exceeds the storage and infiltration capacities of LID/GI. Siting LID/GI in downslope and wet areas (e.g., riparian areas) in the watershed could even increase the peak flows at watershed outlets (Fiori & Volpi, 2020). Therefore, mitigating floods in urban watersheds using LID/GI requires a thorough evaluation of LID/GI beyond determining the number of LID/GI to be placed. Desirable soil storage and infiltration properties and spatial arrangement of LID/GI should also be considered to yield the optimal environmental gains.

The RBS and PR treatments were able to mitigate stormflows (> 99% quantile), reducing the flashiness of storm hydrographs, but not as effectively as the URF or URF+RBS treatments. The RBS and PR scenarios often had lower streamflow than the SQ scenario during storm days, but higher flows one day after. In other words, they helped to reduce the peak stormflow and create a gentler recession limb after storm events. Other empirical studies (Bell et al., 2016; Jefferson et al., 2017; Miller et al., 2021; Schmitter et al., 2016) found limited effectiveness of LID/GI to attenuate flood peaks in existing development and that reduction of more moderate flows is dependent on temporary detention storage and release. Our modeling evaluation further included the spatial arrangement of LID/GI into consideration, with converting all possibly restored areas within the watershed. Our results were consistent with the empirical studies, suggesting even large-scale terrestrial restoration may not yield expected outcomes. The finding also highlighted the need to include grey infrastructures with LID/GI to increase the capacity of detention storage, reduce flashiness of flow regime, and better regulate stormwater peaks in urban watersheds.

The outcomes from all our LID/GI scenarios indicated that solely implementing large-scale of LID/GI practices in older urbanized areas might have limited effectiveness and be insufficient to achieve flood mitigation goals. None of our restoration scenarios showed significant changes of the flashy flow regimes (Figure 11), possibly because the high imperviousness of the watershed (i.e., roofs, driveways, and roads) were not treated adequately to shift towards pre-urbanization conditions without incorporating sufficient detention storage (Jefferson et al., 2017). Moreover, soil compaction in urban areas also reduced soil permeability (e.g., porosity and hydraulic conductivity), resulting in less infiltration and more surface runoff. Introducing engineered soils (Xiao & McPherson, 2011) with appropriate hydraulic properties or performing soil subsoiling/decompaction (Schwartz & Smith, 2016) at LID/GI sites could improve soil conditions, reduce surface runoff, enhance infiltration, and abate flashy flow regimes in urban watersheds.

4.2. Change in components of NO_3^- fluxes

The altered flow regimes produced by the URF and URF+RBS scenarios led to reduced stream NO_3^- export compared to the SQ scenario. In contrast, the RBS and PR scenarios that increased infiltration and baseflows elevated terrestrial export. The higher base flow discharge directly increased NO_3^- fluxes due to the higher NO_3^- concentrations in baseflow. The URF scenario reduced baseflows and NO_3^- flux the most (Table 3). The lack of a significant mitigation of NO_3^-

export towards pre-urbanization conditions in our simulations are consistent with empirical results of Hopkins et al. (2022), although our study involved existing urban site restoration, while Hopkins et al. studied new development with varying levels of LID/GI implementation.

The altered flow regimes and NO_3^- export produced by the upland LID/GI practices, without additional detention storage, had marginal effects on the effectiveness of in-stream restoration. The three scenarios that increased infiltration, baseflow, and NO_3^- export (PR, RBS, and URF+RBS) increased the efficiency of stream restoration compared to the SQ scenario. This increase was likely driven by the higher NO_3^- concentrations and loads in the stream at low flows, which is when stream restoration is most able to facilitate NO_3^- uptake. In contrast to the infiltration scenarios, the URF scenario reduced the efficiency of stream restoration (Figure 11). One possible reason for the reduction in efficiency with the URF scenario is that increased tree canopy uptake resulted in lower NO_3^- delivery to riparian areas and streams, and reduction opportunities for aquatic retention, especially during low flows.

The magnitudes of the changes in stormflow and in-stream NO_3^- load change from LID/GI and stream restoration calculated by the coupling of RHESSys derived streamflow change with WRTDS were small (Figure 12) at the watershed scale. In contrast, changes of internal terrestrial ecosystem NO_3^- retention processes (i.e., denitrification and uptake) derived from RHESSys were much larger, suggesting higher N sinks due to vegetation uptake and denitrification could contribute to significant reduction of N loads (Table 5). The simulated denitrification rate in the SQ scenario (18.2 kg N/ha/y) is consistent with measured lawn denitrification, 14.1 kg N/ha/year, in Baltimore (Raciti et al., 2011), which is much higher than any fluxes associated with stream restoration. Similarly, vegetation uptake rate in forested patches, 110.5 kg/ha/year, is also consistent with literature findings (Cole, 1981; Norby & Iversen, 2006) and very high compared to stream restoration effects. The increase in tree canopy from URF significantly increased uptake, as trees have greater LAI and biomass than grass and consume more N to grow and maintain functionality. The reduction in input from fertilizer associated with conversion of 1.2-km^2 of lawns to forest in the URF scenarios was also significant. The infiltration-based RBS and PR scenarios increased baseflow and induced higher denitrification rates than in the SQ scenario (Figure 9), as the higher infiltration rate provided wetter and more anoxic soil conditions that favor denitrification, showing both on-treatment site and off-site impacts at riparian areas. However, the higher moisture level in soil after infiltration-based LID also elevated internal NO_3^- production by nitrification. The increase in NO_3^- production by nitrification was larger than the increase in NO_3^- consumption by denitrification, so the net effect of the RBS and PR scenarios was to make more NO_3^- available for transport to streams. These treatments increased NO_3^- retention associated with stream restoration, but this effect was much smaller than the increase in NO_3^- flux from nitrification. This effect was also much smaller than the increase in plant uptake after the reforestation-based URF scenario. These results highlight the importance of tree coverage, plant uptake, fertilizer application, and denitrification in urban watersheds, which have larger effects on NO_3^- load compared to stream restoration.

4.3. Uncertainties and future improvement to the framework

While our models have been calibrated, there is still bias in our streamflow simulation compared to USGS observations. The RHESSys model overestimated streamflow during low-flow days in the dormant season and underestimated flow during dry days in the growing season. The low flows caused WRTDS to significantly overestimate NO_3^- concentration at the lowest flows but had little effect on the annual NO_3^- load (< 0.1 kg/ha/year). The lack of simulated sewer inflow and infiltration (I&I) in our current RHESSys model possibly caused the bias in streamflow estimation, and the bias could propagate to WRTDS and cause under- or overestimation of N loads. Infiltration into sanitary sewers may be sufficient to cause significant bypass of the stream gauge (Bhaskar & Welty, 2012), and reduce streamflow when groundwater tables are high. On the other hand, exfiltrating effluent from sanitary sewers may increase groundwater flow and recharge (Delesantro et al., 2022), increasing subsurface nutrient delivery to streams. Using WRTDS to estimate NO_3^- flux change for each restoration scenario encompasses all sources and retention effects. However, WRTDS is not able to evaluate the effects of LID/GI on soil water and biogeochemical processes, especially plant uptake. Therefore, we used RHESSys to better capture the changes in uptake and denitrification caused by LID/GI, and their effects on watershed NO_3^- loads. For example, RHESSys and WRTDS both suggested similar increases in instream NO_3^- load increases in scenarios (i.e., RBS and PR) with infiltration-based LID/GI. However, the large effects of reforestation on water and NO_3^- dynamics could not be simulated in WRTDS, so the ecohydrological detail of RHESSys was needed to quantify the effects of the reforestation scenarios. The two models were thus able to complement each other and overcome their individual limitations. The analytical framework would be improved with better understanding and simulation of sewer inflow and effluent. There is a clear need for additional measurement and modeling of sewer I/I and leakage.

We also note various LID/GI scenarios significantly affected groundwater, and that the assumption that N leakage from sewers is consistent and independent of changes in groundwater and biogeochemical processes induced by LID may not hold. A better understanding of how engineered and natural systems interact would improve our ability to model and managed urban watersheds. The combination of "green" and "grey" solutions (e.g., wetlands restoration, sewer infrastructure retrofit) could also better address the urban flashy flow and NO_3^- export regimes. Lastly, we noted the framework could reasonably assess relative changes of various scenarios of ecosystem restoration from the current conditions, but the absolute changes/results still need further improvement of models until the missing key hydrological processes are included in RHESSys in the future. We also noted our results were derived from a single set of parameters that yield the highest NSE. However, to comprehensively assess uncertainties in ecohydrological and biogeochemical responses, conducting additional simulations using other high-NSE parameter combinations would be recommended.

5. Conclusion

Addressing our research questions, our results indicated that all tested terrestrial restoration methods could mitigate stormflow yield independent of significant detention storage modification, but only modestly. Large scale replacement of lawns with tree cover in URF and URF+RBS scenarios promoted transpiration from increased tree canopy and lowered soil saturation levels, with the exception of periods just before deciduous tree leaf-out. The URF+RBS scenario allowed additional infiltration and evapotranspiration of forest and road drainage, mitigating flood severity the greatest, especially during growing seasons when intense convective storms occur frequently in Baltimore. Infiltration-based LID/GI types (i.e., RBS and PR) increased infiltration which mitigated stormflows but increased baseflow.

Results pertaining to on- and off-site impacts on urban biogeochemical retention of N varied by LID/GI scenarios. URF and URF+RBS scenarios mitigated NO_3^- export by lowering streamflow and increasing vegetation uptake. Infiltration-based RBS and PR scenarios increased NO_3^- loads from enhanced baseflow regimes partially offset the NO_3^- reduction from stream restoration but promoted nitrification and denitrification significantly. NO_3^- retention from denitrification and vegetation uptake were both an order of magnitude greater than the retention from streamflow change and stream restoration. Replacing lawns with forests also displaced fertilization NO_3^- sources. The significant increase of NO_3^- uptake from reforestation and infiltration-based LID/GI suggests increasing tree coverage and LID/GI could be more efficient in retaining NO_3^- within watersheds and reducing load export in streams than stream restoration. Sanitary sewer effluents are assumed unchanged after any types of LID/GI restoration and imperfectly modeled in this study, which introduced uncertainties to instream NO_3^- flux estimation. Further studies are needed to better understand and model these processes to balance N fluxes within watersheds.

Lastly, we found that retrofit of existing development by implementation of increased tree canopy, roadside bioswales, and permeable roads, independent of detention storage, in the medium development intensity watershed did not shift either flow or NO_3^- export regime regimes significantly. Specifically, their capacity to neutralize urban stream syndromes (e.g., higher peak flow, channel erosion, higher nutrient export, etc.) may be limited. Therefore, other types of facilities and efforts (e.g., detention ponds, wetlands, reduced septic and sanitary sewer leakage, etc.) that have greater capacity to regulate stormflows from surface runoff and subsurface N load sources are needed to be coupled with terrestrial LID/GI and aquatic restoration to not only shift the flow and NO_3^- export regimes toward natural and pre-urbanization conditions but also increase the resiliency and ecosystem health of urban watersheds in the future.

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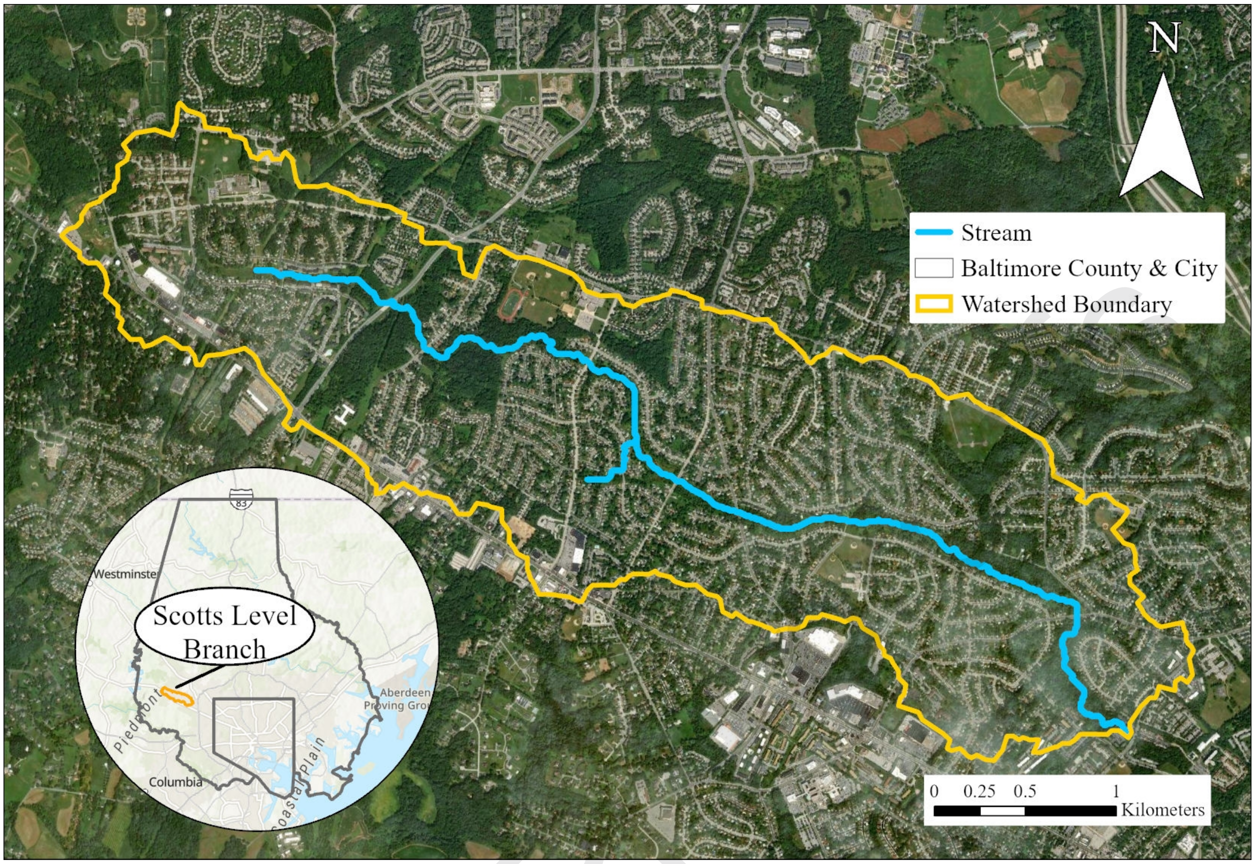

Figure 1. Scotts Level Branch watershed and its delineated stream (see Methods).

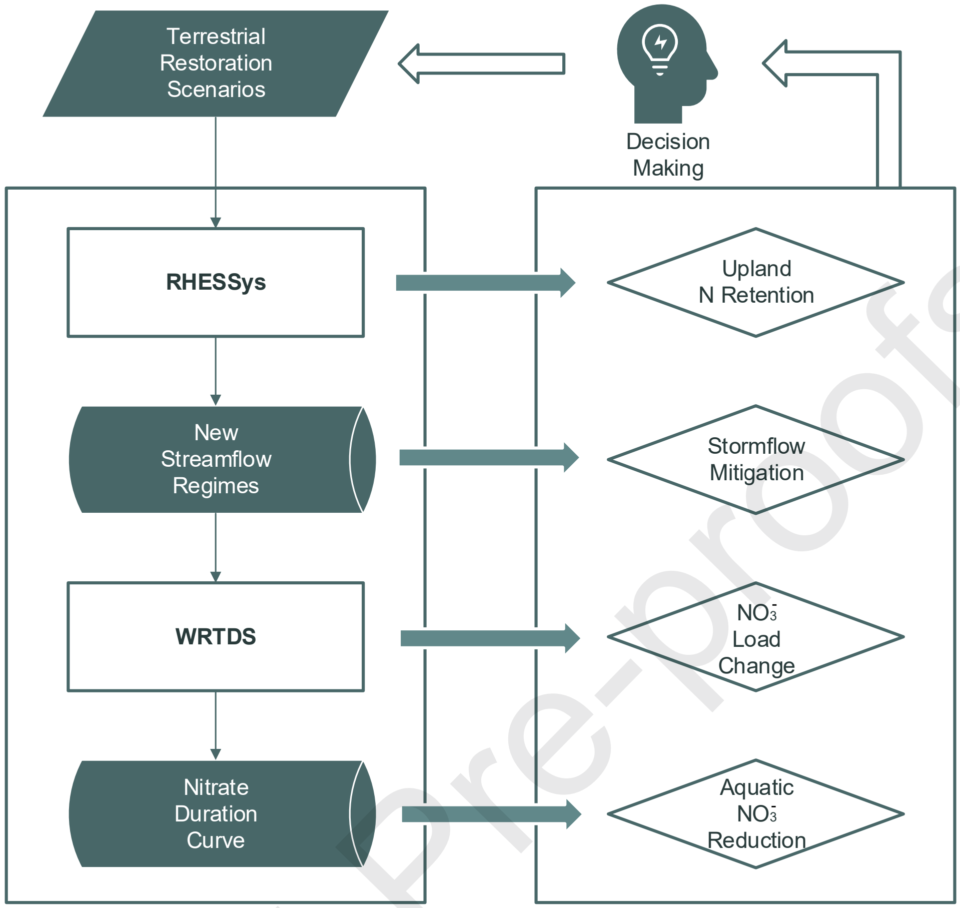

Figure 2. The workflow and structure of proposed framework, which simulates new streamflow regimes and terrestrial ecosystem N cycling from RHESSys and corresponding NO_3^- export regime, to evaluate the effectiveness of ecosystem restoration scenarios in urban watersheds. Aquatic NO_3^- reduction is estimated using regression models developed by Lin et al. (2021) and Zhang et al. (2022).

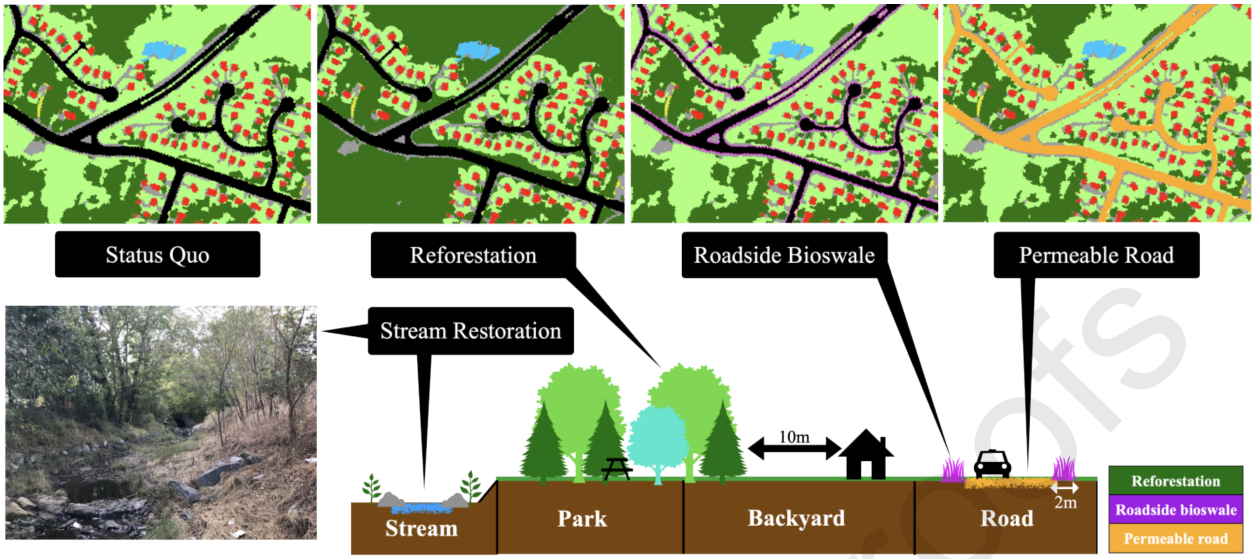

Figure 3. Stream restoration and 1-meter LULC implementing low impact development scenarios: reforestation (URF), roadside bioswale (RBS), and permeable road (PR), in Scotts Level Branch. URF+RBS is the combination of URF and RBS. The photo on the lower left corner shows a finished stream restoration project in Scotts Level Branch.

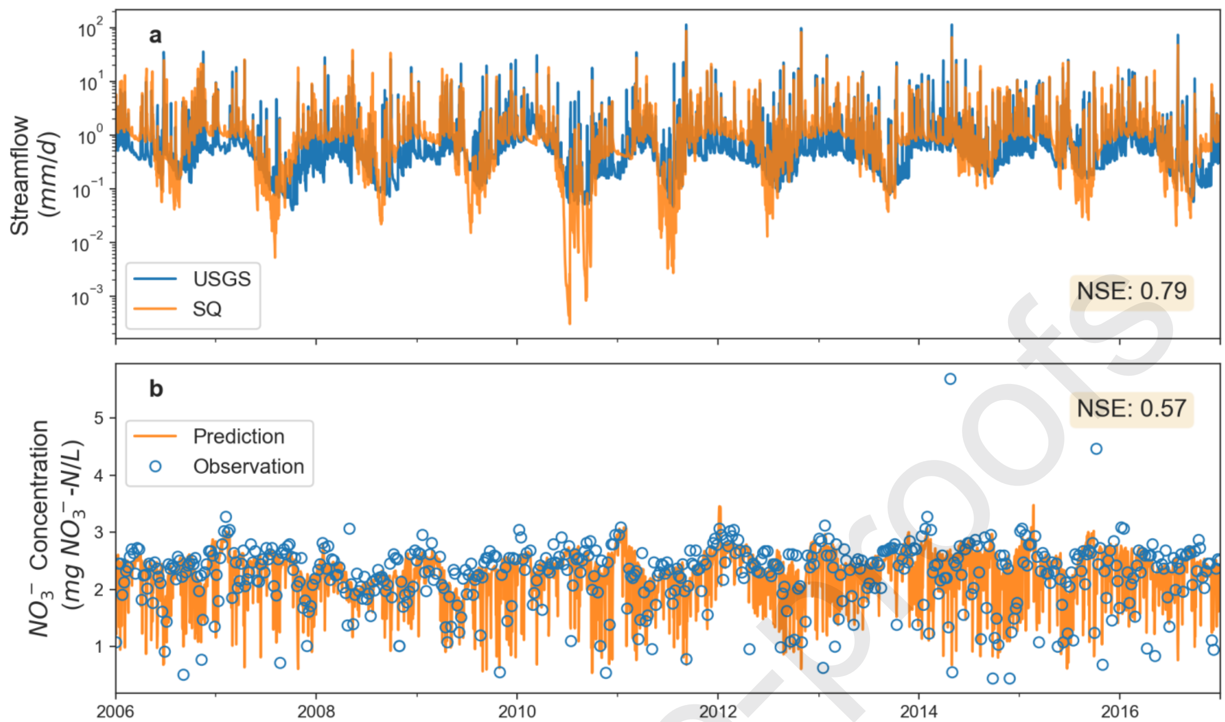

Figure 4. Simulation results for RHESSys streamflow at Scotts Level Branch and mean WRTDS NO_3^- concentration at Delight (bootstrap for 50 times).

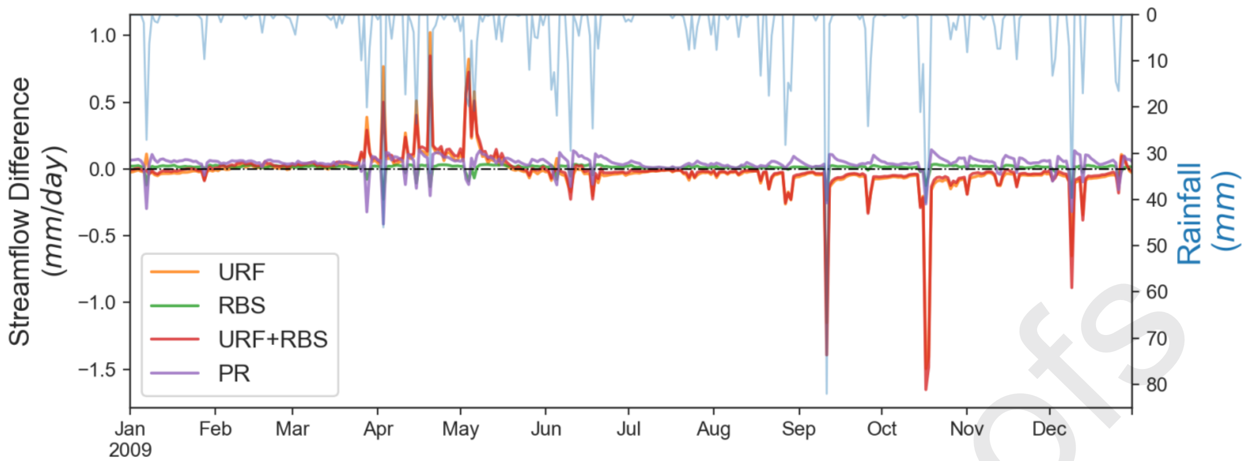

Figure 5. Scotts Level Branch's rainfall and difference of streamflow between status quo and other LID scenarios in 2009.

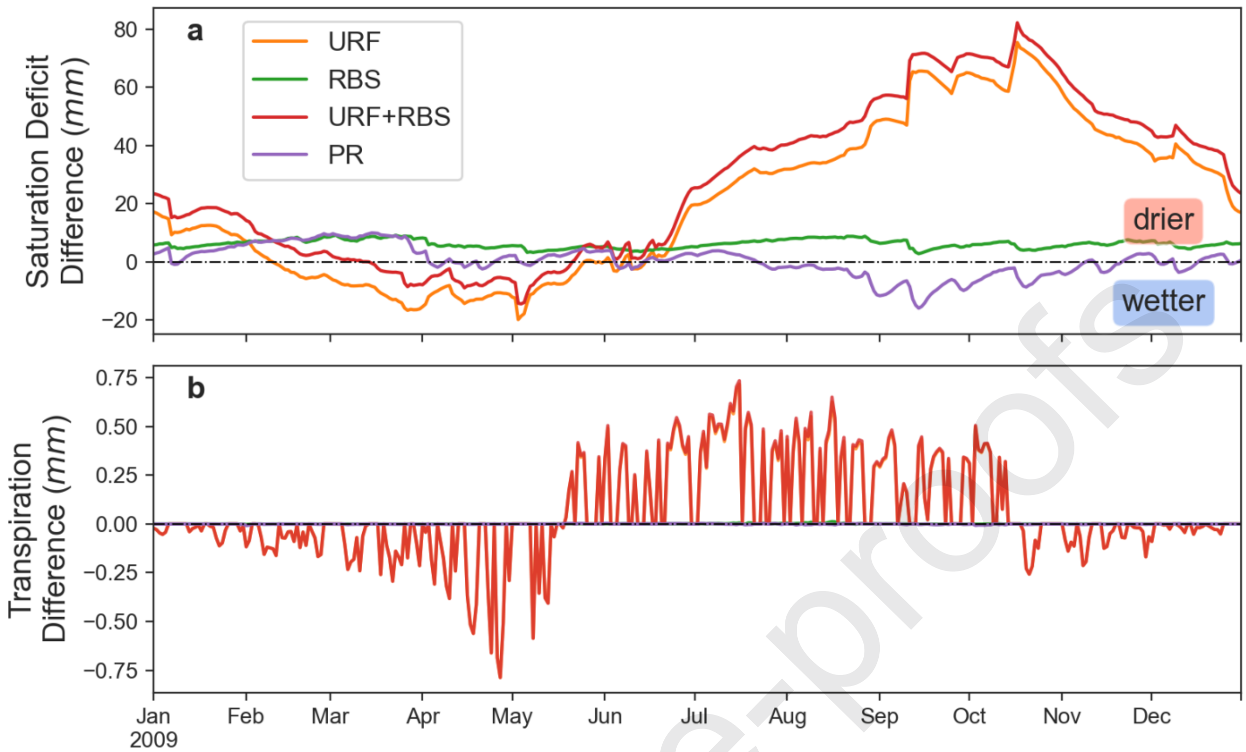

Figure 6. Difference of (a) water table depth and (b) transpiration for all scenarios in 2009 at Scotts Level Branch. Transpiration difference for RBS and PR are almost negligible compared to URF and URF+RBS.

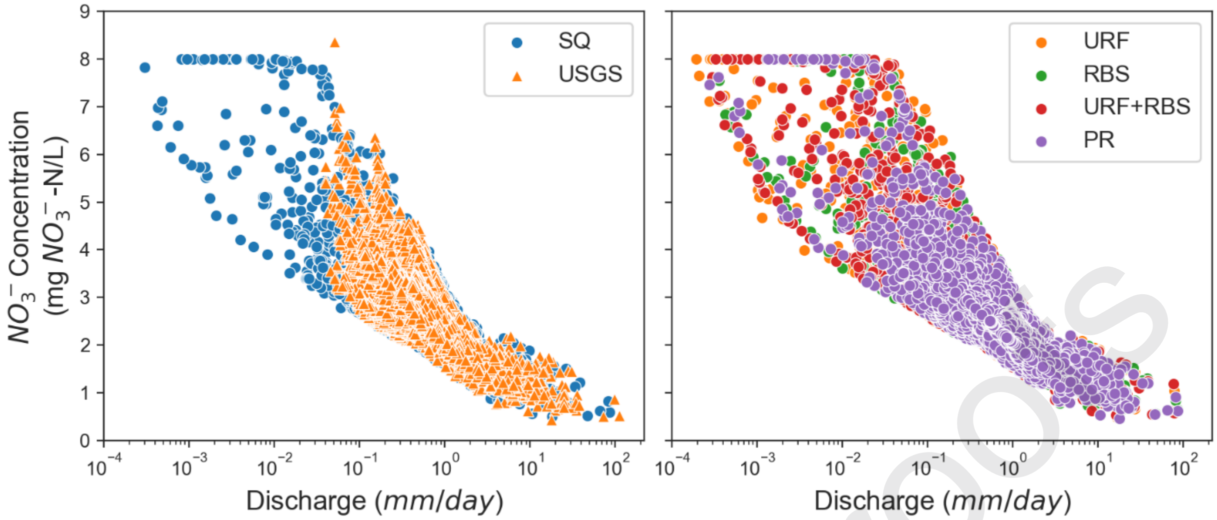

Figure 7. Simulated relationship between NO_3^- concentration and discharge (c-Q) from WRTDS using USGS streamflow records and SQ streamflow simulations (left) and restoration scenarios simulations (right).

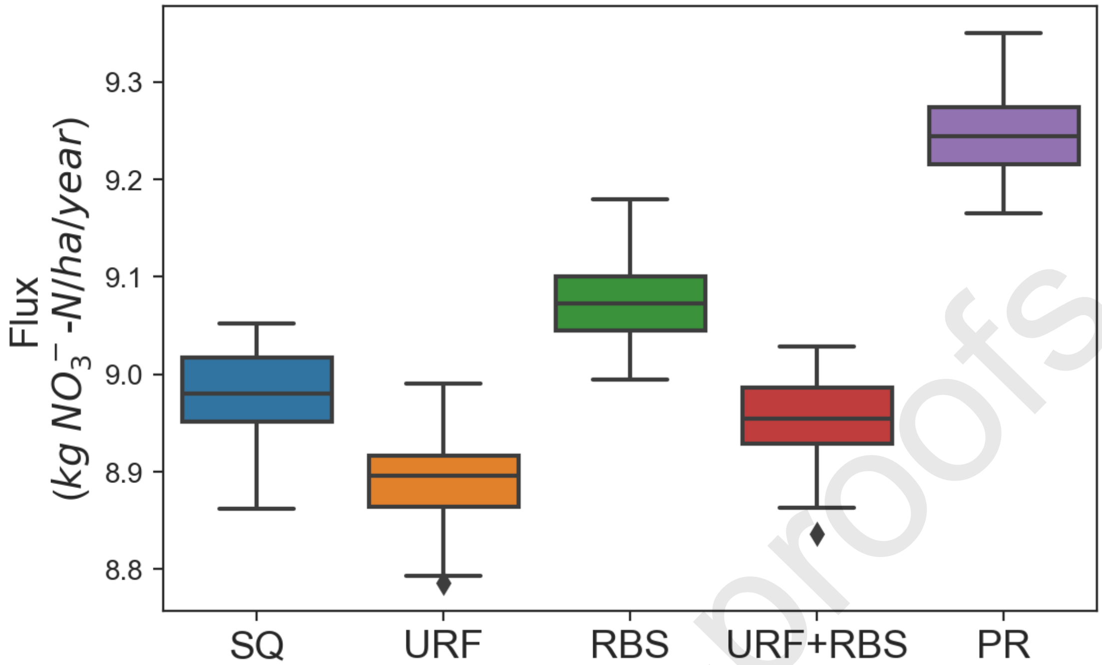

Figure 8. Estimation of mean annual flux load of NO_3^- (kg NO_3^--N/ha/year) for each scenario, simulated from WRTDS and corresponding streamflow simulation of RHESSys.

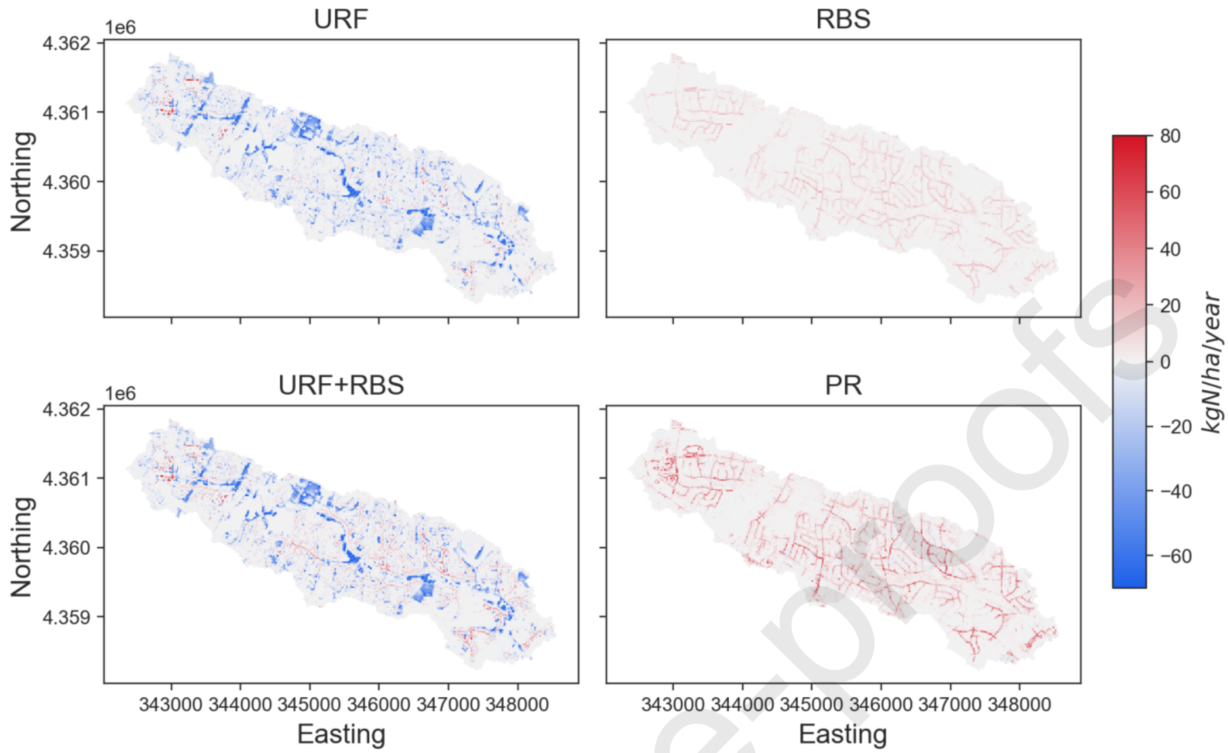

Figure 9. Denitrification change (kg N/ha/year) from SQ at each patch (15 m) in Scotts Level Branch (in projection of NAD83 UTM 18N, meter).

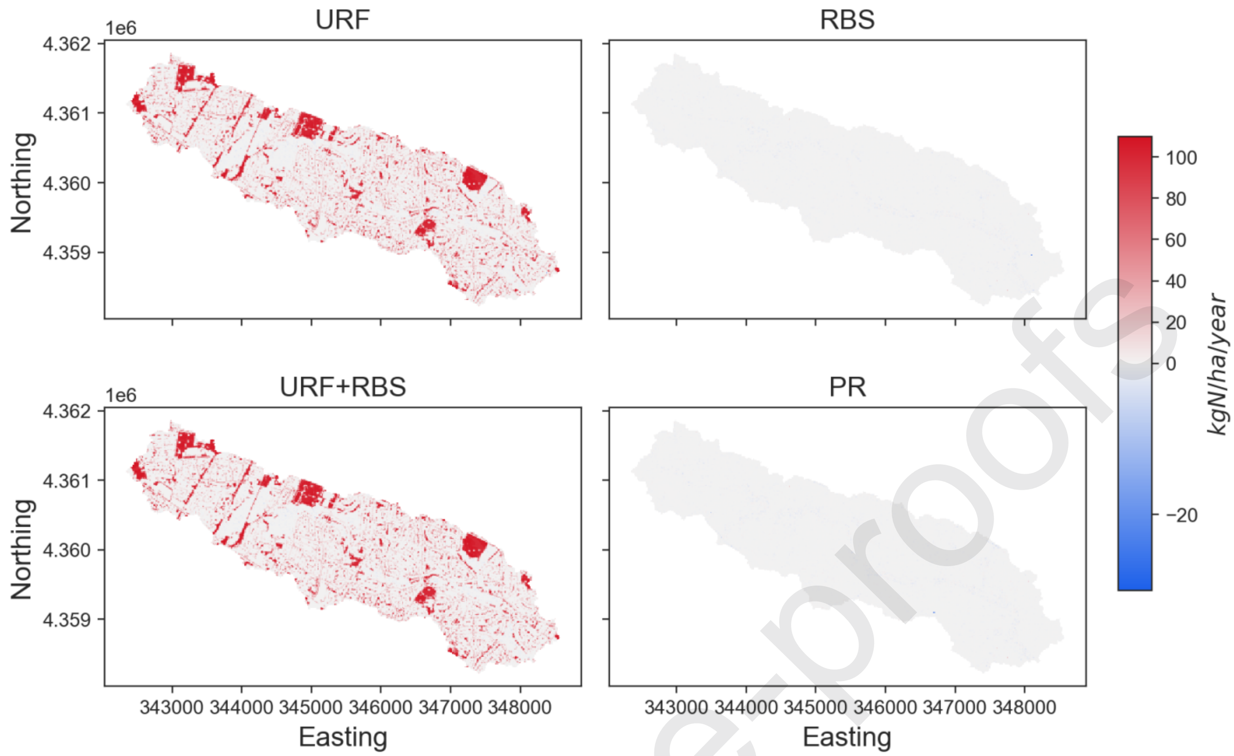

Figure 10. Uptake change (kg N/ha/year) from SQ at each patch (15 m) in Scotts Level Branch (map projection: NAD83 UTM 18N, meter).

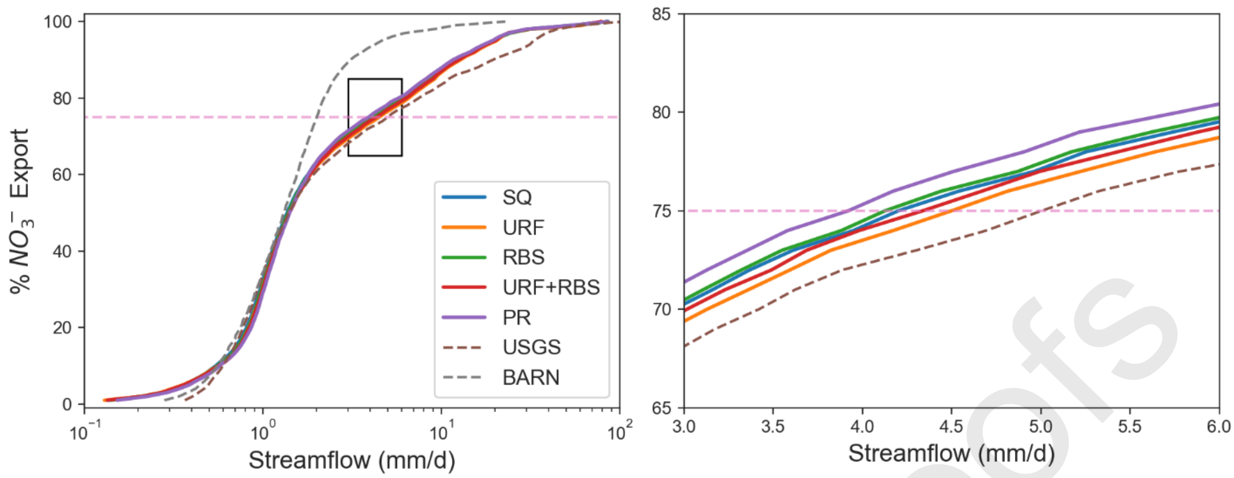

Figure 11. Nitrate (NO_3^-) load duration curve for all scenarios (left), with the Baisman Run in Baltimore (BARN) as a less developed reference, and detailed zoom-in to F75 (right). The 75% NO_3^- export line (grey dashed) is highlighted to aid find corresponding F75 streamflow values.

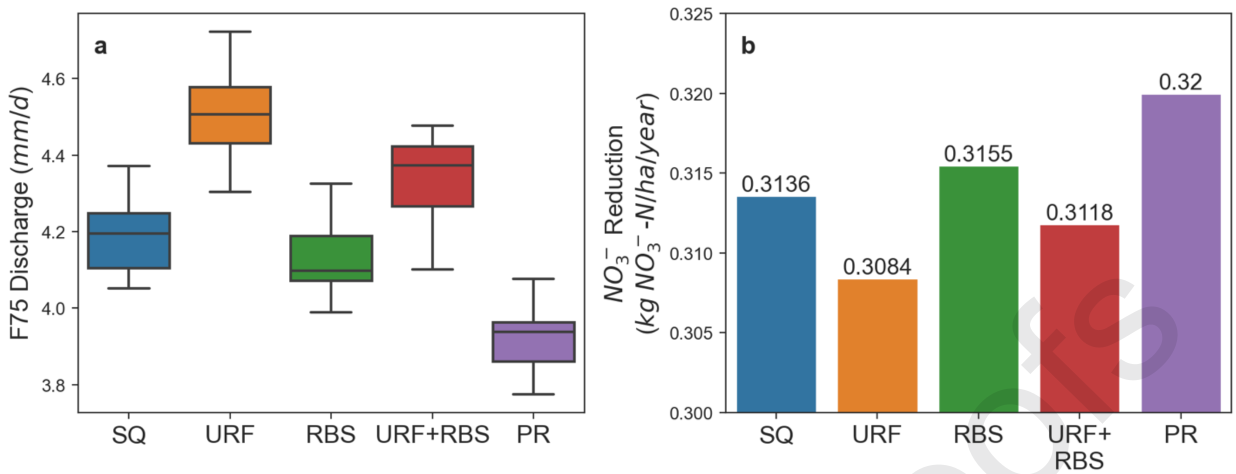

Figure 12. Estimation of F75 (left) and corresponding nitrate (NO_3^-) reduction (kg NO_3^--N/ha/year, right) from stream restoration under open-canopy condition.

Table 1. Description of rules for changing land use and cover and details of sizes converted in SLB.

Scenario	**Details**	**Area Converted (km^2)**
Status Quo (SQ)	The current land use and cover (LULC) condition	-
Urban Reforestation (URF)	Change lawns that are more than 10m from buildings to forest	1.20
Roadside Bioswale (RBS)	Convert the 2m zones (inward) of both sides of current road to bioswale with shrub	0.26
Permeable Roads (PR)	Convert all roads to permeable pavements with K_{sat} = 5	0.78
Urban reforestation and roadside bioswale (URF+RBS)	Combination of urban reforestation and roadside bioswale	1.46

Note: No soil change was considered in RBS. PR increased the saturated hydraulic conductivity (K_{sat}) to 5 for all roads within the study watershed.

Table 2. Calibrated multipliers for RHESSys parameters generating the highest NSE for streamflow.

Sensitivity Parameter	Name	Details	Value
s	m	decay of hydraulic conductivity with depth	0.991
	K	hydraulic conductivity at the surface	0.407
	depth	soil depth	2.799
sv	m	vertical decay of hydraulic conductivity with depth	0.751
	K	hydraulic conductivity at the surface	0.835
svalt	po	pore size index	0.905
	pa	air entry pressure	1.427
gw	sat_to_gw_coeff	bypass fraction to deep groundwater	0.052
	gw_loss_coeff	groundwater storage/outflow parameters	0.189

Note: Details of parameter calibration can be found from RHESSys documentation (https://github.com/RHESSys/RHESSys/wiki/Spinning-up-and-Calibrating-RHESSys#model-calibration)

Table 3. Comparison of mean streamflow (mm/day) at percentile groups from SQ and LID restoration scenarios from 2006 to 2016.

Percentile Group	SQ	URF	RBS	URF+RBS	PR
0 - 5%	0.08	0.06	0.09	0.06	0.11
5 - 25%	0.25	0.21	0.26	0.22	0.29
25 - 50%	0.66	0.64	0.68	0.65	0.72
50 -75%	1.03	1.02	1.05	1.04	1.10
75 - 90%	1.59	1.57	1.61	1.60	1.67
90 - 95%	2.91	2.89	2.92	2.89	2.92
95 - 99%	7.26	7.25	7.19	7.18	7.12
99 - 100%	24.19	23.65	23.94	23.38	23.89
Mean	1.38	1.36	1.40	1.37	1.43

Table 4. RHESSys derived denitrification and uptake rate at the whole watershed, riparian areas, and LID/GI patches before (SQ) and after terrestrial LID/GI restoration scenarios.

Nitrogen Pathway	Location	Scenario Rate (kg N/ha/year)				
		SQ	URF	RBS	URF+RBS	PR
Denitrification	Watershed	18.2	12.1	20.2	13.5	22.7
	Riparian Area	34	20.4	36.9	22.8	41.4
	URF Patches	21.5	14	-	16	-
	RBS Patches	13.1	-	19.4	15.9	-
	PR Patches	13.2	-	-	-	27.1
Nitrogen Uptake	Watershed	62.4	70.1	62.6	70.4	62.8
	Riparian Area	89.7	96.5	89.9	96.9	90.1
	URF Patches	56.7	71.1	-	71.5	-
	RBS Patches	38.5	-	38.9	46.4	-
	PR Patches	38.5	-	-	-	39.3

Note: Results for scenarios without designed types of LID/GI implemented are masked.

Table 5. NO_3^- budget component fluxes and load reduction (kg NO_3^--N/ha/year) from current condition (SQ) and corresponding load changes in four pathways for nitrate (NO_3^-) retention in restoration scenarios.

Model simulation from	**Pathways**	**NO_3^- load**	**Annual NO_3^- load reduction of restoration scenarios from SQ**			
		SQ	URF	RBS	URF+RBS	PR
WRTDS	Flux	9.01	0.12	-0.11	0.04	-0.28
RHESSys	Fertilization	18.29	8.13	0.00	8.13	0.00
	Denitrification	18.20	-6.10	1.92	-4.70	4.46
	Nitrification	51.87	21.40	-3.28	18.91	-7.27
	Uptake	62.35	7.68	0.17	7.98	0.44
	Stream Restoration*	0.31	0.31	0.32	0.31	0.32
	Total Change	-	31.54	-0.98	30.67	-2.33

Note: Expected absolute reductions of NO_3^- load by restoring all streams in SLB are reported in "Stream Restoration*" row. Full-watershed stream restoration has not yet achieved in SQ, and we reported reductions with corresponding F75 for LID/GI scenarios assuming all streams are restored with open-canopy condition (Eq. 1, Zhang et al. 2022).

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Abstract

Urban watersheds have experienced ecosystem degradation due to land cover change from vegetation to impervious areas. This transformation results in increased stormwater runoff, stream channel erosion and sedimentation, and both increased inputs and reduced ecosystem retention of nutrients. Ecosystem restoration practices, including terrestrial and aquatic low impact development (LID), are becoming widely implemented in urban watersheds globally. A major question is how "green" and "grey" infrastructure can be optimally balanced to shift ecohydrological behavior towards pre-urbanization conditions. Traditional stormwater engineering typically controls runoff by temporary storage (detention) and release of stormwater, while LID designs are developed to reduce runoff by a combination of infiltrating precipitation and evapotranspiration, while promoting biogeochemical retention of nutrients. These practices are often combined with stream and riparian restoration that increases nutrient retention and reduces in-stream loads. In this study, we simulated the potential impact of three types of terrestrial LID and green infrastructure (GI) on watershed runoff and nitrate (NO_3^-) loading to local streams, independent of detention storage effects. The treatments included increased tree canopy, vegetated roadside bioswales, and permeable pavement. We then evaluated the individual and interactive impacts of these practices on the effectiveness of NO_3^- load reduction provided by stream restoration, which is affected by the altered runoff and nutrient loading caused by the LID and GI. Urban reforestation provided the highest effectiveness in terms of reducing stormflow and nutrient export, while bioswales and permeable pavement unexpectedly increased in-stream NO_3^- loads. Retrofit of the previously developed watershed by LID/GI alone may not provide sufficient mitigation in stormwater and nutrient loads, and should be balanced with additional grey infrastructure, such as detention ponds, rain cisterns, and sewer system upgrades.

Ruoyu Zhang: Conceptualization, Methodology, Software, Validation, Formal analysis, Visualization, Writing – original draft. **Lawrence E. Band:** Conceptualization, Resources, Funding acquisition, Writing – review & editing. **Peter M. Groffman:** Conceptualization, Resources, Writing – review & editing.

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Scenarios with massive implementation of LID/GI in an urban watershed showed modest streamflow reduction at stormy days.
- Infiltration-based LID could increase baseflow, but result in higher nitrate load in streams.
- LID/GI changed nitrification, denitrification, and tree canopy uptake, not only at "on-site" locations but also "off-site" downstream riparian areas.
- Nitrate retention from stream restoration had no significant change after upland LID/GI restoration.
- Coupling LID/GI and detention infrastructures could better shift urban flow and nitrate load regimes toward pre-urbanization conditions.