Center for Comprehensive, optimaL, and Effective Abatement of Nutrients (CLEAN)

WEB SUMMARY

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RESEARCH OBJECTIVES

The CLEAN Nutrient Center develops and demonstrates sustainable cost-effective nitrogen (N) and phosphorus (P) management strategies to restore watershed systems and attain designated uses. These sustainable solutions encompass technological and infrastructural abatement strategies for urban, agricultural, and hydro-geomorphic systems. Effective and viable policy instruments (incentives and market-based approaches) are also included to facilitate trading among sectors, provide equity along water courses, increase chance of adoption, and minimize costs. The Center's research activities improve the nation's capacity to protect the environment and public health by developing and testing practical and widely-transferable modeling, data and decision support tools for risk and performance assessment of nutrient controls.

MAJOR ACHIEVEMENTS

A team of interdisciplinary researchers from engineering, soil and crop science, economics, were brought together to work with stakeholders in Colorado and North Carolina on pressing nutrient pollutions challenges. The multi-institutional collaboration resulted in establishing the CLEAN Nutrient Center at Colorado State University, which is now administered under the One Water Solutions Institute (OWSI). The Center has forged relationships with state agencies, local commodity groups, and utilities to conduct transdisciplinary research on priority nutrient pollution issues in Colorado.

The methods and analysis tools developed by the Center researchers are deployed as accessible and computationally scalable software. These capacities can be used for analysis in watersheds across the U.S. The use of these tools is supported by OWSI personnel via educational webinars, help desk services, and training workshops. For example, the CLEAN Nutrient Dashboard is currently used in Colorado to assess the effects of agricultural conservation practices, to identify priority watersheds for nutrient pollution restoration and prevention, and to determine costs and water quality effects of Regulations 31 and 85 toward compliance with the numeric nutrient standards.

BROADER IMPACTS

The CLEAN Center research activities have substantially improved our understanding of critical natural processes and management actions that govern fate and transport of nutrients, particularly in semi-arid irrigated river basins. Effective strategies for nutrient control were identified for wastewater treatment (WWT) facilities, urban stormwater and MS4 systems, agricultural production systems, and river/riparian corridors. More importantly, a system-level analysis framework was developed and demonstrated to quantify costs, water quality effects, reliability, resiliency, and equity of various strategies by sector, by systems, and in combinations.

The Center has created data analysis and modeling tools that are now being used by the Colorado Department of Public Health and Environment (CDPHE) along with several other stakeholder groups to identify effective N and P strategies across the State. These tools facilitate development of effective policy instruments, including market-driven approaches such as nutrient trading, at facility to river basin scales.

SUMMARY OF KEY FINDINGS

Project 1: Achieving Nutrient Reductions through Innovative Approaches for Wastewater Management and Water Demand Reduction

Water supply management and reduction of nutrient pollution from urban water systems are two of the most important issues facing utility managers today. While much research exists on nutrient reduction strategies for stormwater and wastewater treatment facilities (WWTF) individually, this research provides a unique analysis across water supply, wastewater, and stormwater sectors to identify most cost-effective strategies for nutrient load reduction in urban settings.

Empirical models were developed to assess the impacts of water management practices (e.g., water reuse and source separation of urine) and nutrient removal from wastewater on nutrient loadings. Subsequently, tradeoffs between nutrient load reduction and costs were explored using multiobjective optimization approaches. Results indicate that source separation and effluent reuse are the most frequent components of effective nutrient removal strategies, and even necessary under stringent nutrient control regulations.

For wastewater treatment, advanced treatment processes are most beneficial in carbon-limited facilities, while their benefits are negligible where adequate carbon for biological N and P removal is available. Advanced technologies that were evaluated in this study include nitrite shunt, 5-Stage Bardenpho, and sidestream processes (e.g., struvite precipitation and ammonia stripping). The findings of this research underline the importance of carbon management at WWTFs.

While infrastructural improvements in WWTFs are likely with the adoption of stringent nutrient regulations, the current research reveal that water management practices and stormwater control measures consistently rank among optimal nutrient load reduction strategies. To meet increasingly stringent target nutrient levels from urban areas, stormwater control measures and water management strategies are needed in combination with advanced nutrient removal systems at WWTFs.

Our research also developed a statistical modeling approach to evaluate the capacity of WWTFs across the U.S. to comply with more stringent nitrogen discharge limits in a changing climate, by adopting options of technology upgrades, operational changes, or emissions trading. A national data set of Discharge Monthly Reports (EPA ICIS/ECHO) comprised of four years of discharge monthly reports from over 200 U.S. treatment plants was used to model capacity for nitrogen removal using a reliability-risk-resilience framework. The most important factors accounting for variability in effluent total ammonia nitrogen (TAN), were the previous month's effluent TAN and the influent flow rate. The importance of prior performance suggests that secondary treatment plants exhibit significant inertia; that is, once in a state of noncompliance, there is a significant likelihood that compliance will not be achieved in the following month, which may impact receiving water quality more than a single month's violation. Furthermore, as modeled limits for discharge of TAN were decreased, facilities fell into one of two categories – likely to comply or likely to violate TAN limits, suggesting that a "cap-and-trade" emissions trading system within a watershed is a possible strategy for meeting total TAN load limits from point sources.

Total Inorganic Nitrogen (TIN) is emerging as a treated water quality limit. Using a time-series model (non-homogeneous Hidden Markov Model, HMM) coupled with multiple regression analysis of data from an operating 0.66 m^3/s (15 million gallons per day) treatment plant, we found that effluent TIN would be predicted from a combination of environmental conditions (season, temperature), effluent TAN, and flow rate. The existence of two statistically distinct temporal regimes supported the importance of prior performance, and identification of effluent TAN as a covariate indicated that biological nitrification may determine overall nitrogen removal.

Project 2: Urban Stormwater Management – Evaluation of Simple Retrofits/Design Enhancements and Development of Simple Assessment Tools

Site-scale testbed studies in North Carolina, Colorado, and Ohio were conducted to design, demonstrate, and evaluate three relatively simple retrofits/design enhancements to popular stormwater control measures (SCMs) with a high potential of widespread adoption across the U.S. These retrofits/design enhancements include: (1) upflow filter retrofits at wet pond's outlets to increase phosphorus sequestration, (2) inclusion of anoxic sumps to improve denitrification within bioretention, and (3) installation of a stormwater harvesting system downstream of permeable pavement to reduce nutrient loads discharged to the storm sewer.

The upflow filter retrofit was able to significantly reduce concentrations of orthophosphate. Due to clogging of the filter media, it is recommended that future applications incorporate microscale pretreatment and/or filter media cartridges for easy removal and replacement. The bioretention retrofit project resulted in increased volume reduction and peak flow mitigation at both retrofit sites; however, no significant differences were noted for N or P concentrations between pre- and post-retrofit monitoring periods. Lastly, the permeable pavement/rainwater harvesting treatment train significantly reduced runoff volumes and peak flow rates. Further, nutrient concentrations were significantly reduced by the treatment train. It is recommended that for future use, water stored in cisterns should see dedicated usage to provide storage volume for subsequent storm events. Overall, the three retrofits/design enhancements appear promising for mitigation of the detrimental effects of stormwater runoff by reducing runoff volumes, flow rates, and effluent nutrient concentrations.

A simple model called "Stormwater Nutrient Calculator" was developed that reconciles readily available data from national databases to determine N and P loadings from urban stormwater / MS4. The model was corroborated for N and P loadings from two urban drainage basins in the City of Fort Collins, CO, and was subsequently used to compute N and P loading from all developed areas in Colorado. The effects of stormwater detention and filtration systems were also examined with and without the upflow filter retrofits. Results indicate that the proposed upflow retrofit of filtration systems provides a cost-effective solution for nutrient reduction from urban stormwater.

Finally, the study examined the impacts of national MS4 regulations on adoption of SCMs on public and private properties. A procedure was developed to identify developed or redeveloped land at the urban drainage scale that is likely to be treated by SCMs based on when the MS4 regulation was applied to the municipality. The performance validity of the procedure was corroborated for the City of Fort Collins, CO, using robust spatial statistics.

Project 3: Nutrient Reductions in Agricultural Watersheds: Intentional Planning, Implementation, and Maintenance

This project investigates factors that influence the water quality effects of agricultural conservation practices at field to watershed scales. Field monitoring and modeling studies were conducted in Colorado and North Carolina to improve understanding of effective approaches for intentional planning and management of conservation strategies in agricultural settings. A set of modeling tools were developed that enable assessments at the edge-of-field to watershed levels.

In Colorado, an edge-of-field monitoring project compared two conservation tillage treatments, minimum tillage (MT) and strip tillage (ST), to a traditional conventional tillage (CT) system under furrow irrigation. Relative to CT, conservation tillage reduced TSS loads by up to 88% in 2015 and by 98% and 87% in 2016 for MT and ST, respectively. TKN was reduced by 80% and 86% in MT and ST respectively when compared to CT. Total P was significantly higher in CT, with an 87% load reduction under MT and ST in 2015 and an 85% load reduction under MT in 2016. Total P concentration correlated well with TSS concentrations. Reduced tillage and residue management are effective BMPs in sediment and nutrient abatement in irrigation and storm runoff.

In North Carolina, water quality responses were monitored at the outlet of three agricultural watersheds (~250-500 ha) for three years (2015 – 2017). Annual N, P, and sediment exports were determined for each watershed. Land use data and management practices were also collected. A hurricane in 2016 caused an estimated 38, 61, and 43 percent loss of TN export for the three different watersheds as a result of the storm. Estimated TP export during 2016 of 0.94, 1.87, and 2.20 kg TP/ha-yr for the three watersheds was much greater due to the hurricane than losses for 2015 or 2017. Total N and P input and export were correlated; the more nutrients applied, the greater the nutrient load. Therefore, it is stipulated that practices such as nutrient management should result in similar percent reductions in export.

Project 4: Fluvial Instability and Riparian Degradation: Evaluating and Reducing Nutrient Loading from Channel-Riparian Interfaces

This project evaluates fluvial erosion processes and their effects on nutrient delivery. A new parsimonious, mechanistic, watershed-scale model called "River Erosion Model (REM)," was developed for simulating channel erosion processes and associated fine sediment and adsorbed P loading. REM is a valuable new tool for quantifying pollutant loading from channel evolution and exploring different management options.

The model development activities also improved fundamental understating of critical channel evolution processes. For example, rigorous sensitivity and uncertainty analysis on the Bank Stability and Toe Erosion Model showed how major controls on bank erosion are relatively consistent across soil type and vegetation. Furthermore, new sediment transport equations were developed that are easier to apply at the watershed scale, hence enabling a comprehensive analysis of sediment transport processes for a variety of applications.

The REM tool was applied in two watersheds to simulate potential channel evolution and associated pollutant loadings. For these study areas, channel erosion was not a significant source of P but did contribute significant fine sediment pollution. In a recent study, REM was used in conjunction with the EPA's Stormwater Management Model (SWMM) to explore the relative effects of stormwater management and stream restoration for controlling channel erosion. The results indicate that stormwater management can be more effective at reducing channel instability but that coordinated implementation of both in-channel and watershed controls results in the greatest water quality benefits.

Project 5: Effective Incentives and Viable Trans-Sectoral Trading Strategies

This project examines social factors and policies that facilitate or impede successful planning, management, and implementation of nutrient control strategies, including agricultural conservation practices. Specifically, the research investigated viability/feasibility of nutrient trading in North Carolina and Colorado. Nutrient and transport data for over 3,700 fields in North Carolina was used to build sophisticated supply curves for nutrient credits. A companion model of demand was built for urban nutrient point-source contributors. The resulting model was used to determine potential for trading, and to determine how commonly cited elements of trading, such as trading ratios and baselines, can limit trading opportunities.

Concepts learned were generalized to all U.S. programs in the journal article: Policy Utopias for Nutrient Credit Trading Programs with Nonpoint Sources (Hoag et al., 2017). We estimated that only about 5% of U.S. watersheds with threats from nutrients would have economic, physical and institutional (utopian) conditions suitable for successful programs. We also discussed how to improve the likelihood of success outside of these utopian watersheds. In addition, the model was used to examine stacking ecosystem services, such as nitrogen and phosphorus abatement. It was shown that farmers expect premiums above the actual cost to adopt conservation practices, and that these premiums could double the cost of effective subsidies to encourage adoption. We also found that policies regarding quality and quantity sometimes work at cross purposes.

Project 6: Nutrient Data, Analysis, and Modeling Dashboard

An accessible and computationally scalable integrated nutrient data and modeling system is developed that can be used to: (1) identify major watersheds that account for N and P loads at scales reflecting the needs of communities, regulators, and managers, e.g., Hydrologic Unit Code (HUC) 8 or similar scales; and (2) assess effects of nutrient abatement options and potential changes in land use and climate on a HUC 12 or similar scale. The platform-independent system is available as an online tool and is applicable for watersheds across the U.S. All data analysis and modeling components are deployed as web services, and thus, can be accessed from desktop and mobile devices.

Demonstration watersheds were set up using the data and modeling information from projects 1-5 to create options for watershed prioritizations, nutrient TMDL analysis, and healthy watershed assessments. Specifically, the system includes decision support capacities that enable characterization of nutrient sources by sector and region. Also, various components in the system-level decision support tool enable use attainability analysis, regulation compliance, and TMDL planning and implementation. The technology was transferred to communities across Colorado, including the Colorado Department of Public Health and Environment (CDPHE).

Project 7: Assessing Nutrient Management Tradeoff and Targets under Uncertainty

This project develops and demonstrates an integrative and adaptive framework that enables the development of system-level optimal strategies for targeted implementation of N and P load reduction options on a HUC 12 (or similar scale). The framework facilitates assessing tradeoffs and targets associated with different nutrient management solutions. The framework can be used to create information about the sustainability of alternative solutions with a system view of nutrient management. The system-characterization indicators are available from the CLEAN Nutrient Management Decision Support System (NM-DSS)described in Project 6.

System-level metrics were developed to facilitate integration of outputs from all sectors, including: N and P loads, costs, system reliability, system resilience, equity, and likelihood of adoption. Several outranking multi criteria decision analysis techniques (e.g. AHP and PROMETHE II) were encoded to enable selection of system-level nutrient management solutions at the system level that are consistent with the priorities of stakeholders in the watershed.

Demonstration studies in the Big Dry Creek and Cache la Poudre River watersheds in Colorado were conducted to identify technological and policy solutions that provide the greatest opportunities for nutrient reduction at the watershed scales. Social, economic and infrastructural barriers to sustainable nutrient management were explored. Furthermore, methods were developed to propagate data and modeling uncertainties in the assessment of nutrient control measures in various sectors. The role of these uncertainties in the selection of system-level optimal strategies for nutrient control was examined.

PRODUCTS

- 45 peer-reviewed journal articles
- 58 conference papers and presentations
- 4 MS theses
- 7 PhD dissertations
- 5 webinars (2,500+ views)
- 10 models and analytical tools

STAKEHOLDER WORKSHOPS

The CLEAN Center conducts annual stakeholder workshops to provide an opportunity for representatives of wastewater utilities, stormwater systems, agricultural producers, land managers, and researchers. The workshops provide a vehicle to discuss the current status of nutrient controls and innovations, including advances in modeling and analysis technologies as well as challenges and opportunities within the evolving Clean Water Act regulatory structure. The annual workshops are focused on stakeholder interaction and community engagement.

Over the last five years, the CLEAN Center has generated valuable data and analysis tools. The Center continues to enhance documentation and access to the tools and information generated by the research activities. The Center leverages support from state and local agencies, along with private sector stakeholders, to promote ongoing activities and new products.

MODELS & TOOLS

CLEAN Nutrient Management Decision Support System (NM-DSS)

The CLEAN Center developed the NM-DSS, a web-tool that enables assessment of nutrient contributions from various sources, identification of optimal nutrient control strategies, and potential effects of incentives, trading, and policy alternatives. The NM-DSS summarizes contributions from urban stormwater, wastewater treatment facilities, irrigated agriculture, and background and compares them against instream nutrient loads for available stream monitoring stations. The dashboard is currently on version 1.1 with irrigated agriculture data available for the South Platte, Republican, and Arkansas River basins in Colorado. The remaining data is available state wide. The dashboard is used by the Colorado Department of Public Health and Environment and other stakeholders for nutrient control in watersheds across the State. More information is available at: http://onewatersolutions.com/our-software/tools/nutrient-control/

Edge of Field Conservation Planning Application

The Edge of Field Conservation Planning application (EOFCP) allows producers, their advisers, scientists, and engineers to compare potential and modeled water quality and crop yield impacts from the implementation of agricultural nutrient, irrigation and tillage conservation best management practices (BMPs). It also provides additional information on BMP implementation and calculates nutrient recommendations with user inputs. Users can also use the N-index and P-index risk modules to evaluate fields for N and P losses. Once a field is mapped, EOFCP provides information on site characteristics that can show how nutrient management practices may impact water resources.

Stormwater Nutrient Loading Calculator

The tool computes N and P loads from urban stormwater systems. Hydrological responses are simulated using the Schueler's Simple Method, while nutrient concentrations are specified probabilistically based on urban land use types. The effects of SCMs are modeled using treatment efficiencies reported in the International BMP Database. The primary advantage of the tool is that its inputs can be created from national databases, and thus, it can be applied nationally.

River Erosion Model

The River Erosion Model (REM) is a watershed-scale model for simulating river channel erosion and associated pollutant loading. REM is as simple as possible – including the necessary erosion processes while limiting data requirements to make it easier to apply. REM simulates channel bed erosion and deposition, bank erosion and channel widening, meander bend migration, and knickpoint erosion throughout an entire watershed, including any tributaries to the main channel. Taking this watershed-scale approach is important because channel changes in one part of the basin can impact erosion processes elsewhere. In addition to simulating these erosion processes, REM calculates associated fine sediment and phosphorus loading, based on user-supplied streambank phosphorus concentrations. This provides an estimate of total watershed pollutant loading and can even tell the user what part of the watershed is contributing the most pollution. More information is available at: http://github.com/rodlammers/REM.

Watershed Rapid Assessment Program

The Watershed Rapid Assessment Program (WRAP) is a data summary tool that extracts, organizes, and analyzes data and information at various watershed scales, including hydrologic unit code (HUC) 12, HUC 10, and HUC 8 levels. Utilizing the extracted data, the WRAP tool calculates a number of watershed health indicators to create an overall summary of the watershed condition. This tool summarizes readily available geospatial characteristics including land use, land cover, soils, climate, stream discharge, water quality, stream classification and impairment status, as well as census data from USGS, USDA, NOAA, and EPA data resources. The WRAP tool allows users to conduct a variety of analyses ranging from simple watershed summaries to more complex analyses such as TMDL planning and implementation. More information is available at: http://onewatersolutions.com/our-software/tools/colorado-collaborative/watershed-assessment/

Healthy Watershed Report

The Healthy Watershed Report is an output generated by the Watershed Rapid Assessment Program (WRAP). This program extracts, organizes, and analyzes data and information at various watershed scales, including HUC 12, HUC 10, and HUC8 levels and summarizes readily available geospatial characteristics including land use, land cover, soils, climate, stream discharge, water quality, stream classification and impairment status, and census data from USGS, USDA, NOAA, and EPA data resources. In addition to the data extraction, a number of watershed health indicators are calculated based on the EPA's Healthy

Watershed methodology. More information is available at: http://onewatersolutions.com/our-software/tools/colorado-collaborative/watershed-assessment/

Watershed Prioritization Dashboard

The Watershed Prioritization Dashboard is web tool that interfaces with a preprocessed summary of watershed health indicators from the Healthy Watershed Assessment Report. These indicators can then be combined in the interface with in Multi-Criteria Decision Analysis (MCDA) tool to prioritize watersheds based on their indicators and user specified weights for importance of various categories. This facilitates a large-scale assessment of watersheds which can help prioritize watersheds in need (low health indicators), watersheds in need of protection (high health indicators) and many more scenarios.

Reg. 85 Data Analysis

The Regulation 85 (Reg. 85) Data Analysis Tool is a dashboard statistical summary of wastewater treatment facility nutrient monitoring data for Colorado. It summarizes current conditions in upstream, downstream and effluent nutrient concentration. It also includes a recommended data sample size calculator based on a methodology by Rachel et al., (2014) that recommends sample sizes based on variability in existing datasets.

303d Stream Assessment Tool

The 303d Stream Assessment tool is a web tool to automate data processing of stream water quality data as it relates to stream standards based on the method used by the Colorado Department of Public Health and Environment (CDPHE). These results will be combined by CDPHE personnel for recommendation of new or changed impairments for waterbodies in Colorado.

Low Flow Analysis Tool (DFLOW)

Low Flow Analysis is calculation of design low flow conditions based on stream monitoring data using the EPA DFLOW model. It operates on stream flow monitoring station data and performs statistical regressions to determine the user specified type of low flow condition.

Stream Segmentation Database (Reg. 31 Data Viewer)

The Stream Segmentation Database (Reg. 31) is a dashboard for viewing Colorado Regulation 31 data, water quality standards for streams.

Fish Monitoring Sites Data Viewer

The Fish Monitoring Sites data viewer is a dashboard for viewing Colorado fish monitoring sites (typically lakes and reservoirs) and summarizes warnings about use or consumption of fish from these sources like mercury in fish tissue warnings.