# Climate, Water, Energy Nexus: Impact of Aerosols on Hydropower Generation in California

Farzana Kabir [1], Nanpeng Yu[1], Balakrishna Sastry[2], and Vibhu Kaushik[2]

[1]Electrical and Computer Engineering, University of California, Riverside, Riverside, CA 92521-0429, USA
[2]Southern California Edison, Rosemead, CA 91770 USA
fkabi001@ucr.edu, nyu@ece.ucr.edu, Balakrishna.Sastry@sce.com, Vibhu.Kaushik@sce.com

***Abstract*—Hydropower generation is a crucial link in the climate-water-energy nexus. It has been discovered that natural and anthropogenic aerosols have a great influence on meteorological variables such as temperature, snowpack, and precipitation, which, in turn, impact the inflows into hydropower reservoirs. This paper takes the next logical step to explore the impact of aerosols on hydropower generation and revenue. A comprehensive framework is developed to quantify the impact of aerosols on hydropower generation and revenue by integrating the Weather Research and Forecasting Model with Chemistry, a statistical hydrologic forecasting model, and the hydropower operation optimization toolbox. A case study is performed in the Big Creek Hydroelectric Project in California. The simulation results show that aerosols reduce inflows into the reservoirs of Big Creek hydroelectric system by 1-10%. This leads to a 6% reduction of annual hydropower generation, causing a $2.8 million loss in annual revenue.**

***Index Terms*—Aerosol, Climate-Water-Energy nexus, hydropower, inflow.**

## I. Introduction

Water and energy are intrinsically interconnected. Water is required for nearly all forms of energy production and electricity generation. On the other hand, energy is needed for the treatment, recycling, transportation, and distribution of water [1]. Climate change and increased demand for water and energy are creating scarcity and uncertainty in water and energy systems. The strong interdependence between the two systems means that disturbance in one of the systems will likely lead to vulnerabilities within the other system. To mitigate these vulnerabilities, it is imperative to closely study the interplay among the water, climate, and energy systems.

Hydropower generation is a crucial link in the climate-water-energy nexus. Climate change causes rises in average temperature, shifts in precipitation, snowmelt, and runoff patterns, disruptions in availability of water, and increases in climate variability. The shifts in precipitation, snowmelt, and runoff patterns, in turn, affect the scheduling of hydropower plant operations. Aerosols are a big source of uncertainty in the projections of climate change. They exert a great influence on the hydrological cycle in a region through their influence on meteorological variables, such as temperature, snow water equivalent (SWE), and precipitation [2], [3]. A detailed literature review of the impact of aerosols on these meteorological variables can be found in [4]. In general, light absorbing aerosols increase air temperature and reflective aerosols decrease air temperature. Aerosols reduce precipitation and SWE by 10% over mountain tops in the Sierra Nevada region [5]. A detailed description of effects of aerosols on precipitation and SWE in California is provided in [5]. Meteorological variables, in turn, can significantly influence inflows into the hydropower reservoirs and water availability for hydropower generation. Therefore, it is critical to understand and quantify the impact of aerosols on hydropower generation and revenue for the purpose of vulnerability assessment.

The objective of this paper is to quantify the impact of aerosols on hydropower generation and revenue of the Big Creek Hydroelectric Project located on the upper San Joaquin River system in the Sierra Nevada Mountains of Central California. This evaluation requires regional scale assessment because the impact of aerosols on climate differs by region. Previously, we developed a comprehensive framework [4] to quantify the impact of aerosols on inflows into higher elevation hydropower reservoirs by integrating the Weather Research and Forecasting Model with Chemistry (WRF-Chem) and a statistical inflow forecast model. We performed the case study in the Big Creek Hydroelectric Project. The simulation results showed that the presence of aerosols results in a significant reduction of annual reservoir inflow by 4-14%. Aerosols were found to significantly reduce the amount of inflows in the summer when the marginal value of water is high and slightly increase the inflow in the spring when run-off risk is high. Hence, it is hypothesized that the presence of aerosols can be detrimental to the optimal utilization of hydroelectric power plants.

In this study, we take the next logical step to quantify the impact of aerosols on hydropower generation and revenue. To this end, we integrate the hydropower optimization toolbox, Vista Decision Support System (DSS) [6] into the framework developed in [4]. We obtain the simulations of meteorological variables with and without aerosol impacts from WRF-Chem simulations conducted in the San Joaquin Valley of California. We use those to generate the inflows into the hydropower reservoirs with and without considering the impact of aerosols using the statistical inflow forecast model. Then, we feed the inflow projections with and without aerosol effects into the Vista DSS to determine the optimal operation schedules of the hydropower system for both scenarios.

This study was sponsored by California Energy Commission under grant #EPC-14-064.

The unique contributions of this study are listed as follows:

1. This paper develops a comprehensive framework for evaluating the impact of aerosols on hydropower generation and revenue by seamlessly integrating the numerical weather forecasting model (WRF-Chem), a statistical inflow forecast model, and the hydropower operation optimization toolbox.

2. The impact of aerosols on hydropower generation and revenue is quantified for the Big Creek Hydroelectric System. The simulation results show that aerosols lead to significant reduction in annual hydropower generation and revenue.

The existing research studying effects of climate change and human activities on hydropower generation and revenue focus on the effects of carbon dioxide and several other greenhouse gases. The impact of climate change on two high elevation hydropower systems in California: the Upper American River Project and the Big Creek Hydroelectric Project are estimated in [7]. They simulated the operations of the two hydroelectric projects with historical data and data generated from four climate change scenarios. The climate change scenarios result in reduced runoff and earlier runoff that cause a reduction in hydropower generation for both hydropower systems. The hydropower generation in 137 high elevation systems are explored in [8] under three climate change scenarios: wet warm, dry warm, and warming only. They found that dry warming and warming only climate change scenarios reduced average hydropower revenues whereas wet warming scenario saw an increase in revenue. Other studies are restricted to large lower elevation water supply reservoirs in California [9], [10]. Our study differs from the existing ones by studying the impact of aerosols on hydropower generation in a higher elevation hydroelectric system in California.

The rest of the paper is organized as follows. Section II discusses the study area. Section III describes the overall framework of the study. Section IV describes the hydropower plant operation optimization problem. Section V describes the technical methods: the WRF-Chem Model, the statistical inflow forecast model, and Vista DSS. Section VI presents the case study. Section VII shows the impact of aerosols on hydropower generation and revenue. Finally, Section VIII concludes the paper.

## II. Background

The Big Creek Hydroelectric Project is a cascaded hydroelectric system owned and operated by Southern California Edison (SCE). The primary source of water for inflows into the hydropower reservoirs is the runoff generated from the snowmelt from the Sierra Nevada mountains. It has a total installed capacity of 1000 MW accounting for approximately 20% of SCE's total generation capacity. The hydroelectric system includes 27 dams, 23 generating units in nine power houses, underground tunnels, and six major reservoirs. Water from the lakes in higher elevation are routed through the nine powerhouses and discharged into the lakes in lower elevations, which are connected through tunnels and penstocks. Florence Lake and Lake Thomas Alva Edison are the higher elevation reservoirs of the system. The dam at Florence Lake captures runoff from the South Fork San Joaquin River, diverting it through the Ward Tunnel towards the Portal Powerhouse. Lake T.A. Edison discharges some of its water to the Ward Tunnel. Water running through Portal Powerhouse gets discharged into the Huntington Lake where it is in turn diverted to the lakes at lower elevation, namely, Shaver Lake, Mammoth Pool, and Redinger Lake through other power houses.

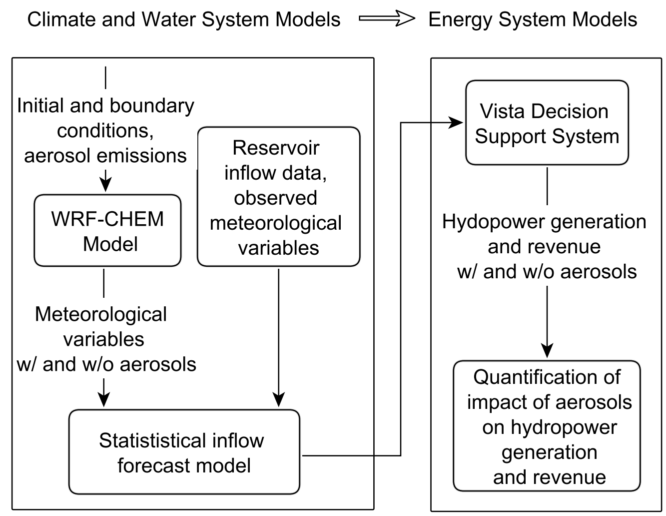


Fig. 1. Overall framework for quantifying the impact of aerosols on hydropower generation and revenue

## III. Framework

Fig. 1 shows the overall framework for quantifying the impact of aerosols on hydropower generation and revenue. The workflow is as follows. First, we run a version of Weather Research and Forecasting Model with Chemistry and fully coupled aerosol-meteorology-snowpack module [11], [12]. The outputs of the model include, with and without considering the impacts of aerosols, the meteorological variables, such as daily mean temperature, accumulative snow water equivalent, and incremental precipitation in the San Joaquin Valley of California. Then, we feed these meteorological variables, along with historical reservoirs inflow data, into the statistical inflow forecast model. These statistical models produce reservoirs inflows with and without considering the aerosols impacts, which we, in turn, feed into the hydropower operation optimization model. The Vista DSS then conducts hydroelectric system optimization over a one-year horizon to maximize the generation revenue of the hydropower facility. Finally, we quantify the impact of aerosols on hydropower generation and revenue by comparing the hydropower generation and revenue results with and without considering aerosols.

## IV. Problem Formulation

In order to estimate the impact of aerosols on hydropower generation in a hydro year, we use Vista DSS to optimize the generation schedule of the cascaded hydropower system. The goal is to maximize the hydropower system's revenue from providing energy, spinning reserve, frequency regulation up, and frequency regulation down services subject to physical, operational, and contractual constraints. The decision variables include the generation units' status and the amount of generation from each powerhouse. The optimization algorithm assumes that the cascaded hydroelectric system is a price taker in the electricity market. The inputs to the optimization include the inflows to various reservoirs and prices for energy and ancillary services. The hydropower plant operation optimization problem is formulated as follows.

$$\begin{aligned}Max \sum_{n=1}^{N}\sum_{t=1}^{T}\{U_{nt} \times (P_{nt} \times f_t + c_t^{res} \times P_{nt}^{res} \\ + c_t^{reg,up} \times P_{nt}^{reg,up} + c_t^{reg,down} \times P_{nt}^{reg,down}) \\ - F(U_{nt}, P_{nt}, P_{nt}^{res}, P_{nt}^{reg,up}, P_{nt}^{reg,down})\}\end{aligned}$$

subject to

$$P_n^{\min} \leq P_{nt} \leq P_n^{\max}, \quad n = 1, \ldots, N, \quad t = 1, \ldots, T$$

and other operational and contractual constraints.

$U_{nt}$ denotes the up/down status of generation unit $n$ at hour $t$ (0: unit down, 1: unit up). $P_{nt}$ denotes the power generation of unit $n$ at hour $t$. $P_{nt}^{res}$, $P_{nt}^{reg,up}$, and $P_{nt}^{reg,down}$ are the spinning reserve capacity, frequency regulation up, and frequency regulation down capacity respectively, scheduled for unit $n$ at hour $t$. $f_t$ represents the forecasted energy price ($/MWh) for hour $t$. $c_t^{res}$, $c_t^{reg,up}$, and $c_t^{reg,down}$ denote the forecasted price ($/MW) for spinning reserve service, frequency regulation up service, and frequency regulation down service for hour $t$. $F$ is the operation and maintenance cost of the cascaded hydroelectric system. $P_n^{\min}$ and $P_n^{\max}$ denote the minimum and maximum rated capacity of unit $n$. $N$ is the number of generation units and $T$ is the number of hours in a water year,

## V. Technical methods

### A. Vista Decision Support System

In order to maximize the revenue from operating a hydroelectric project, it is crucial to determine the optimal operation schedules of various powerhouses and reservoirs. At the same time, hydroelectric projects often have multiple additional functions, such as flood control, navigation, irrigation, water supply, and recreation. Vista DSS is a toolbox which assists in both planning and operation of the hydroelectric systems to ultimately maximize the value of hydropower generation while helping hydroelectric systems to serve additional functions such as water management and flood control. We present three key modules of the Vista DSS below. The first module is used to develop a representation of the physical system. The second module models individual powerhouses. The third module describes the physical, operational, and contractual constraints.

*1) Physical System Representation:* A water resource system can be disaggregated into a number of hydraulically independent basins for modeling purposes. A hydraulic system consists of rivers and watersheds. Nodes are points of interest in the water resource system being modeled. For example, nodes can represent reservoirs, tailwater junctions, river junctions, sources, and sinks. Reservoir and river junction nodes combine a number of inflow and outflow channels in the network. An arc is a directed line segment that joins an upstream node to a downstream node. There are four types of arcs: inflow, power, spillway, and river reach. Inflow arcs represent inflow into the river system to be modeled, power arcs represent one or more turbines and their associated flow, spillway arcs represent the total flow through spillway structures, and river reach arcs indicate physical conveyances such as natural or man-made channels.

Physical structures in a river system such as reservoir and hydropower plants are represented mathematically along with estimated parameters. A storage reservoir is represented by its full supply level (FSL), dead storage level (DSL) and the coefficients of the polynomial defining the storage elevation-volume relation. River reach arcs are used to model flow travel time and attenuation en route. The Muskingum-Cunge channel flow routing method is employed here which assumes that a storage in a single river reach is related to its inflows and outflows. The routing coefficients are determined by fitting the routing equation to the observed field data so that the sum of weighted residual errors is minimized. Channel water levels data are collected from the flow gauges, which are converted into discharge by a stage-discharge rating curve. Spillway discharge is modeled as a function of reservoir elevation and spillway opening.

*2) Hydropower Plant Modeling:* The power generation from a single generating unit is defined by a power polynomial. The power equation represents a fundamental relationship between discharge, net head and efficiency.

$$\mathrm{P} = \mathrm{C} \times \eta_p \times \mathrm{Q} \times \mathrm{h}_n \tag{1}$$

where $P$ is the generated power, $C$ is a coefficient, $\eta_p$ is the overall generating efficiency, $Q$ is the turbine discharge, and $h_n$ is the net head. Based on this theoretical relationship, the power polynomial for each unit can be approximated by a third order equation that represents unit power generation as a function of the head and the discharge along with all the head-losses acting on that unit.

$$P = a + b \times Q + c \times Q^2 + d \times Q^3 \tag{2}$$

where $P$ is the power produced by one unit, $Q$ is the discharge flowing through the unit, and $a, b, c, d$ are functions of unit gross head $h$.

$$a = a_1 + a_2 \times h + a_3 \times h^2 \tag{3}$$

Here, $b, c,$ and $d$ have similar relationships with the unit gross head, $h$. The estimation of the power polynomial coefficients can be formulated as a multiple linear regression problem. The solution should satisfy these two conditions: (i) the second derivative of efficiency with respect to discharge should be less than 0 and (ii) the derivative of power with respect to discharge should be greater than or equal to 0 over a unit's discharge range.

*3) Constraints:* There are three types of constraints in the Vista DSS: physical, operational, and contractual constraints. Physical constraints represent mandatory physical operating limits such as size of the lake, limitations of generation units and tunnels, and minimum and maximum turbine limits. Operational constraints include limitations for reservoir elevation, discharge speed, and scheduled releases. The contractual constraints model the restrictions on hydroelectric project operations due to water rights, minimum fish flows and recreational requirements, etc. Every imposed constraint lowers the total revenue of the hydroelectric project. However, these operational and contractual constraints can be violated at a cost. The constraints are prioritized by their relaxation cost.

### *B. WRF-Chem Model*

The WRF-Chem model [11] is a weather research and forecasting system which simulates chemistry and aerosols simultaneously with meteorology. This model has been extensively used to study regional air quality and their interactions with weather and climate (e.g., [3], [5], [12]–[15]). In this study, we use the WRF-Chem version 3.5.1, which includes aerosol interactions with radiation, cloud, and snowpack [12]. In the WRF-Chem control (CTRL) experiment, we run the model at 4 km horizontal resolution with the model domain covering California and surrounding regions. The initial and boundary conditions are provided by the European Center for Medium-Range Weather Forecasts Interim Re-Analysis for meteorology and the global Model for Ozone and Related chemical Tracers, version 4 [16] for chemistry. Anthropogenic aerosol emissions are obtained from US EPA 2005 National Emissions Inventory (NEI05; US EPA, 2010). Dust emissions are calculated using the DUST TRANsport model (DUSTRAN) scheme [17] following [15]. More details of the model setup can be found in [5]. The model performance on simulating aerosols and meteorological variables in California were evaluated in [5], [15]. In a CLEAN simulation, we turned off local aerosol emissions and set aerosols from boundary conditions as zero, but kept chemical components from boundary conditions with aerosol chemistry on. Thus, meteorological variables from the WRF-Chem CTRL and CLEAN simulations represent conditions with and without the impact of aerosols respectively.

### *C. Dynamic Regression Model*

In this study, we use dynamic regression models [18] as the statistical inflow forecast model to estimate the inflows into various reservoirs based on the meteorological variables. A dynamic regression model uses time lagged explanatory variables to forecast the dependent variable while modeling the error term with an ARIMA model [19]. The model can be written as Equation 4.

$$Y_t = \mu + \sum_{i=1}^{M} \frac{\omega_i(B)}{\delta_i(B)} B^{b_i} X_{i,t} + \frac{\theta(B)}{\phi(B)} a_t \tag{4}$$

where $Y_t$ is the dependent variable, $X_{i,t}$ is the i-th explanatory variable, $\omega_i(B)$ is the numerator polynomial of the transfer function, $\delta_i(B)$ is the denominator polynomial of the transfer function, $b_i$ is the dead time, $B$ is the backshift operator, $\phi(B)$ is the autoregressive operator, $\theta(B)$ is the moving-average operator, and $a_t$ is the white noise. We performed model fitting by applying relevant theory to choose the input meteorological variables and then following standard methodology for building dynamic regression models. Details of the model fitting procedure can be found in [4].

## VI. Case Study

We conduct the case study in the Big Creek Hydroelectric System of California.

### *A. Simulation of Hydropower Reservoir Inflows*

Historic inflows for Lake T. A. Edison and Florence Lake are available for water year 2010-2015. A water year or a hydrological year is a 12-month period between October 1 of one year and September 30 of the next year. We divide the observed inflows and meteorological variables into a training set and a test set. We form the test set by withholding the data for the last water year, i.e., water year 2015, from the model identification and estimation process. The rest of the data work as the training set. We collect the meteorological data and average those over three weather stations, Kaiser Point (KSP), Volcanic Knob (VLC), and Upper Burnt Corral Coral (UBC) located within a $0.4 \times 0.4^o$ grid box with center at $(37.32^o N, -118.97^o E)$. The WRF-Chem CTRL and CLEAN simulations of the meteorological variables are available for the water year 2015 at the grid box location. We compute inflow forecasts into these two lakes with and without aerosols for water year 2015 using a dynamic regression model.

We assume that inflows from the Bear Creek are about 90% of the Lake Edison inflows as the two inflows are highly correlated. The historic inflow data for Huntington Lake, Shaver Lake, Redinger Lake and Mammoth lake are not available before water year 2015. We utilize the statistical inflow forecast model of Florence Lake as a proxy because its location is physically closer to these lakes compared to Lake Edison. We use the WRF-Chem CTRL and CLEAN simulations of meteorological variables performed at $0.4 \times 0.4^o$ grid boxes with center at the location of Huntington Lake, Shaver Lake, Mammoth pool, and Redinger lake to estimate the inflows into these lakes respectively with and without considering the impact of aerosols. We assume that the ratio of simulated inflows with and without the impact of aerosols to the observed inflows for these lakes are the same as that of the Florence lake. The inflows at one of these Lakes $L$ can be calculated as follows.

$$Y^L = \frac{Y^{FL}\left(X_{\text{WRF-Chem simulations at lake } L}\right)}{Y^{FL}_{OBS}} \times Y^L_{OBS}$$

where $Y^L$ denotes the estimated inflows with or without considering the impact of aerosols at Lake $L$, $Y^{FL}$ represents the simulated inflows with or without considering impact of aerosols at Florence Lake, $X$ denotes WRF-Chem CTRL or CLEAN simulations of meteorological variables performed at a $0.4 \times 0.4^o$ grid box with center at the location of lake $L$, $Y^L_{OBS}$ is observed inflow at Lake $L$, and $Y^{FL}_{OBS}$ is observed inflow at Florence Lake.

### *B. Calculating the Impact of Aerosols on Hydropower Generation and Revenue*

We use the Vista DSS to optimize the operation schedule of hydropower plants over a one hydro year horizon to maximize the Big Creek Hydroelectric Project's revenue. Because both 2014 and 2015 are dry years, no recreational requirements for reservoir elevation level are placed on Huntington Lake. We assume that the impact of aerosols on the side flows into Dam 5, Dam 6, and Pittman are negligible given that these inflows are extremely small in dry years and cannot be stored.

We feed the inflow forecasts of the lakes into the Vista DSS to determine the optimal generation schedules for water year 2015 by maximizing the revenue of the hydroelectric system while meeting the physical and operational constraints. The optimization algorithm has a weekly time step. We formulate the hydro operation optimization problem as a mixed integer linear programming problem by approximating non-linear constraints as linear ones.

## VII. Result and analysis

### A. The Impact of Aerosols on Hydropower Reservoir Inflows

We quantify the impact of aerosols on reservoir inflows for water year 2015. The percentage change in inflows caused by aerosols can be calculated by Equation 5.

$$\frac{Inflow_{\text{w/ Aerosols}} - Inflow_{\text{w/o Aerosols}}}{Inflow_{\text{w/o Aerosols}}} \times 100\% \qquad (5)$$

As shown in Table I and Table II, the presence of aerosols results in a reduction in annual inflows by 1-10% for all of the lakes. The presence of aerosols leads to lower annual inflows due to reduced SWE, precipitation, and snowmelt. Significantly lower annual inflows can be observed for Lake Edison and Florence Lake due to the impact of aerosols. However, the reduction in inflows is not as significant in the other reservoirs with lower elevations. This can be explained by the fact that the impact of aerosols on SWE is very strong around the higher elevation reservoirs having a 22% difference between the WRF-Chem CTRL and CLEAN simulations whereas the impact is in the order of 1-6% in the lower elevation reservoirs. Note that, the reservoir inflows in the Big Creek Hydroelectric Project is snowmelt dominated [4].

For seasonal analysis, we first define the four seasons as follows: fall is defined as the period of 10/01-12/21, winter is defined as 12/22-03/20, spring is defined as 03/21-05/31, and summer is defined as 06/01-09/30. As shown in Table II, the impact of aerosols on inflows is more pronounced in the summer. Significantly lower inflows can be observed during summer in Lake Edison and Florence Lake due to the impact of aerosols. Lower prior season's SWE, lower current season's snowmelt, and lower precipitation result in lower inflows in summer for Lake Edison and Florence Lake. The impact of aerosols on inflows during summer are less significant for the other reservoirs with lower elevation due to weak influence of aerosols on SWE and snowmelt in lower elevation reservoirs. The impacts of aerosols on inflows are much smaller for all lakes in spring. In spring, dust aerosols enhance solar absorption and lead to higher temperature, snowmelt, and inflows. On the other hand, in spring, aerosols lead to lower precipitation, which results in a reduction of the inflows. The aggregated effect of aerosols on inflows through temperature, snowmelt, and precipitation is a small reduction in inflows in the spring. Although the percentage change in inflows caused by aerosols in fall and winter are high, the magnitude of change in inflows are small. This is because the levels of inflows are very low in fall and winter. A detailed discussion of the impact of aerosols on inflows into the reservoirs can be found in [4].

TABLE I
Annual reservoir inflows under different aerosol conditions

| Lake | CTRL ($acreft$) | CLEAN ($acreft$) |
|---|---|---|
| Edison | 47,683 | 50,353 |
| Florence | 85,541 | 92,793 |
| Huntington | 34,756 | 35,804 |
| Mammoth | 222,732 | 225,737 |
| Redinger | 4,689 | 4,791 |
| Shaver | 8,097 | 8,245 |

TABLE II
The impact of aerosols (%) on annual and seasonal reservoir inflows

| Lake | Annual | Fall | Winter | Spring | Summer |
|---|---|---|---|---|---|
| Edison | -5 | -1 | -0.5 | 1 | -15 |
| Florence | -10 | -8 | -12 | -0.5 | -23 |
| Huntington | -3 | -6 | -8 | -1 | -7 |
| Mammoth | -1 | -5 | -11 | -0.8 | -1 |
| Redinger | -2 | -6 | -10 | -1 | 0 |
| Shaver | -2 | -8 | -5 | -1 | -1 |

### B. The Impact of Aerosols on Hydropower Generation and Revenue

We calculate the impact of aerosols on hydropower generation and revenue for the Big Creek Hydroelectric Project for water year 2015. Table III shows the results. In water year 2015, aerosols reduced Big Creek's generation by 89,356 MWh and revenue by approximately $\$2.8$ million. This is equivalent to a 6% reduction in hydropower generation and 4% reduction in revenue. Note that, 2015 is the driest year on record. Hence, the revenue generated is very low for the size of the hydropower plant. The loss of hydropower generation and revenue are caused by the reduction in annual inflows due to aerosols. Aerosols reduced inflows to higher elevation reservoirs by 5-10% and inflows to lower elevation reservoirs by 1-2%. The reduction in inflows to higher elevation reservoirs is more important for a cascaded hydroelectric project. This explains why the loss in hydropower generation is around 6%. The percentage reduction in revenue is smaller than that of the power generation. This is because the loss in hydropower generation can be somewhat offset by the efficient scheduling

TABLE III
Impact of aerosols on hydropower generation and revenue in water year 2015.

| | Period | CTRL | CLEAN | Difference | (%) |
|---|---|---|---|---|---|
| MWH | Annual | 1,502,330 | 1,591,686 | 89,356 | -6 |
| | Fall | 89,907 | 99,135 | 9,228 | -9 |
| | Winter | 189,796 | 193,647 | 3,851 | -2 |
| | Spring | 231,395 | 267,710 | 36,315 | -13 |
| | Summer | 991,232 | 1,031,216 | 39,984 | -4 |
| Revenue | Annual | 70,954,360 | 73,818,350 | 2,863,990 | -4 |
| ($) | Fall | 6,868,430 | 7,291,490 | 423,060 | -6 |
| | Winter | 11,275,690 | 11,321,170 | 45,480 | -0.4 |
| | Spring | 8,866,110 | 9,821,320 | 955,210 | -10 |
| | Summer | 43,944,160 | 45,384,410 | 1,440,250 | -3 |

TABLE IV
IMPACT OF AEROSOLS ON HYDROPOWER GENERATION REVENUE BASED ON REVENUE TYPE IN WATER YEAR 2015

| Products (revenue) | CTRL($) | CLEAN ($) | Difference ($) |
|---|---|---|---|
| Energy | 47,886,920 | 50,292,810 | 2,405,890 |
| Spinning reserve | 6,717,860 | 6,719,640 | 1,780 |
| Regulation up | 9,774,540 | 9,784,180 | 9,640 |
| Regulation down | 6,575,040 | 7,021,720 | 446,680 |

and operation of the hydroelectric project. These findings are consistent with the findings in [8].

It can be seen that the impact of aerosols on generation and revenue is small during low inflow periods (fall and winter). The impact is high during high inflow periods (spring and summer). This finding is in agreement with the result that the impact of aerosols on inflows is more significant during high inflow seasons. Although there is a significant reduction in inflows into the two higher elevation reservoirs (15-23%) in summer, the percentage reduction in generation and revenue are not as significant. This is because both water year 2014 and 2015 are dry years. The reservoirs have plenty of unused storage capability to mitigate the impact of aerosols on generation in summer by storing inflows in spring.

The impact of aerosols on the Big Creek Hydroelectric Project's revenue from providing energy, spinning reserve, frequency regulation up and frequency regulation down services are shown in Table IV. It can be seen from the table that the reductions in revenue from providing energy and frequency regulation down services are much more significant than that of spinning reserve and frequency regulation up service. The significant reduction in energy revenues can be explained by lower inflows due to the presence of aerosols. The amount of frequency regulation down service provision of a generator is limited by its energy schedule. Hence, there is a significant reduction in frequency regulation down service revenue.

## VIII. CONCLUSION

In this paper, we develop a comprehensive framework to quantify the impact of aerosols on hydropower generation and revenue by synergistically combining the WRF-Chem model, a statistical inflow forecast model, and the hydropower operation optimization model, Vista DSS. We conduct the case study to quantify the impact of aerosols on the Big Creek Hydroelectric Project's generation and revenue in California. The results show that aerosols reduce inflows into high elevation reservoirs by 6-10% and low elevation reservoirs by 1-3% in a water year. The presence of aerosols lead to a reduction in hydropower generation by 89,356 MWh (6%). The presence of aerosols also results in a staggering $\$2.8$ million loss in revenue in a water year. The results reported in this paper provides another strong justification for implementing stricter environmental regulations to reduce anthropogenic aerosol emissions.

## REFERENCES


[1] A. M. Hamiche, A. B. Stambouli, and S. Flazi, "A review of the water-energy nexus," *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 319–331, Nov. 2016.

[2] T. P. Barnett, J. C. Adam, and D. P. Lettenmaier, "Potential impacts of a warming climate on water availability in snow-dominated regions," *Nature*, vol. 438, no. 7066, pp. 303–309, Nov. 2005.

[3] Y. Qian, W. I. Gustafson, L. R. Leung, and S. J. Ghan, "Effects of soot-induced snow albedo change on snowpack and hydrological cycle in western United States based on Weather Research and Forecasting chemistry and regional climate simulations," *J. Geophys. Res.-Atmos.*, vol. 114, no. D3, p. D03108, Feb. 2009.

[4] F. Kabir, N. Yu, W. Yao, L. Wu, J. Jiang, G. Yu, and H. Su, "Impact of aerosols on reservoir inflow: a case study for Big Creek Hydroelectric System in California," *Hydrological Processes*, vol. 32, pp. 3365–3390, Aug. 2018.

[5] L. Wu, Y. Gu, J. H. Jiang, H. Su, N. Yu, C. Zhao, Y. Qian, B. Zhao, K.-N. Liou, and Y.-S. Choi, "Impacts of aerosols on seasonal precipitation and snowpack in California based on convection-permitting WRF-Chem simulations," *Atmos. Chem. Phys.*, vol. 18, no. 8, pp. 5529–5547, Apr. 2018.

[6] "Vista Decision Support System," https://www.hatch.com/en/Expertise/Services-and-Technologies/Vista-Decision-Support-System.

[7] S. Vicuna, R. Leonardson, M. W. Hanemann, L. L. Dale, and J. A. Dracup, "Climate change impacts on high elevation hydropower generation in Californias Sierra Nevada: a case study in the Upper American River," *Climatic Change*, vol. 87, no. 1, pp. 123–137, Mar. 2008.

[8] K. Madani and J. R. Lund, "Estimated impacts of climate warming on Californias high-elevation hydropower," *Climatic Change*, vol. 102, no. 3, pp. 521–538, Oct. 2010.

[9] N. T. VanRheenen, A. W. Wood, R. N. Palmer, and D. P. Lettenmaier, "Potential implications of PCM climate change scenarios for Sacramento San Joaquin River Basin hydrology and water resources," *Climatic Change*, vol. 62, no. 1, pp. 257–281, Jan. 2004.

[10] S. K. Tanaka, T. Zhu, J. R. Lund, R. E. Howitt, M. W. Jenkins, M. A. Pulido, M. Tauber, R. S. Ritzema, and I. C. Ferreira, "Climate warming and water management adaptation for California," *Climatic Change*, vol. 76, no. 3-4, pp. 361–387, Jun. 2006.

[11] G. A. Grell, S. E. Peckham, R. Schmitz, S. A. McKeen, G. Frost, W. C. Skamarock, and B. Eder, "Fully coupled online chemistry within the WRF model," *Atmos. Environ.*, vol. 39, no. 37, pp. 6957–6975, Dec. 2005.

[12] C. Zhao, Z. Hu, Y. Qian, L. Ruby Leung, J. Huang, M. Huang, J. Jin, M. G. Flanner, R. Zhang, H. Wang, H. Yan, Z. Lu, and D. G. Streets, "Simulating black carbon and dust and their radiative forcing in seasonal snow: a case study over North China with field campaign measurements," *Atmos. Chem. Phys.*, vol. 14, no. 20, pp. 11 475–11 491, Oct. 2014.

[13] L. Wu, H. Su, and J. H. Jiang, "Regional simulations of deep convection and biomass burning over South America: 1. Model evaluations using multiple satellite data sets," *J. Geophys. Res.-Atmos.*, vol. 116, no. D17, p. D17208, Sep. 2011.

[14] L. Wu, H. Su, and J. H. Jiang, "Regional simulation of aerosol impacts on precipitation during the East Asian summer monsoon," *J. Geophys. Res.-Atmos.*, vol. 118, no. 12, pp. 6454–6467, Jun. 2013.

[15] L. Wu, H. Su, O. V. Kalashnikova, J. H. Jiang, C. Zhao, M. J. Garay, J. R. Campbell, and N. Yu, "WRF-Chem simulation of aerosol seasonal variability in the San Joaquin Valley," *Atmos. Chem. Phys. Discuss.*, vol. 17, no. 12, pp. 7291–7309, Nov. 2017.

[16] L. K. Emmons, S. Walters, P. G. Hess, J.-F. Lamarque, G. G. Pfister, D. Fillmore, C. Granier, A. Guenther, D. Kinnison, T. Laepple, J. Orlando, X. Tie, G. Tyndall, C. Wiedinmyer, S. L. Baughcum, and S. Kloster, "Description and evaluation of the model for ozone and related chemical tracers, version 4 (MOZART-4)," *Geosci. Model Dev.*, vol. 3, no. 1, pp. 43–67, Jan. 2010.

[17] W. J. Shaw, K. Jerry Allwine, B. G. Fritz, F. C. Rutz, J. P. Rishel, and E. G. Chapman, "An evaluation of the wind erosion module in DUSTRAN," *Atmos. Environ.*, vol. 42, no. 8, pp. 1907–1921, Mar. 2008.

[18] A. Pankratz, *Forecasting with Dynamic Regression Models*. New York: John Wiley & Sons, Jan. 1999.

[19] G. E. P. Box, G. M. Jenkins, G. C. Reinsel, and G. M. Ljung, *Time Series Analysis: Forecasting and Control*. Hoboken, New Jersey: John Wiley & Sons, Jun. 2015.