Sandia National Laboratories

Hardening forested watersheds to wildfire to enhance downstream water quality for critical energy infrastructure

Authors/Affiliations:

Joseph Lafayette Crockett, Sandia National Laboratories
Dan Krofcheck, Sandia National Laboratories

Focal Area

This white paper focuses on water-for-energy stability by exploring the importance of developing insights into the risk of critical energy infrastructure to upstream water quality impacts resulting from severely burned forested watersheds.

Existing Challenge

The stability of energy production in the US is vulnerable to the quality of surface water used in installations. High turbidity and water temperatures can drastically reduce cooling efficiency in power plants (Macknick et al. 2016), while high sediment loads can cause damage to hydropower production equipment. Increased downtime and maintenance costs reduce the capacity of this stable infrastructure to accommodate catastrophic energy demands, which have led to shutdowns or reduced generation due to high water temperatures (Macknick et al. 2016). Forested landscapes are key contributors to the availability and quality of water (e.g., Brucker et al. 2025), and thus this reliance highlights a key risk: These forests are vital for maintaining water quality, yet disturbances such as severe wildfires can drastically alter water quality emerging from them. Wildfire behavior has changed in the last few decades with fires burning hotter, larger, and consuming more vegetation per acre burned (Iglesias et al. 2022, Parks et al. 2025). These high-severity fires lead to increased sediment loads, turbidity, and elevated water temperatures in downstream water bodies (Chen, J., & Chang, H. (2023), Smith et al. 2011). Hardening vulnerable watersheds to fires with vegetation management such as targeted use of prescribed fire and mechanical thinning can mitigate risks to the water quality important to a stable energy infrastructure. However, to understand the risks in this coupled system will require complex modeling of water flow in different scenarios that utilize vegetation, soils, and fire impacts to determine downstream water impacts. In the near-term, existing physics based models can be utilized, however; the complexity of interactions between fire severity, watershed characteristics, and hydrological responses may require a more efficient approach to modeling these dynamics, such as leveraging physically constrained AI/ML models capable of quickly simulating water quality at low computational cost.

Near-Term Opportunity

In the near-term, using existing physics-based water flow models to simulate the movement of water with high turbidity, temperatures and sediment loads from severe fires to power installations will enhance the ability of installations to make informed decisions in real time to upstream fires. In the event of a fire, power installations could utilize these models to extend time for planning for the impacts of decreased water quality on their systems, allowing for, e.g.,

additional sediment control mechanisms to be implemented upstream. In addition, Burned Area Erosion Response (BAER) teams could utilize these models to prioritize erosion control management on burned slopes that are more likely to increase sediment loading in hydropower dams or water-based cooling systems in nuclear, coal, or natural gas plants.

As the water quality impacts from fires can be mitigated through the usage of pre-fire vegetation management, simulating management scenarios impacts on power installations will provide additional opportunities for long-term planning to harden watersheds for energy resilience. Coupled with landscape models that simulate the change in forested landscapes as a function of time, weather, management, and disturbance, these water quality simulations will assess the cumulative effects of various forest management strategies over time, allowing stakeholders to evaluate the effectiveness of different approaches in reducing fire severity and improving watershed resilience. Accomplishing these goals of quantifying and responding to critical energy infrastructure vulnerabilities to burned watersheds may require constrained physics AI/ML models that accurately represent these complex systems while incorporating uncertainty calculations. Current physics-based models are often computationally expensive and challenging to parameterize, limiting their utility in scenario analysis. By integrating constrained physics AI/ML models, the efficiency and effectiveness of these assessments can be enhanced, enabling managers to incorporate water quality impacts on power installation stability into informed decisions regarding forest management and fire mitigation strategies. Constrained physics AI/ML models have been advancing into similar spaces, such as weather forecasting (Taccari et al. 2022), subsurface flow modeling (Kim et al. 2024), and flood risk simulations (Gu et al. 2020, Zhou et al. 2022). Developing similar models for water dynamics from forested systems would fill a critical gap in our ability to determine and characterize uncertainty of downstream water quality impacts from post-fire flooding, impacts to energy generation from decreased water quality, planned fuels management, and ecosystem changes from forest to other vegetation states.

Success Measures

The success of hardening watersheds to protect critical water-energy infrastructure will be evaluated based on three key components: 1) successful simulation of altered water quality at the power installation and any decreases in energy generation from increased sediment, water temperatures, and turbidity as compared to historical records; 2) the degree of deviation of AI-based models from physics-based water models in simulating water quality from burned watersheds; and 3) the effectiveness of fuel management scenarios on energy production (e.g., target reduction in water quality degradation) and improvements in energy generation efficiency.

Further, the success of modeling these coupled systems, either with existing physics-based water models or AI/ML models, can be assessed with close communication with utility operators. BAER teams will also be a key source of feedback: successful modeling will optimize erosion control decisions, leading to quicker response and lower costs for these teams. This assessment will evaluate the models' reliability in improving response times, reducing downtimes, and decreasing maintenance costs due to fire-caused changes in water quality. Successfully hardening watersheds will mitigate the risk of catastrophic fires in vulnerable watersheds to the stability of power generation.

References

Brucker, C. P., Livneh, B., Rosario-Ortiz, F. L., Yao, F., Williams, A. P., Becker, W. C., ... & Rajagopalan, B. (2025). Wildfires drive multi-year water quality degradation over the western United States. *Communications Earth & Environment*, *6*(1), 489.

Chen, J., & Chang, H. (2023). A review of wildfire impacts on stream temperature and turbidity across scales. *Progress in Physical Geography: Earth and Environment*, *47*(3), 369-394.

Dennison, P. E., Brewer, S. C., Arnold, J. D., & Moritz, M. A. (2014). Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters*, *41*(8), 2928-2933.

Gu, H., Xu, Y. P., Ma, D., Xie, J., Liu, L., & Bai, Z. (2020). A surrogate model for the Variable Infiltration Capacity model using deep learning artificial neural network. *Journal of Hydrology*, *588*, 125019.

Iglesias, V., Balch, J. K., & Travis, W. R. (2022). US fires became larger, more frequent, and more widespread in the 2000s. *Science advances*, *8*(11), eabc0020.

Kim, S., Lee, E., Hwang, H. T., Pyo, J., Yun, D., Baek, S. S., & Cho, K. H. (2024). Spatiotemporal estimation of groundwater and surface water conditions by integrating deep learning and physics-based watershed models. *Water Research X*, *23*, 100228.

Macknick, J., Zhou, E., O'Connell, M., Brinkman, G., Miara, A., Ibanez, E., & Hummon, M. (2016). *Water and climate impacts on power system operations: the importance of cooling systems and demand response measures* (No. NREL/TP-6A20-66714). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Parks, S. A., Coop, J. D., & Davis, K. T. (2025). Intensifying fire season aridity portends ongoing expansion of severe wildfire in western US forests. *Global Change Biology*, *31*(8), e70429.

Smith, H. G., Sheridan, G. J., Lane, P. N., Nyman, P., & Haydon, S. (2011). Wildfire effects on water quality in forest catchments: A review with implications for water supply. *Journal of Hydrology*, *396*(1-2), 170-192.

Taccari, M. L., Nuttall, J., Chen, X., Wang, H., Minnema, B., & Jimack, P. K. (2022). Attention U-Net as a surrogate model for groundwater prediction. *Advances in Water Resources*, *163*, 104169.

Zhou, Y., Cui, Z., Lin, K., Sheng, S., Chen, H., Guo, S., & Xu, C. Y. (2022). Short-term flood probability density forecasting using a conceptual hydrological model with machine learning techniques. *Journal of Hydrology*, *604*, 127255.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. *SAND2025-13769O*