Improved quantification of river nutrient loading for better water quality and more efficient energy use

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Focal Area(s): Multi-sector dynamics involving agriculture practices, water quality and energy.

Existing Challenge: It has been observed that the ultimate limitation to the AI boom is electricity and cooling, both of which are intrinsically linked to water and energy. Since both water and energy supplies are finite, various user sectors, including industrial manufacture, agriculture, and power plants, have to compete for their allocation. Water quality, defined by its chemical, biological, and physical properties, is intensely impacted by agricultural practices, and maintaining healthy water demands a substantial amount of energy. In some US states, such as California and Illinois, a significant amount of irrigation water is used to sustain cropland productivity. However, unassimilated fertilizers (particularly nitrogen fertilizers) and pesticides leak into rivers and underground aquifers, degrading water quality through a series of biochemical processes. This incurs additional energy costs for water processing before it can be used for other purposes, including drinking water, power generation, and equipment cooling. Besides, poor water quality is one major risk to hydropower generation due to corrosion of facilities, thereby limiting energy production. Moreover, the synthesis of nitrogen fertilizer via the Haber-Bosch process is extremely energy-intensive, consuming 1-2% of the world's annual energy supply, primarily from natural gas. Consequently, any improvement in managing agricultural water use and the quality of its outgoing water will contribute to enhancing the water and energy security in the US.

Currently in the US, facilities responsible for water supplies, such as wastewater treatment plants or large pumping stations for aqueducts, are major electricity consumers. However, a critical challenge arises from the lack of high-resolution spatiotemporal data regarding water quality and usage. These data deficiencies often force the planning for water treatment to adopt the conservative, worst-case assumptions about the receiving river's condition and the demand from agricultural irrigation. Such conservative planning, due to the uncertainties in actual water and electricity allocations, can lead to scenarios that treatment plants might be over-treating water when river conditions are favorable, leading to unnecessary energy expenditure, or conversely, under-preparedness for sudden pollution events or increased demand could result in insufficient treatment, posing risks to public health and the environment.

Near-Term Opportunity: The scientific community has made significant progress in predicting water and nutrient levels at the US national scale, including agricultural areas. For instance, the land module of the Department of Energy's Energy Exascale Earth System Model is able to simulate natural land and cropland water use together with river flow and water management, although at coarse resolution (10-50 km grid resolution). Meanwhile, remote sensing products and AI tools are integrated into powerful platforms to map surface water quantity and quality at a resolution of a few meters. In particular, the Alpha-Earth platform is able to provide a digital representation of the earth as high as the 10mx10m resolution. By linking these tools' predictive capability with the water and energy management tools used by state-level stakeholders, we are positioned to improve the water and energy allocation under various conditions.

Specifically, the predictive capabilities can be expanded to address the identified challenges via:

- High-resolution spatiotemporal data for water quality and usage: Predictive models can integrate and downscale satellite imagery, sensor networks, and hydrological models to generate high-resolution, real-time data on water quality parameters (e.g., nutrient levels, pesticide concentrations) and water usage across agricultural landscapes. This will move beyond conservative, worst-case assumptions and provide accurate inputs for water treatment planning.
- Forecasting pollution events and demand fluctuations: Advanced predictive analytics, incorporating machine learning and AI, can forecast sudden pollution events (e.g., due to heavy rainfall and runoff) and predict agricultural irrigation demand under various climate conditions. This allows for proactive adjustments in water treatment and allocation, preventing both over-treatment and under-preparedness.
- Optimizing fertilizer and pesticide application: Predictive models can simulate the fate and transport of unassimilated fertilizers and pesticides, identifying areas at high risk of leakage into rivers and aquifers. This information can then be used to optimize application rates and timing, minimizing environmental degradation and the associated energy costs for water processing.
- Assessing climate change impacts on water-energy nexus: Predictive models can project the long-term impacts of different climate change scenarios on water availability, agricultural productivity, hydropower generation, and the energy intensity of water management. This will enable more resilient and sustainable water and energy allocation strategies and help build more responsive and resilient infrastructure.
- Improving hydropower generation efficiency: By predicting water quality issues that could lead to corrosion of facilities, predictive models can inform

maintenance schedules and operational adjustments to prevent damage and optimize energy production from hydropower.

By leveraging these predictive capabilities, we can move towards more informed, adaptive, and energy-efficient management of water resources, ultimately enhancing water and energy security in the US.

Success Measure: We expect that the metrics to measure the success of research projects aimed at addressing the identified challenges and opportunities could be:

- Amount of reduced energy consumption for water management: (1) Decrease in electricity usage by wastewater treatment plants and large pumping stations. (2) Reduced energy expenditure due to optimized water treatment based on accurate river conditions.
- Improved water quality: (1) Lower levels of unassimilated fertilizers (particularly nitrogen) and pesticides in rivers and underground aquifers. (2) Reduced instances of water quality degradation due to agricultural practices.
- Enhanced water and energy security:(1) Improved allocation of water and energy resources under various climate conditions. (2) Increased resilience of water and energy systems to environmental disasters, e.g. floods, droughts and heatwaves.
- Optimized agricultural practices: (1) More efficient fertilizer and pesticide application rates and timing, minimizing environmental leakage. (2) Improved cropland productivity with reduced environmental impact. (3) Improvement in cropland profit with savings in fertilizer, water and energy use.
- Increased hydropower generation efficiency: (1) Reduced corrosion of hydropower facilities due to improved water quality. (2) Optimized energy production from hydropower and saving in infrastructure investment through informed maintenance and operational adjustments.
- Better data availability and utilization: (1) Availability of high-resolution spatiotemporal data for water quality and usage. (2) Improved accuracy in forecasting pollution events and agricultural irrigation demand.
- Proactive management of water resources: (1) Ability to make proactive adjustments in water treatment and allocation, preventing both over-treatment and under-preparedness. (2) Implementation of more informed, adaptive, and energy-efficient water resource management strategies.

Reference

Capdevila-Cortada, M. Electrifying the Haber–Bosch. *Nat Catal* **2**, 1055 (2019). https://doi.org/10.1038/s41929-019-0414-4