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Evaluating the longevity of in-stream phosphorus legacies: A downstream cascade of recovery following point source remediation

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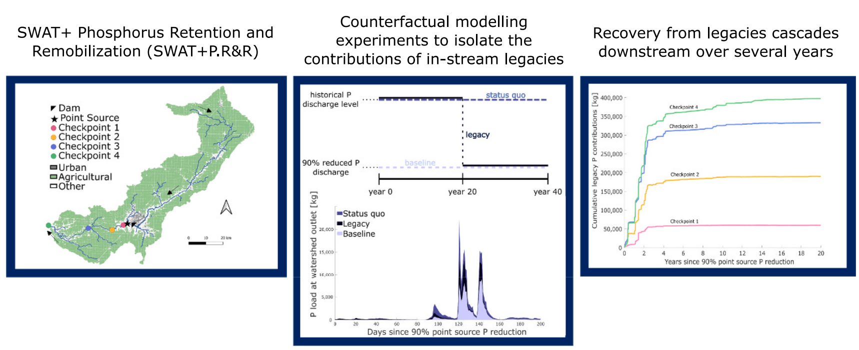
HIGHLIGHTS

- We model counterfactual watershed scenarios to isolate the contributions of in-stream legacies to phosphorus (P) loads.
- Results quantify cascading P load recovery, where recovery takes longer at locations further downstream from remediation.
- In a U.S. corn belt watershed, in-stream legacies are not exhausted until 9 years after remediation.

GRAPHICAL ABSTRACT



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ABSTRACT

In-stream phosphorus (P) legacies cause lags between upstream remediation and downstream load reductions. However, the length of these lags is largely unknown, especially for long stream distances. As a result, lag time estimates at the large-watershed scale have been abstract and sometimes understated. Here, we leverage a large area watershed model with newly improved in-stream P simulation (SWAT+P.R&R) to evaluate the magnitude, longevity, and spatial cascade of legacy P remobilization in a U.S. corn belt watershed. Our results illustrate the "spiraling recovery" of P loads after a hypothetical point source remediation, where locations further downstream take longer to recover to baseline load levels. At the watershed outlet, in-stream legacy P contributions are equivalent to 30% of the baseline average annual P loads for three years after remediation. In-stream legacies do not approach exhaustion (95% remobilized) until at least 9 years after remediation. In hypothetical weather scenarios beginning with dry years, legacy contributions persist even longer. These findings (1) suggest that in-stream legacies could impact P loads for years to decades in large river basins, (2) support explicit accounting for spatial scale in future studies of in-stream legacies, and (3) provide concerning implications for water quality recovery in large river basins.

Abbreviations: P, phosphorus; SWAT+P.R&R, Soil and Water Assessment Tool plus Phosphorus Retention and Remobilization; USRW, Upper Sangamon River Watershed; SDD, Sanitary District of Decatur; NPS, non-point source.

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1. Introduction

Remobilization of legacy phosphorus (P) has thwarted the achievement of P load reduction goals for river basins worldwide (Kleinman et al., 2019; McCrackin et al., 2018; Muenich et al., 2016; Powers et al., 2016; U.S. Environmental Protection Agency, 2022). Moreover, the length of time these legacy impacts will last is still largely unknown (Lintern et al., 2020; Meals et al., 2010; Sharpley et al., 2013; Withers et al., 2014). Particular to legacy P located *within streams*, it has been difficult to scale up residence times from a river reach to a large watershed (Basu et al., 2011; de Vente and Poesen, 2005; Haygarth et al., 2012; Powers et al., 2016; Sharpley et al., 2013; Withers and Jarvie, 2008) especially when considering total P rather than dissolved P only (Simpson et al., 2021; Weigelhofer et al., 2018). Some studies have focused only on dissolved P, the form that directly contributes to algal blooms and hypoxia (Davis et al., 2009; Jarvie et al., 2017; Smith et al., 2015), and have suggested that in-stream legacy impacts on dissolved P loads last <1 year (Jarvie et al., 2013, 2006; Meals et al., 2010) and are insignificant in magnitude compared to annual loads (Jarvie et al., 2008; McDaniel et al., 2009). However, particulate P can be transformed into dissolved P during or after transport, especially in rivers that discharge to marine environments, making particulate P relevant as well (Froelich, 1988; Hu et al., 2020; Jordan et al., 2008; Jordan et al., 1991). While particulate P might only be stored within a given river reach for a short time, e.g., until the next high flow event (Collins et al., 2005; Dorioz et al., 1998; Jarvie et al., 2012; Owens et al., 2001; Walling et al., 1998), particulate matter moves downstream in a stop-and-start fashion and could take years or decades to traverse long distances (Ancey, 2020; Einstein, 1942; Emelko et al., 2016; Hamilton, 2012; Pizzuto et al., 2014; Trimble, 2009). Indeed, for both dissolved and particulate P forms, water quality improvements (i.e., lower P concentrations in the water column) should be expected to cascade downstream in a “spiraling recovery” of sorts, with greater distance from remediation associated with longer times to recover and reach a new equilibrium (Chen et al., 2018; Ensign and Doyle, 2006; Newbold et al., 1983; Sharpley et al., 2013; Withers and Jarvie, 2008).

However, estimates for the longevity of in-stream P legacies in large watersheds, i.e., cascading for long stream distances, are rare and abstract (Chen et al., 2018; Hamilton, 2012; Meals et al., 2010; Sharpley et al., 2013; Withers et al., 2014; Withers and Jarvie, 2008). Estimates at scale are especially important for in-stream legacies, compared to legacies in soils, because channel residence times increase with watershed area while hillslope residence times do not (Botter et al., 2010; Botter and Rinaldo, 2003; Hrachowitz et al., 2016). Long-term, cascading recovery is exceedingly difficult to observe: a suitable sampling campaign would have to be high-frequency (to capture fleeting sediment transport events), long-term (i.e., multiple years or decades), spatially vast, and include measured remediation (Lijklema, 1993; Pace et al., 2022; Withers and Jarvie, 2008). Even having such data, attributing observed P loads to specific sources, e.g., in-stream legacies versus contemporary landscape yields, is an open challenge (Apostel et al., 2021; Jarvie et al., 2012; Kreiling et al., 2023; Stackpoole et al., 2019; Westphal et al., 2019; Withers et al., 2014). Counterfactual simulations with watershed models could help resolve the source attribution challenge, but until now, modelling tools had not been suitable for evaluating large-scale, cascading water quality recovery: models either had been computationally restricted to small spatial scales or lacked mechanisms for in-stream P accumulation and remobilization (Chen et al., 2018; Haygarth et al., 2012; Lijklema, 1993; McCrackin et al., 2018; Van Meter et al., 2021; Wallington and Cai, 2023).

Lacking concrete evidence to the contrary, short timescales (e.g., less than one year) have sometimes been assumed for in-stream legacy impacts on total P loads, without regard for streamwise distance (i.e., for watershed scale) (Jarvie et al., 2012, 2013; Meals et al., 2010). In fact, in the Mississippi River Basin, at least four state-level nutrient loss reduction plans have set interim goals that exactly match the timing of goals set by the Gulf of Mexico Hypoxia Task Force – to reduce P loads by 25% before the year 2025 (Illinois Environmental Protection Agency, 2021; Indiana State Department of Agriculture, 2021; Missouri Department of Natural Resources, 2023; Tennessee Department of Environment and Conservation, 2021; U.S. Environmental Protection Agency, 2014). These plans implicitly assume that in-stream legacies will not cause any lags between the load reductions achieved at a state's borders and those at the mouth of the Mississippi River. Thus, the plans may not be realistic.

Here, we leverage a large-area watershed model with newly improved in-stream P simulation (Soil and Water Assessment Tool + Phosphorus Retention and Remobilization, SWAT+P.R&R) to evaluate the magnitude, longevity, and spatial cascade of legacy P remobilization after a hypothetical point source P reduction (Wallington and Cai, 2023). In this study we ask: when considering total P and cascading recovery over large stream distances, how long do in-stream legacies contribute to P loads? Further, we evaluate how potential dry periods might delay the spiraling recovery of water quality. This study provides a novel and concrete characterization of the longevity of in-stream P legacies and cascading water quality recovery after point source remediation.

2. Materials and methods

2.1. Testbed watershed and model background

We conduct this study in the Upper Sangamon River watershed (USRW), a 3681 km^2 priority watershed of the Gulf Hypoxia Task Force located in the US Corn Belt (Illinois Environmental Protection Agency, 2021; U.S. Environmental Protection Agency, 2022). While 80% of land in the USRW is intensively managed for agriculture, P loads at the watershed outlet are strongly influenced by point source discharge from the Sanitary District of Decatur (SDD). SDD, located just downstream of the Lake Decatur dam (see Fig. 1), receives P-laden wastewater from large grain processing facilities. SDD discharged approximately 600 Mg P annually from 2001 to 2020 (Li et al., 2021a, 2021b). However, P discharge regulations from the Illinois EPA are forthcoming (Illinois Environmental Protection Agency, 2019), and SDD is preparing to remove over 90% of the P from their effluent (Writer, 2016). Watersheds across the US Midwest may experience similar, parallel trajectories to

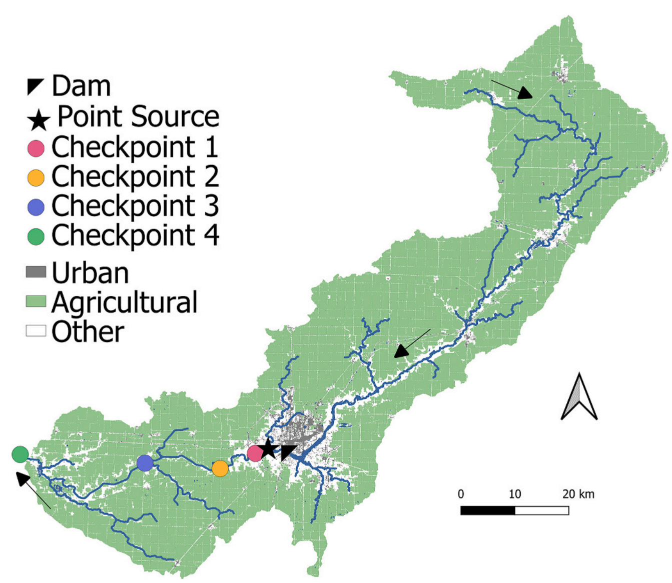

Fig. 1. Map of the Upper Sangamon River Watershed (USRW). Flow direction is indicated by arrows. Model outputs are generated at 4 indicated checkpoints downstream of the point source.

the USRW (Juneja et al., 2022; Ruffatto et al., 2022). Thus, the timescale of P load recovery following remediation at SDD is a timely and important question both for stakeholders in the USRW and the Mississippi River basin at large.

We simulate hydrology and nutrient dynamics in the USRW using the SWAT+P.R&R model (Wallington and Cai, 2023). SWAT+ itself is a widely used watershed model for simulating the impacts of agricultural management practices on hydrology and water quality (J. G. Arnold et al., 2012). SWAT+ models are customized for watersheds according to data for elevation, soil, and land use (including agricultural management practices); are forced by precipitation, temperature, and other weather inputs; and generate daily or sub-daily outputs for streamflow, crop yield, water quality, and other watershed responses (Neitsch and Arnold, 2011). SWAT+P.R&R improves upon the SWAT+ model by tracking accumulation and depletion of P in streambeds and simulating diffusion of dissolved P, adsorption and desorption of P to sediment, and deposition and erosion of particulate P. Model validation in the USRW showed that SWAT+P.R&R accurately reproduced the temporal variability of in-stream P retention-and-remobilization near the SDD discharge location, while the existing SWAT+ model did not. Moreover, results from SWAT+P.R&R helped clarify a seeming conflict between data-based estimates of P retention in the USRW and prevailing theory about P retention (Wallington and Cai, 2023). While the model still has its own limitations, the validated improvements of SWAT+P.R&R make it uniquely capable of characterizing the cascade of in-stream legacy P remobilization at the large watershed scale.

For this study, the SWAT+P.R&R model of the USRW is calibrated manually using the SWAT+R package (Schuerz, 2019) to identify the 100 “best” model parameterizations to show the uncertainty range and the robustness of the model results. In total, 24,000 model parameterizations were simulated, and the 100 parameterizations selected were those that met minimum performance criteria for all variables and monitoring locations and maximized combined performance for P loads and in-stream P remobilization downstream from SDD. See Text S2 and Table S5 for details of the calibration process, initial parameter search ranges, distributions of final parameter values, and the parameter values in the best overall parameterization.

2.2. *Counterfactual modelling experiments to isolate legacy P*

We conduct three counterfactual modelling experiments to isolate the contributions of in-stream legacy P to future P loads in the USRW. The experiments focus on the remobilization of legacy P after point source remediation, which isolates the impacts of in-stream legacies (as opposed to impacts from legacies throughout the landscape-stream continuum) and highlights the spatial cascade of recovery from a specified point of origin (Fig. 1). Across the three experiments, all model inputs are identical *except* the P discharged by SDD, and in all three experiments, we simulate forty years of watershed response divided into a historical period (2001−2020) and a future period (2021–2040). The P discharge scenarios are as follows: (a) “status quo” scenario – SDD discharges the observed (very high) amount of dissolved P during the historical period and continues high dissolved P discharge in the future, (b) “baseline” scenario – SDD discharges 10% of the observed dissolved P discharge (i.e., 90% removal) during the historical period and continues at this level in the future, and (c) “legacy” scenario – SDD discharges the observed (very high) amount of dissolved P during the historical period but then switches to 90% P removal for the future according to SDD future plans. On day 1 of the future period, the only difference between the legacy and baseline scenarios is the concentration of P built up in the streambed between SDD and the watershed outlet. Therefore (and since the legacy and baseline scenarios have identical inputs throughout the future period), in the future period any difference in P loads from the baseline to the legacy scenario is due to the contribution of in-stream legacy P that had been trapped within the stream network (between SDD and the watershed outlet) during the historical period of the legacy scenario. Similarly, comparing the legacy and status quo scenarios highlights the water quality recovery achieved by P removal. To investigate the spatial cascade of legacy P recovery, we examine and compare P loads at four checkpoints located 4.6, 17.1, 34.2, and 70.7 km downstream from SDD (see Fig. 1). Note, the first checkpoint was included in the model calibration (as well as other locations not downstream of SDD), and the final checkpoint is the USRW outlet.

2.3. *Estimating historical accumulation of legacy P*

The total P trapped in the watershed from 2001 to 2020 is calculated by taking the difference between the total P sources (i.e., both point source and non-point sources (NPS)) and the P loads exported at the watershed outlet, during the entire period. We also allocate the exported P to the various P sources in the watershed as follows: (1) Point source P – estimated as the increase in watershed P export from a simulation with zero point source discharge to a simulation with the full point source discharge; (2) NPS P originating upstream of the Lake Decatur dam – estimated as the P exported from the reservoir multiplied by the P transmission fraction (P outflow divided by P inflow during the entire period) of each main channel reach between the reservoir and the watershed outlet; and (3) NPS P originating downstream of the dam – estimated as the watershed P export minus the export contributions from the point source or upstream of the dam. The trapped P is likewise allocated to each source.

2.4. *Design of weather scenarios for sensitivity analysis*

Observed weather is used to force the model during the historical period and to create synthetic weather series to force the model during the future period. For each year in the future period, a year from the historical period is selected at random, and the observed weather from the selected historical year is copied for the given future year (e.g., year 2021 repeats the same weather as year 2017, year 2022 repeats 2008, and so on. See Table S6 for full time series). The SDD discharge from the selected historical year is also copied for the given future year – applying 90% P removal as appropriate per the scenario description. This simplistic method for generating synthetic weather and SDD discharge scenarios preserves the correlation between SDD operations and weather, which is notable as SDD also treats combined sewer overflow. We test sensitivity to the synthetic weather – in particular, sensitivity to the waiting time before wet years, which have higher flushing power – by simulating “wet”, “dry”, and “dry-then-wet” scenarios. For the “wet” (“dry”) scenario, only the 3 wettest (driest) years from 2001 to 2020 are used to generate synthetic weather and SDD discharge during the future period. For the “dry-then-wet” scenarios, the future period begins with the same sequence of weather-years as in the “dry” scenario but after a prescribed time (2, 4, 6, 8, or 10 years) switches to match the sequence in the “wet” scenario (see Table S6 for full time series). These synthetic weather scenarios are *not* crafted to represent realistic future weather scenarios or climate change but rather to investigate how dry weather might extend the longevity of in-stream P legacies.

3. Results and discussion

3.1. *Historical accumulation of legacy P within the USRW stream network*

SWAT+P.R&R results (with the best overall parameterization, here and elsewhere unless otherwise noted) indicate that over half of the P that entered the stream network during 2001–2020 was trapped within the stream network (see Fig. 2). In particular, over half of the P discharged by SDD was trapped, accumulating in reaches along the main stem of the Upper Sangamon between the SDD discharge point and the USRW outlet. This large stock of P that accumulates for the status quo

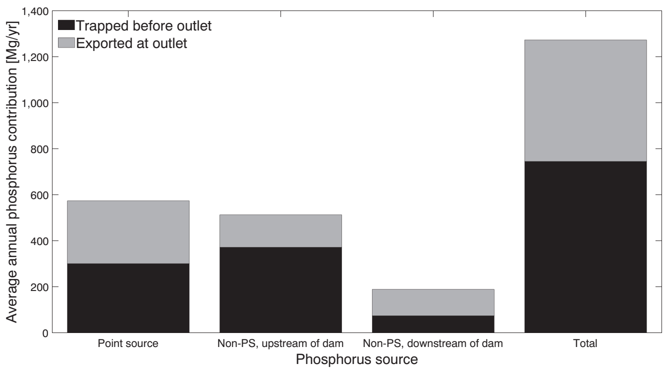

Fig. 2. Historical P trapping in the Upper Sangamon River stream network.

and legacy scenarios is then available for remobilization and export during the future period, whereas, for the baseline scenario, far less P accumulates between SDD and the USRW outlet during the historical period due to the assumed remediation (90% P removal at SDD during 2011–2020).

3.2. Legacy P remobilization mechanisms and dynamics

The P that accumulated in streams during the historical period is remobilized in the future period by diffusion of dissolved P (which persists in streambeds and banks for months, see Jarvie et al., 2013; Jarvie et al., 2006; Meals et al., 2010) and erosion of particulate P (which persists in streambeds and banks for years, see Chen et al., 2018; Sharpley et al., 2013; Withers and Jarvie, 2008; Wohl, 2015). To emphasize these different mechanisms of remobilization, we begin by examining just the first 200 days of the future period, immediately after 90% P removal begins for the legacy scenario (see Fig. 3). For the first 50 days after P removal in the legacy scenario, during which streamflow happens to be low (Fig. 3a), the streambed between SDD and the watershed outlet is consistently a source of dissolved P via diffusion (Fig. 3b). The bed contributes as much as several hundred kg of dissolved P in a single day. In contrast, the streambed is a small *sink* for dissolved P in the baseline scenario during this window and a large *sink* for dissolved P in the status quo scenario. However, beyond 50 days after P removal in the legacy scenario, the streambed is only a significant source of dissolved P during rising flows (see Wallington and Cai, 2023 for discussion of hysteresis in P retention and remobilization dynamics), and otherwise there is little diffusion of dissolved P. These results support previous findings that remobilization of in-stream legacy P *by diffusion* is relatively short-lived following point source remediation (Jarvie et al., 2013; Jarvie et al., 2006; Meals et al., 2010).

Compared to remobilization by diffusion, remobilization by erosion of particulate P from the streambed persists for a longer time and is of a far greater magnitude (Fig. 3c). Note, although the P discharged by the point source is dissolved, these particulate P legacies also develop as the dissolved P adsorbs to sediment. For the legacy scenario, during high flows occurring between future days 120 and 160, net P erosion from the streambed reaches several *thousand* kg on multiple days – an order of magnitude greater than fluxes by diffusion. For the baseline scenario, because less P had accumulated in streambed sediments during the historical period, the streambed is a much smaller source of particulate P during these erosion events (Figs. 3d). For the status quo scenario, because streambed P concentrations are not being drawn down, the streambed is an even larger source of particulate P during these erosion events.

Ultimately, remobilization of built-up in-stream P by diffusion and erosion causes higher downstream P loads for the legacy scenario compared to the baseline scenario, especially during high flow events (Fig. 3d). The dark blue band in Fig. 3d, the difference between P loads at the watershed outlet for the baseline and legacy scenarios, indicates

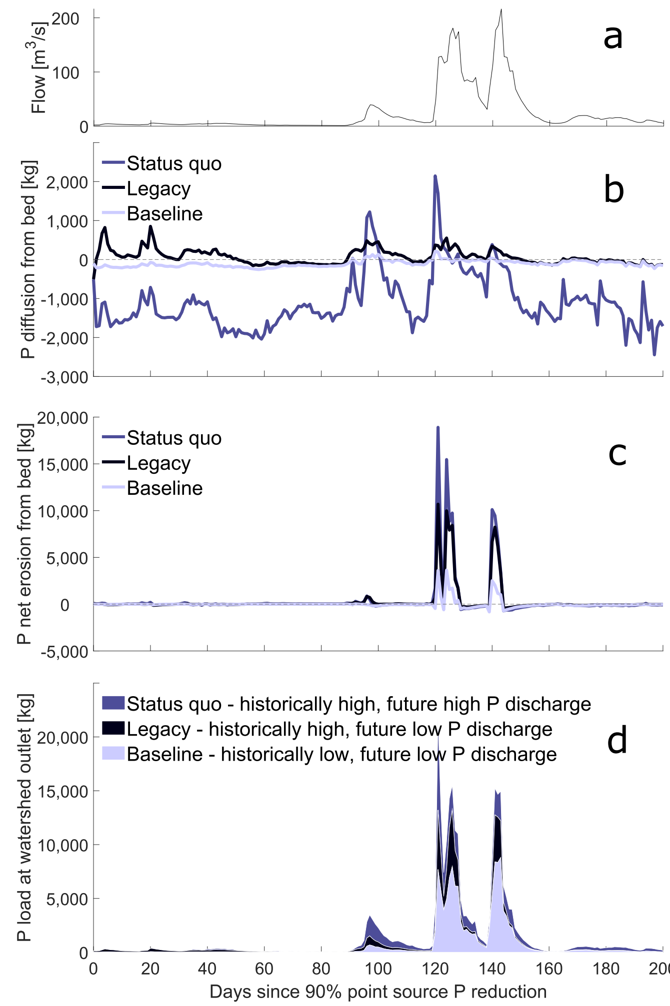

Fig. 3. P loads and remobilization during the first 200 days of the future period simulated. (a) Streamflow, (b) net dissolved P diffusion from the streambed to the water column (negative values indicate the bed is a P sink), (c) net erosion of particulate P from the streambed (negative values indicate net P deposition), and (d) P loads at the watershed outlet under the three counterfactual modelling scenarios.

the contributions of in-stream P legacies. During the first 50 days after P removal begins, when flows happen to be low, almost 100% of P loads in the legacy scenario are derived from diffusion of legacy P from the streambed. In fact, P loads in the legacy scenario are nearly equal to those of the status quo scenario (where 100% P discharge continues) during these early days – that is, the difference in how the streambed acts as a source versus sink of dissolved P in the two scenarios almost entirely offsets the 90% P removal occurring in the legacy scenario. While legacy diffusion becomes insignificant after a few months of P removal, Fig. 3d shows that substantial erosion of legacy particulate P continues further into the future. Indeed, results below show that in-stream legacy P contributes significantly to watershed P loads for years after P removal has begun at SDD.

3.3. Years-long, cascading recovery from in-stream legacy P

We now widen our scope of analysis to the full 20-year future period and address our main motivating question: when considering total P and cascading recovery over large stream distances, how long do in-stream legacies contribute to P loads?

SWAT+P.R&R results indicate that the reaches further downstream from the point source discharge are less impacted but also take longer to recover after remediation. Figs. 4a-d show the streambed P concentration for the reaches between each model checkpoint, both during the historical and future periods. During the historical period, streambed P concentrations increase for all four reaches, indicating the accumulation of P. Noting the different scales for the vertical axes in Figs. 4a-d, the more upstream reaches are most impacted by the point source and the streambed P concentration builds up to over 1000 mg P/kg sediment while the most downstream reaches only build up concentrations to approximately 300 mg P/kg. However, after 90% P removal begins at the point source (indicated by the dashed vertical line in Figs. 4a-d), the streambed P concentration in the most upstream reach returns to the baseline level within 2–3 years of the future period, while the streambed P concentration in the most downstream reach takes approximately 10–12 years to return to the baseline level.

Fig. 5 shows the cumulative in-stream legacy contributions to P loads at each checkpoint of the USRW, as indicated in Fig. 1. The cumulative legacy contribution is the difference in cumulative P loads between the legacy and baseline scenario at a checkpoint. For example, at the USRW outlet (which is checkpoint 4, green in Figs. 1 and 5), the cumulative legacy P contribution in Fig. 5 is equal to the area of the darkest blue band in Fig. 3d (if Fig. 3d were extended for all 20 years). Note, when legacy P is remobilized from the first reach (i.e., from between the point source and checkpoint 1), that legacy P contributes to P loads at checkpoint 1 but also can (possibly, eventually) continue being transported downstream and contribute to P loads at checkpoints 2, 3, and 4. Similarly, in-stream legacies located in reaches 2 or 3 (on the first day of future simulation, i.e., of year 21) can contribute to P loads at the checkpoints further downstream. Thus, the difference in legacy contributions to P loads at two consecutive checkpoints indicates the degree to which the individual reach between the checkpoints acts as a net sink or source of legacy P.

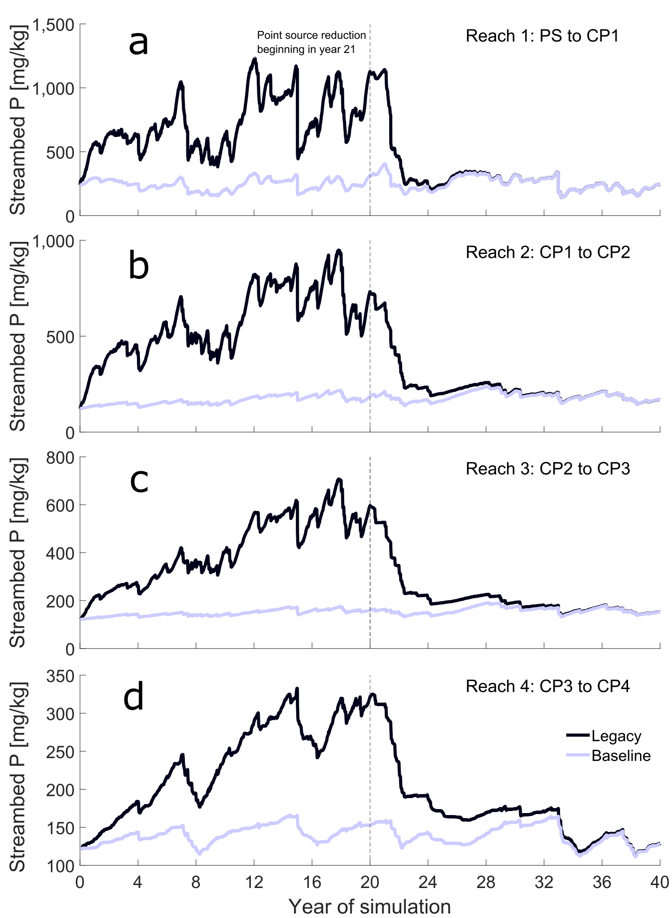

Fig. 4. Streambed P concentrations for the four reaches downstream of the point source, each between the checkpoints indicated in Fig. 1.

The results in Fig. 5 indicate that the contributions of in-stream legacies to P loads dramatically increase with distance downstream from the remediated point source. Over the entire 20-year future, approximately 50 Mg of legacy P is remobilized and exported past the first model checkpoint. In comparison, nearly 400 Mg of legacy P is remobilized and exported past the final checkpoint (the watershed outlet). The increasing legacy P contributions at more downstream checkpoints indicates that, for this watershed, each individual reach acts as a net source of legacy P in the long term. Moreover, although the *concentrations* of P that accumulated in downstream reaches were low compared to more upstream reaches, these downstream stores of legacy P extend over large distances (36.5 km for the final reach, compared to just 4.6 km for the first reach); therefore, even at lower streambed concentrations, the downstream reaches act as *large* sources of legacy P, and thus the legacy contributions to P loads increase dramatically at more downstream checkpoints. These results demonstrate that, in large watersheds, locations further downstream from a remediated P source can be subject to much larger in-stream legacy impacts than locations close to the remediated source (Withers and Jarvie, 2008). Note, in other watersheds, a long-term depositional reach could be a net sink of legacy P for an extended period of time after remediation, and thereby, legacy contributions to long-term P loads could decrease going downstream (Maavara et al., 2020; Pizzuto et al., 2014; Sharpley et al., 2013; Trimble, 2009).

The results presented in Fig. 5 also illustrate the temporal element of cascading water quality recovery following point source remediation. While over 300 Mg of the legacy P exported from the watershed (i.e., past the final checkpoint) occurs during the first 3 years after point source remediation, non-trivial legacy P contributions persist for several years further into the future. Fig. 6 emphasizes the relationship between recovery time and downstream location. As an indicator of the water quality recovery time, we use the time until 95% of the eventual 20-year-total legacy P export has been reached (legacy P contributions are approximately zero by the end of the 20-year future period at all checkpoints). By this measure, the time to recovery at the four checkpoints (from upstream to downstream) are 3.3 years, 5.5 years, 7.9 years, and 9.3 years (see Fig. 6). This result supports existing, conceptual discussions of phosphorus spiraling and quantitatively characterizes the timescale and cascading nature of recovery from in-stream P legacies, which had been missing from existing work (Chen et al., 2018; Sharpley et al., 2013). In light of this and the above finding, all estimates for the timescale or magnitude of in-stream P legacies should explicitly state the spatial scale (i.e., stream distance between remediation and water quality recovery evaluation) at which the estimate is made and how spatial scale might affect the estimate – practices that are not currently followed in the literature. Moreover, these findings dispute claims that in-stream P legacy impacts last less than one year (such as by Jarvie et al. (2013, 2006) and Meals et al. (2010) who consider primarily dissolved P or by Dorioz et al. (1998), Jarvie et al. (2012), and Sharpley et al. (2013) who consider only reach scale dynamics). Rather, when considering total P and long stream distances, these results show that in-stream P legacy impacts can last several years. This result supports (in a concrete manner) the existing (but abstract) statements in the literature that particulate legacy P could take years to exit a watershed (Chen et al., 2018; Meals et al., 2010; Sharpley et al., 2013; Wohl, 2015). Further, these results clarify that such long-term, particulate P legacies can develop from *point source* P discharges, despite the discharged P being in dissolved form (in contrast to some previous suggestions such as in Meals et al., 2010).

These results and analysis offer the first concrete characterization of the magnitude, longevity, and spatial cascade of legacy P remobilization after a hypothetical point source P reduction. Future work to further improve the SWAT+P.R&R model (see Wallington and Cai, 2023 for discussion) or to develop corroborating models would increase the

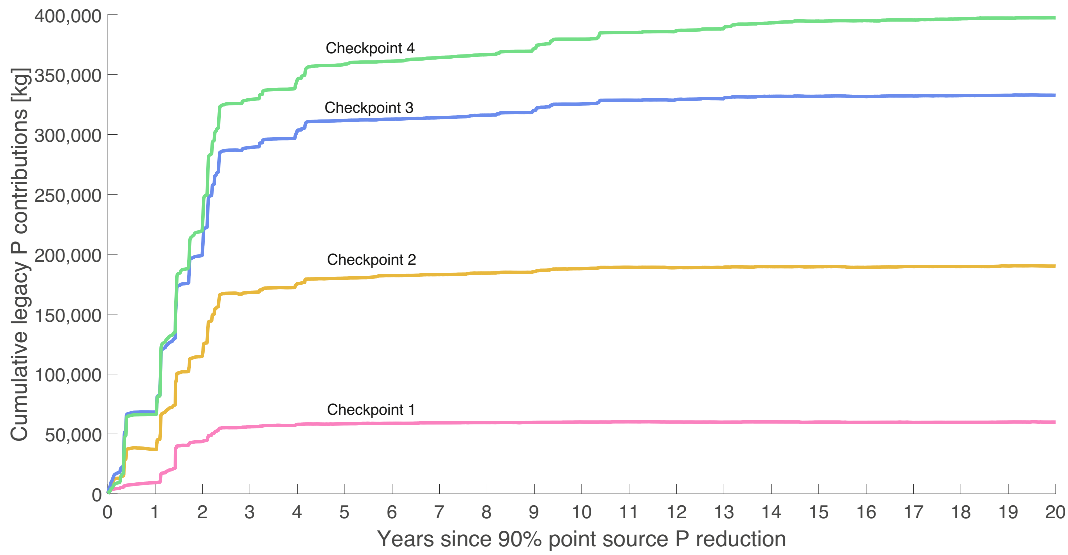

Fig. 5. Cumulative in-stream legacy contributions to P loads at each stream checkpoint, as indicated in Fig. 1.

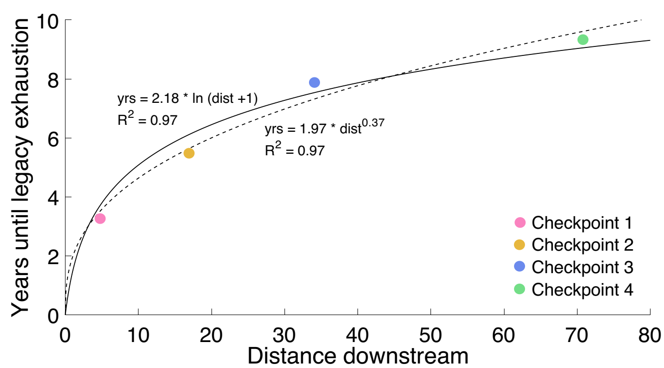

Fig. 6. Time required for water quality recovery according to distance downstream from the remediated point source. Trend lines (meant only to emphasize the general nature of the relationship) and equations are provided for a power law fit (dashed line) and a logarithmic fit (solid line).

reliability of such characterizations. Notably the most impactful limitation of SWAT+P.R&R is actually likely to result in *underestimation* of the amounts and timescales of legacy P remobilization: SWAT+P.R&R imposes a constant thickness for the simulated streambed layer, and as a result, large amounts of in-stream legacy P can be "buried" and lost from the simulated system (see Wallington and Cai, 2023).

3.4. Sensitivity of findings to model parameter and future weather uncertainty

Model results under the 100 different "best" parameterizations exhibit meaningful differences in the legacy P export at the watershed outlet, but nonetheless, all parameterizations support the conclusions offered above (see Fig. 7a). Over all 100 simulations, the total legacy P exported from the watershed ranges from 252 Mg to 512 Mg (the result above for the best parameterization is 397 Mg). The time until 95% of the legacy P has been exported from the watershed ranges from 9.0 years to 14.2 years (result for the best parameterization is 9.3 years). In all parameterizations, the majority of the legacy P remobilization occurs within the first 3 years after point source remediation, but non-trivial remobilization events persist for several years longer. This sensitivity analysis raises (to a degree) the confidence of the insights offered in this study, despite model limitations of SWAT and SWAT+P.R&R.

Simulation results from "normal", "dry", "wet", and "dry-then-wet" future scenarios show that precipitation (and subsequent streamflow) has little effect on the ultimate amount of legacy P exported from the USRW but dramatic effect on the time until that legacy P is exported (see Fig. 7b). Excluding the 20 years of dry weather scenario, the total legacy P exported only varies within the narrow range of 397 to 444 Mg across weather scenarios. However, the time until 95% of the legacy P has been exported varies from 4.3 years to 14.1 years. These results emphasize that dry weather (or to be more precise, low flows resulting from low precipitation) following point source remediation will increase the longevity of in-stream legacy P impacts and delay water quality recovery until a sufficient number of high flows pass and "flush" the system. In contrast to *reach scale* studies of sediment transport, one high flow event is not sufficient to remobilize nearly all in-stream legacy P in the stream network (Collins et al., 2005; Owens et al., 2001; Sharpley et al., 2013; Walling et al., 1998); rather, *many* high flow events are required to nearly exhaust the in-stream legacy P stores.

Finally, Fig. 8 shows the in-stream legacy P contributions to future annual P loads for the USRW, for all 100 "best" parameterizations under the "normal" weather scenario. Note, the legacy contribution in each year is specifically with reference to the baseline P load *in that same year*, which varies year-to-year. For reference though, the annual average P load in the baseline scenario is 302 Mg, and the annual average P load in the status quo scenario is 581 Mg. In the first year after point source remediation, in-stream legacies contribute a 30%–60% increase to P loads. During each of the first 3 years after remediation, in-stream legacies contribute at least 90 Mg P to annual loads – equivalent to 30% of the average annual baseline load. Relative to baseline loads in the same year, in-stream legacies contribute at least a 10% increase in annual loads for these first three years. For some parameterizations, in-stream legacies can contribute more than a 5% increase to annual P loads for 7 years. The results here and above illustrate that remobilization of in-stream legacy P can indeed contribute significant increases to annual total P loads over several years when accounting for the downstream cascade of water quality recovery.

4. Conclusions

Using the recently developed SWAT+P.R&R model, we conducted counterfactual modelling experiments to isolate the contributions of in-stream legacies to P loads. Our results confirm previous findings that P remobilization by diffusion is short-lived (months) but, in contrast, remobilization by erosion of particulate P lasts much longer (years) and is of a far greater magnitude. In three ways, our results demonstrate that

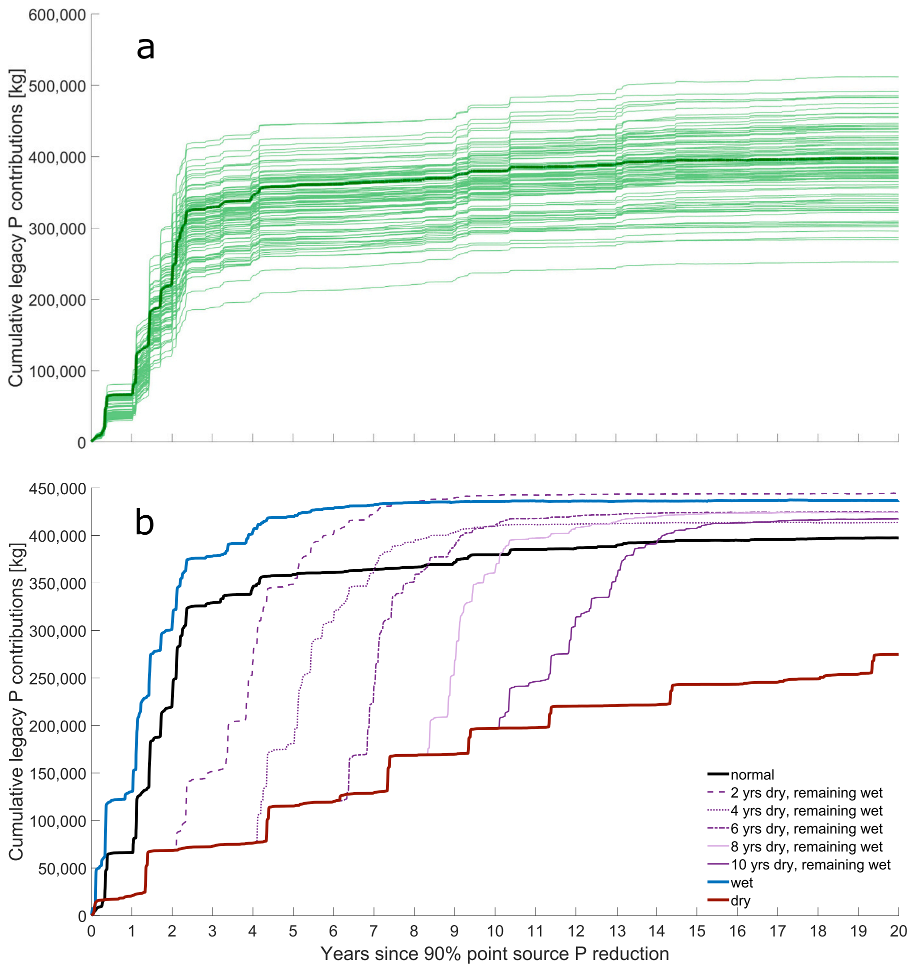

Fig. 7. Sensitivity of cumulative legacy P contributions at watershed outlet (checkpoint 4) results to (a) model parameterization and (b) future weather.

P load reductions and legacy exhaustion incur significant lag times and that lag times increase for locations further downstream from the point of remediation: (1) streambed P concentrations recover to baseline levels in 2–3 years for the most upstream reach but 10–12 years for the most downstream, (2) in-stream legacies contribute 50 Mg to future P loads at the most upstream checkpoint but 400 Mg at the most downstream, and (3) non-trivial legacy P contributions persist for 3 years at the most upstream checkpoint but 9 years at the most downstream. These findings hold up qualitatively for the 100 best parameterizations of the SWAT+P.R&R model, and the timescales could be even greater if the future begins with a period of dry weather. Based on these results, future estimates of timescales for in-stream P legacies should explicitly account for spatial scale. Moreover, these results show, with specific estimates, that in-stream legacies can last much longer than sometimes assumed previously (e.g., longer than one year).

4.1. Implications for the achievement of Gulf of Mexico P load reduction goals

The results here show that water quality recovery (measured as total P load reductions) following point source remediation will be delayed by years-long, downstream-cascading remobilization of in-stream legacy P. Pertaining to hypoxia in the Gulf of Mexico, it is important to note that (1) delays will be especially long because large stream distances separate subwatersheds of the Mississippi River basin from the Gulf of Mexico and (2) total P legacies (not just dissolved P) are especially important because particulate P is susceptible to dissolution in the marine environment. Therefore, state-level environmental agencies must consider the total P load reduction lags that are induced by in-stream legacies when they make and implement their nutrient reduction plans. Results here indicate that it would take at least 9 years after remediation to export built-up in-stream legacy P past the USRW outlet (70 km downstream from the remediated point source). Extrapolation of this relationship to the Gulf of Mexico (2640 km downstream) suggests that in-stream legacies could contribute to Gulf P loads for 17 to 36 years (see trendlines in Fig. 6). However, this estimate should be treated as highly uncertain considering the differences in stream conditions between the USRW and the reaches of the Mississippi River watershed which lie beyond the USRW outlet. Nonetheless, if the goals of the Hypoxia Task Force are indeed to be met in a timely fashion (they have already been delayed before), states will need to reach equivalent load reductions years, or even decades, in advance of the Task Force's targets.

CRediT authorship contribution statement

Kevin Wallington: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Ximing Cai:** Funding acquisition, Supervision, Writing – review & editing. **Margaret Kalcic:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no competing interests.

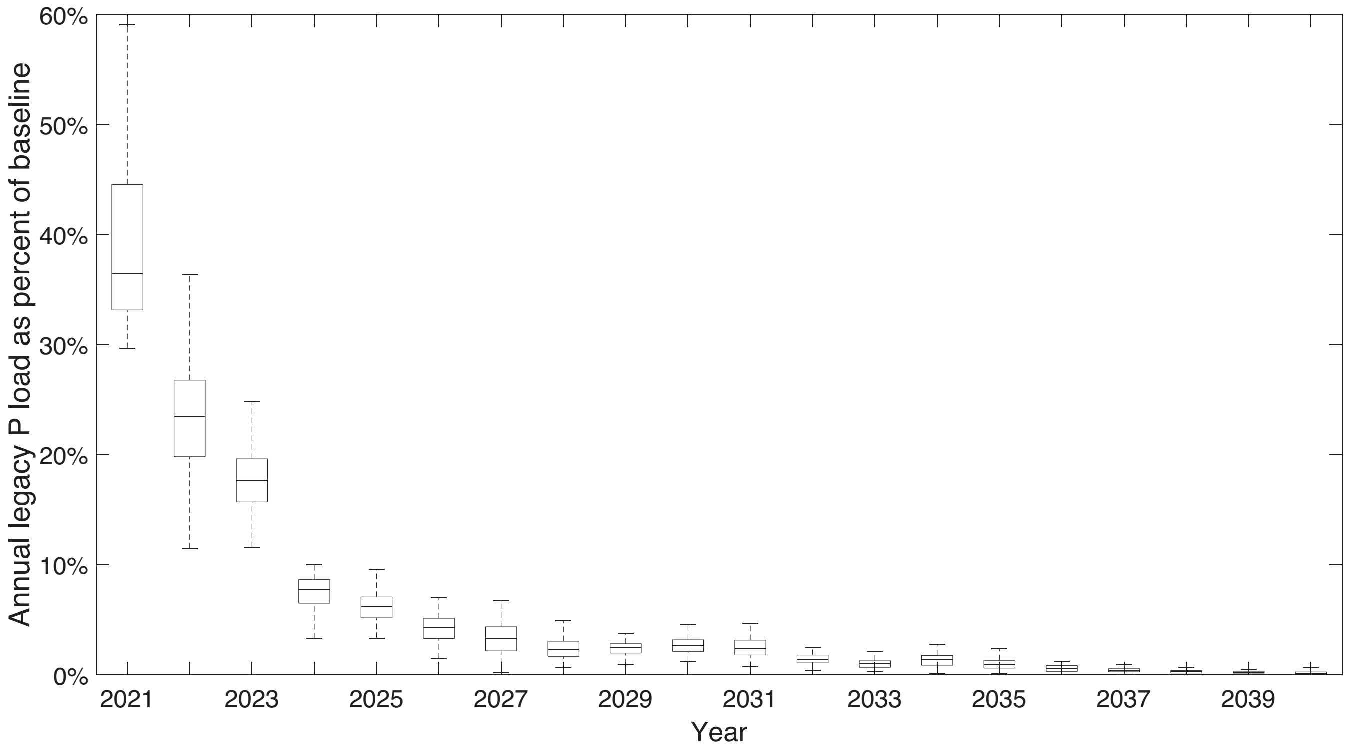

Fig. 8. Annual contributions of in-stream legacies to P loads at the Upper Sangamon River Watershed outlet, relative to baseline loads in each given year. Point source remediation beginning on day 1 of year 2021.

Data availability

All code and data used for this paper is available at https://github.com/kevin-wallington/Instream_LegacyP

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168711.

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