Using random forest algorithms and globally sourced data to improve floating treatment wetland design and stormwater pond performance

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Highlights

- Pond design features were the most influential to effluent water quality, while the addition of FTWs to ponds provide limited additional treatment benefits (mostly to P and TSS).
- Effluent nutrients and TSS were higher in deeper ponds treating larger drainage areas; model results suggest maximum pond depths and loading ratios of 1.75 m and 200:1, respectively.
- Increased FTW aerial coverage and planting density to improve P and TSS reduction (after considering changes to other pond features).

Introduction

As passive treatment technologies with relatively little maintenance requirements, wet retention ponds represent a broadly accepted approach to mitigate peak flow rates of stormwater runoff in cities worldwide. The primary features of wet retention ponds include a permanent pool, which provides for inter-event storage, and an outlet structure designed to detain and slowly release runoff from the pond via drawdown orifice(s). Beyond peak flow mitigation, wet retention ponds provide for effective removal of suspended solids and particulate-bound pollutants, which are removed via sedimentation between rain events. However, wet retention ponds provide limited removal of dissolved pollutants because they lack the treatment mechanisms (e.g., vegetation, hydric soils, filtration, etc.) found in other types of SCMs, such as constructed wetlands.

Floating treatment wetlands (FTWs), also referred to as constructed floating wetlands (CFWs), or artificial vegetated islands, among other terms, represent an approach to retrofit these treatment mechanisms into existing wet retention ponds which has gained widespread popularity in recent years. As their name implies, FTWs are vegetated systems which rely on a buoyant structure constructed of various natural (e.g., coco coir, bamboo) or artificial (e.g., foam-injected plastic pipe) materials to float on the surface of a pond. The emerging macrophytes planted in FTWs grow hydroponically, with dense root systems extending into the water column which support the growth of microbial biofilms and contribute to pollutant removal. Treatment occurs as runoff flows through the root zone, where pollutants are removed via flocculation, sedimentation, and plant uptake. Several features of FTWs make them attractive options as retrofits to existing retention ponds. Because they fit within the footprint of an existing system, FTWs require no additional land or earth moving activities for operation. Further, FTWs do not detract from storage volumes of existing wet retention ponds (because they float). FTWs also have low construction and maintenance costs and enhance the aesthetics of wet ponds.

FTW research has grown exponentially in the last 30 years, which have been reviewed in several articles published in the last decade (e.g., Headley & Tanner 2012; Pavlineri et al. 2017; Colares et al. 2020). While these articles provide valuable summaries on the state of the science and identify opportunities for future work, they often lack the statistical analysis needed to craft design guidance and identify strategies which optimize the pollutant removal provided by FTWs. Further, they often focus solely on FTWs and ignore the role of wet retention pond design in stormwater treatment. To address this knowledge gap, this study relied on data from eight international field-scale studies of FTWs implemented in wet retention ponds coupled with a tree-based machine learning approach (random forest) to evaluate the design and environmental variables which influence nutrient and total suspended solids (TSS) removal. Findings from models were then used to identify design strategies for both FTWs and wet retention ponds which may improve stormwater treatment performance.

Methodology

Dataset Description

Data from eight international studies of field-scale FTWs treating stormwater runoff in four countries (Germany, Australia, New Zealand, and the USA) were included in this meta-analysis. Information gleaned from each of the studies included design parameters of both the FTWs and the retention ponds in which they were installed, catchment characteristics, rain event summary statistics, and influent and effluent concentrations of TSS and eight N and P compounds of interest. Data collected from a control pond or prior to FTW installation were also included in the meta-analysis to capture baseline treatment performance provided by the retention ponds. Sample sizes in the dataset ranged from n=127 (particle-bound phosphorus; PBP) to n=182 (total nitrogen; TN), which provided a robust framework to assess the impact of FTWs in field-scale stormwater treatment.

Random Forest Modeling

Random forest regression analyses, a tree-based machine learning algorithm, were used to model effluent pollutant concentrations and evaluate the influence of various pond/FTW design, catchment, rain event, and environmental characteristics on treatment provided by the retention ponds and FTWs. After fitting models using the full suite of predictor variables (n=15), a recursive variable elimination procedure was implemented to incrementally remove “noise” from less-important variables until the configuration which produced the best prediction accuracy was identified. Models were replicated 25 times to verify trends and account for the inherent variability in model performance. Once final model configurations were determined for each pollutant, partial dependence plots (PDPs) were used to visualize the effects of each predictor variable on predicted effluent concentrations considering the average effects of the remaining variables included in final models.

Results and discussion

Variables related to pond design and catchment characteristics generally received the highest rankings in final model configurations, while FTW variables were often found lower in the rankings. Pond depth and loading ratio (i.e., ratio of catchment area to pond surface area; LR) consistently received the highest rankings, followed by catchment characteristics (e.g., imperviousness), influent pollutant concentrations and rain event characteristics. Model results indicate that pond and catchment characteristics were the most influential to effluent water quality discharged from wet retention ponds, while design elements of FTWs are less critical to the treatment of many nutrients (aside from TP). The effects of select predictor variables on model predictions of effluent TN, TP, and TSS concentrations are shown in Figure 1.

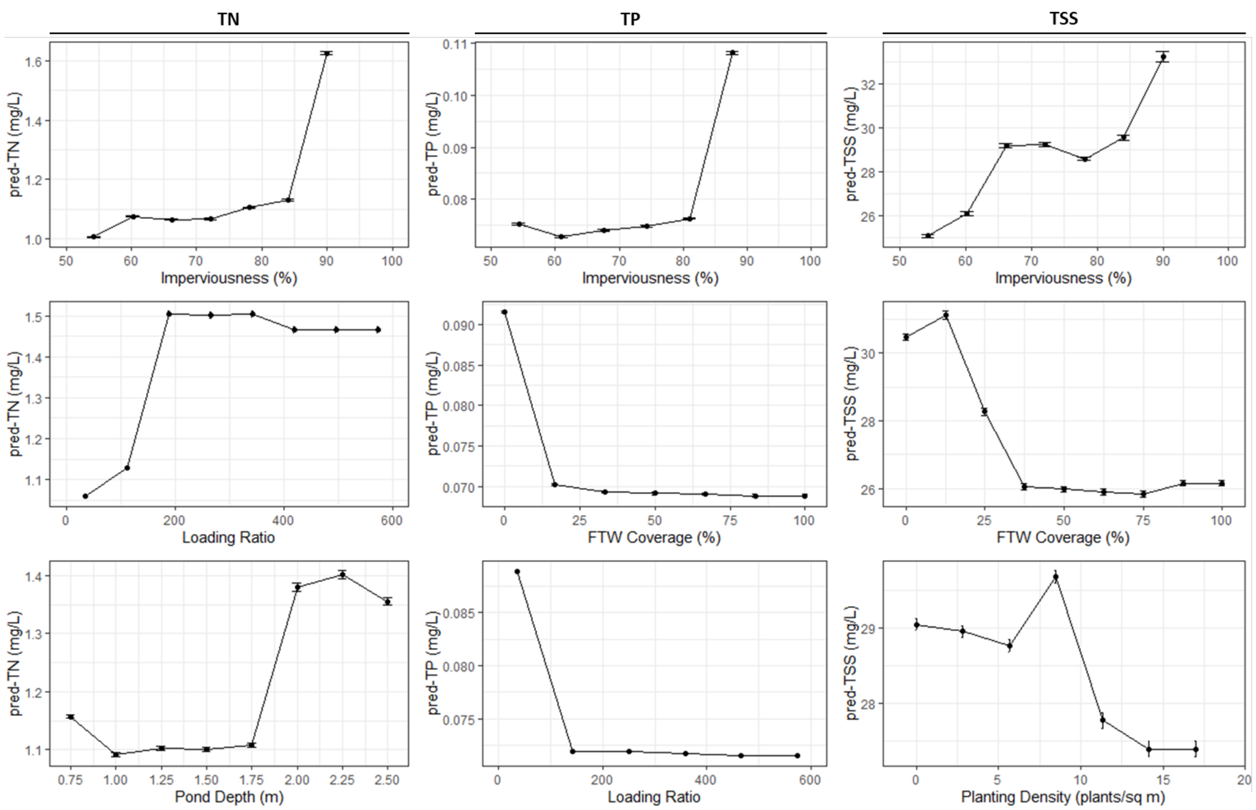

Figure 1. PDPs illustrating the effects of select predictor variables on predictions of effluent TN, TP, and TSS concentrations.

Results indicate that pond design elements should be prioritized while keeping the limited influence of FTWs in context. Coupled with variable rankings and informed by trends observed in PDPs, designs can be developed which optimize influential parameters to enhance treatment of a pollutant of interest. For example, predicted effluent concentrations tended to be higher as pond depths and LR increased, since these factors caused opportunities for bypass beneath FTW root zones and higher pollutant loads per unit surface area. Thus, pond depths and LR should not exceed 1.75 m and 200:1, respectively. Though not influential to N treatment, results indicate that FTWs provide some benefit to P and TSS reduction. In both instances, treatment may be enhanced by increasing FTW aerial coverage and planting density.

Conclusions and future work

Random Forest modeling using data from eight international studies of field-scale FTWs was performed to investigate the factors which influence nutrient and TSS treatment in retention ponds. Results demonstrate that pond design and catchment features were the most influential to treatment, while the benefits of FTWs were limited and contributed primarily to removal of P and TSS. Studies should investigate variables that could not be considered in this work (e.g., root length) and the efficacy of other retrofit measures (e.g., real time control) to enhance FTW contributions to stormwater treatment.

References

Colares, G. S., Dell'Osbel, N., Wiesel, P. G., Oliveira, G. A., Lemos, P. H. Z., da Silva, F. P., Lutterbeck, C. A., Kist, L. T., & Machado, Ê. L. (2020). "Floating treatment wetlands: a review and bibliometric analysis". Sci. Total Environ., 714, 136776.

Headley, T. R., & Tanner, C. C. (2012). "Constructed wetlands with floating emergent macrophytes: an innovative stormwater treatment technology". Crit. Rev. Environ. Sci. Technol., 42(21), 2261-2310.

Pavlineri, N., Skoulikidis, N. Th., & Tsihrintzis, V. A. (2017). "Constructed floating wetlands: a review of research, design, operation and management aspects, and data meta-analysis". Chem. Eng. J., 308, 1120-1132.