nature sustainability

SUPPLEMENTARY INFORMATION

https://doi.org/10.1038/s41893-019-0326-y

In the format provided by the authors and unedited.

Scope and limitations of drought management within complex human–natural systems

William K. Jaeger[1*], Adell Amos[2], David R. Conklin[3], Christian Langpap[1], Kathleen Moore[4] and Andrew J. Plantinga[5]

[1]Department of Applied Economics, Oregon State University, Corvallis, OR, USA. [2]School of Law, University of Oregon, Eugene, OR, USA. [3]Oregon Freshwater Simulations, Portland, OR, USA. [4]School of Marine and Environmental Affairs, University of Washington, Seattle, WA, USA. [5]Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, USA. *e-mail: wjaeger@oregonstate.edu

Supplementary Information

Scope and Limitations of Drought Management within Complex Human-Natural Systems

Authors: William K. Jaeger[1*], Adell Amos[2], David R. Conklin[3], Christian Langpap[1], Kathleen Moore[4], Andrew J. Plantinga[5]

Affiliations:

[1] Department of Applied Economics, Oregon State University, Corvallis, OR 97331, USA.

[2] School of Law, University of Oregon, Eugene, OR 97403, USA.

[3] Oregon Freshwater Simulations, Portland, 1915 NE 55th Ave., Portland, OR 97213, USA.

[4] School of Marine and Environmental Affairs, University of Washington, Seattle, WA 98195, USA.

[5] Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, USA.

*Corresponding author. E-mail: wjaeger@oregonstate.edu

Supplementary Methods

Our analysis is based on scenarios run using a spatial-temporal simulation model called Willamette Envision. The supplementary information contained in this appendix includes methods and data for the Willamette Envision model. Additional details for many elements of the model are found in Supplemental Information published elsewhere [1]. This document also includes supporting information and explanations related to the set of policy actions introduced in the modelled scenarios, as well as background supporting the modelling of private and public responses to the water shortage.

A. Model platform

The Willamette Water 2100 (WW2100) model was developed to generate spatial-temporal simulation pathways in the Willamette River Basin (WRB) in Western Oregon, USA. It uses a platform called Envision, developed at Oregon State University by John Bolte [2]. *Envision* consists of several hundred thousand lines of C++ code and runs as a 64-bit Windows application. The model of the landscape is made up of attributed map polygons called Integrated Decision Units (IDUs) that cover the spatial extent of the WRB. The WW2100 Envision model incorporates a suite of sub-models to simulate processes that affect the distribution, movement, supply and demand for water in the WRB. As these component models run, they retrieve and store information from attributes within the IDU layer. The dataset archived here consists of 164,892 polygons attributed with starting values representing January 1, 2010, the first day simulated in model runs. Most IDUs cover an area of between 2 and 700 hectares (5 and 1730 acres). Each IDU has 189 attributes representing landscape conditions including aspects of economics, land use, law, hydrology, climate, and vegetation (e.g., land use type, land value, annual maximum evapotranspiration (ET), forest use predictive value). The program enables a range of different system components to interact and communicate via a representation of a landscape, utilizing a shared data repository that represents instantaneous conditions at specific locations. Each time the Envision model runs, it draws as its input the outputs from other component models (e.g., hydrology, climate, farmer crop decisions, urban water use, reservoir management decisions) running within the framework. Envision synchronizes models as they step through time on their own time scales. For example, it runs a hydrological model with a daily time step 365 times before running, for example, an economic model with a yearly time step.

B. Spatial representation

Data are stored in ESRI shapefiles representing the stream network and landscape polygons (the IDUs). The IDU layer was developed by intersecting the catchment shapefile with a composite dataset representing land use and land cover in the WRB. This catchment shapefile provides information needed by the hydrology model to connect the landscape to individual stream reaches. The land use/land cover dataset was developed by combining information from two sources: i) a US Forest Service dataset (GNN) representing the forested portions of the basin and ii) US Department of Agriculture datasets (NASS CDL) representing all other portions of the basin.

The spatial configuration of these IDUs (mean size = 19.2 ha) for forestland was based on Landsat remote sensing data and forest inventory data[3,4]. The Integrated Landscape Assessment Project (ILAP) also provided a species-level vegetation classification. We assigned a stand age to each forested IDU based on an overlay of the IDU coverage with a reference stand age coverage. For stand age $\leq$ 25, the coverage used Landsat-based LandTrender results[5,6], which evaluate the pixel-level trajectories of a vegetation-relevant spectral vegetation index. Stand age in 2010 was determined from the year of disturbance. For stand age > 25, we used a stand age coverage derived from Landsat-based Gradient Nearest Neighbour Analysis[7]. Boundaries for land ownership and protection status were from the U.S. Geological Survey, National Gap Analysis Program[8]. For non-forested land, the National Agricultural Statistics Service (NASS) data is derived from LANDSAT imagery and is designed to closely capture the crops grown as part of the agricultural system.

Daily time step processes include stream flow, snowmelt, snow and canopy sublimation, infiltration and percolation, evapotranspiration, irrigation decisions, urban water use, and the exercise and enforcement of water rights. Annual time step processes include spatial distribution of population and income changes, expansion of urban growth boundaries, urban water price, crop choices, agricultural land value, forest wildfire, upland forest type, forest harvest, land use transition (for example from agricultural or forest uses to developed uses). Most WW2100 modelling scenarios simulate the period from January 1, 2010 through December 31, 2099. However, two scenarios were also run with a simulation period from January 1, 1950 - December 31, 2009 to allow comparisons of modelled future conditions to a modelled past. These scenarios used simulated historical climate data as a model forcing, but population, economics and land cover characteristics remained at 2010 levels.

Across the WW2100 study area, the initial land use on each IDU is determined by overlaying a set of spatial data layers, which include data from the US Geological Survey National Land Cover Data (NLCD)(http://landcover.usgs.gov/) and the USDA Cropland Data Layer (CDL)(https://nassgeodata.gmu.edu/).

C. Stream network

The stream network and associated catchments were taken from the National Hydrography Dataset version 2 (NHD+V2)[9]. Only the main flowpath, as defined by the NHD+V2 dataset, was used. The main flowpath does not diverge in the downstream direction, an assumption that is built into the routing model. It is a subset of the full NHD+V2 stream network. The topological relationships between stream segments were defined using the ToNode and FromNode attributes of the NHD+V2 Value Added Attributes (VAA) table.

D. Feedbacks and linkages

Figure 5 in the article identifies some of the main linkages within and between the economic models and the biophysical models. Changes in the human system models over time are mainly driven by increases in population and income. These changes alter land prices and lead to development of agricultural and forest land. Population and income growth also result in changes in urban water use and water prices, and there are changes in water use resulting from land use changes. Water use in agriculture is influenced by land use changes as well as by the direct effects of climate on crop choice, crop water demand, irrigation decisions, and timing of farming practices, including planting.

Surface water diversions for irrigation and urban uses reduce streamflows, including those required for instream regulatory minimum environmental flows. As a result, low streamflows can trigger water shutoffs for relatively junior water right holders. These shutoffs can affect farm income and farmland prices, which in turn influence the probability of land use change to alternative uses.

Water releases from federal reservoirs reflect detailed multiple-objective management rules that include protecting instream flows at various downstream control points. As a result, changes in downstream water use for cities and farms will feedback to influence reservoir releases, which in turn alter reservoir fill levels and benefits from reservoir recreation. Changes in forest land use including land development, tree planting and harvests, and wildfires will affect snow accumulation, sublimation and melt; and forest evapotranspiration, all of which may have significant effects on streamflows.

E. Climate, population, hydrology, forests, evapotranspiration, calibration

Detailed descriptions of models and methods for these components of Willamette Envision are available in a related publication.[1] For the current analysis, we are interested in the representation of inter- and intra-annual streamflow variability and the frequency and magnitude of resulting drought events. The climate scenarios in Willamette Envision are based on over 40 general circulation models (GCMs). While there is high uncertainty about future droughts, the downscaled GCM outputs indicate that by the year 2100, the WRB will be between 1.1 °C (2 °F) and 7 °C (12.6 °F) warmer than today. Winter temperatures are projected to rise between 0.5 °C (33 °F) and 5.5 °C (42 °F). The months of July to September are projected to warm about 2 °C (3.6 °F) more than in winter. Climate models differ about whether the WRB will be drier or wetter, but the majority of climate model runs examined show slightly wetter winters and drier summers.

The Willamette Basin's hydrology is characterized as having a mismatch between winter inflows and summer demand. The valley is prone to flooding from November to March due to precipitation on saturated soils, atmospheric rivers, and snowmelt, whereas streamflows are lowest during the dry summer farming season. Variability in Willamette River flows at Salem occurs despite the management controls made possible by the 13 federal reservoirs. In the drought year simulation evaluated in this paper, the federal storage reservoirs are collectively unable to meet target fill levels anytime between February and May due to very limited winter and spring inflows and high downstream demands for water. The shortfall in the ESA minimum flows amounts to 641 gigalitres (GL) (520,000 acre-feet). Since 1969 (when construction of the federal reservoir system in the Willamette Basin was completed), the flows at Salem have fallen at least 15% below the ESA-minimum flow one year in ten, and 10% below the ESA-minimums nearly one year in five (Supplementary Figures 1A and 1B). For part of this period, however, the ESA-mandates had not yet been implemented.

The Willamette Envision model generates scenarios for the period 2010-2099. The resulting hydrographs of flows at Salem are represented in Supplementary Figures 2A and 2B, along with the ESA minimum flows, the simulated drought baseline, and the 2015 actual flows. For these modelled trajectories a shortfall of at least 5% is estimated to occur nearly one year in ten.

The Willamette Envision model was also run for a "high climate change" scenario based on the HadGEM2-ES-RCP8.5 GCM. The resulting hydrographs of flows at Salem are represented in Supplementary Figures 3A and 3B, along with the ESA minimum flows, the simulated drought baseline, and the 2015 actual flows. For these modelled trajectories a shortfall of at least 5% is estimated to occur three years in ten.

F. Model components

1. Urban water use responses and policies

Residential households use almost two thirds of all publicly supplied water in the U.S., with roughly 15% (seven billion gallons per day) of this use allocated to outdoor (landscape and lawn) irrigation[10,11]. Practically every region in the U.S. has experienced drought-induced water shortages since the beginning of the century[11], and the frequency of drought is expected to increase[12]. Local governments have responded to drought by implementing a variety of policies to induce water conservation in urban areas, such as use restrictions, information campaigns, social comparisons, financial incentives for technology adoption, and rate increases.

The evidence on the effectiveness of non-price approaches is mixed. Information campaigns usually have small effects[13,14], and the effect of appeals to prosocial preferences and provision of social comparisons wane over time.[14,15] Rebates and incentive programs may not be cost-effective[16]. Mandatory use restrictions can be effective in reducing household water use[17,18] but they can have costly welfare implications due to household heterogeneity in willingness to pay for scarce water.

Economists prefer price-based mechanisms, mainly because they are expected to be cost-effective and yield welfare gains relative to use restrictions[19]. However, their use is frequently limited by political considerations and regulatory constraints[15,18]. Another common argument against price-based approaches is that they are believed to be ineffective because consumers are not expected to significantly adjust their water use in response to rate increases, i.e. because the demand for water is inelastic. While this is indeed the case (estimated price elasticities range roughly between -0.4 and -0.5)[20], it means that consumers' response to rate increases is less than proportional, but not that there is no response.

The urban water use models include demand functions for residential and non-residential urban water use for four major urban areas in the WRB: the Portland metropolitan area, Salem, Corvallis, and Eugene – Springfield. There is a separate model that combines residential and non-residential demand for smaller urban areas. The model of residential water demand predicts total daily water used by residential customers (in hundreds of cubic feet – ccf) as a function of price ($/ccf), pricing structure (increasing block rate or flat rate), city population, median household income, and population density (persons/square mile). The model of non-residential water demand predicts total daily water use by non-residential costumers (in ccf) as a function of price, total city industrial (manufacturing) income, total city commercial income, and population. We adjust residential demand for seasonality by decomposing daily water use into outdoor and indoor use components, based on twenty-four years of daily data from Portland Water Bureau. Total predicted yearly water demand is divided by 365 to obtain daily use, and then multiplied by indoor and outdoor fractions to reflect seasonality. Additional details on the urban water modelling, data, and model validation can be found in the SI for an associated publication.[1]

2. Agricultural water use responses and policies

Farmers in the WRB typically own and cultivate multiple fields and each year make decisions about which crops to grow on each field, whether to irrigate those fields with water rights, what equipment to use on which fields, etc. We model these decisions at the parcel (or IDU) level as representative of farm-level decisions. A survey was conducted in the fall of 2012 to collect data from farmers about their irrigation and crop choice decisions for a sample of parcels over the previous six years. See [1] for details.

Crop choice and irrigation decisions are interdependent. Farmers may make crop choices and irrigation decisions simultaneously or, if sequentially, in either order. In the WRB most major crops can be grown either with or without irrigation at different times. The correlations in these decisions are reflected in the crop cover data and irrigation survey data, and represented by crop choice probabilities. In addition, farmland rent reflect profits from farming and irrigation decisions.

In general farmers will not plant or irrigate land that is expected to generate no profit or rent. The economic rent or annual profit from farming a given piece of land can play an important role in farm decisions to plant a crop, irrigate, or transition out of farming. Our estimation of farmland rent takes a Ricardian approach that is common in models of the economic returns to agriculture. Details of these hedonic estimations can be found in a related publication[1]. Land value is assumed to equal the net present value of future rents from putting the land to its highest value use. As a result we expect to see variation in land values and annual rents due to characteristics of the land that would influence agricultural productivity such as soil quality and precipitation or irrigation water rights.

Reflecting these empirical findings, each IDU has an estimated annual agricultural rent reflecting soil quality, whether the parcel has an irrigation water right, and other attributes. Some lands are not highly productive, and irrigation will not increase their annual rent or profit. In these cases, the model will not plant a crop if the estimated rent is less than $1 per acre. Additionally, if the incremental value of irrigation ("the irrigation rent premium") is less than a parameterized value (*min_irp* , which represents the minimum irrigation rent premium and also defaults to $1/acre), the model will not irrigate the parcel. With the introduction of an irrigation fee to promote water conservation in agriculture, the *min_irp* is increased by the amount of the fee. The fees are increased from $10/acre to $40/acre in ten dollar increments. At the $40/acre level most farmers will not find it profitable to irrigate.

3. Reservoir operations

Discharge in the WRB is regulated by 13 federally-owned reservoirs. The reservoirs were originally constructed with the primary purpose of regulating flood flows. This operational objective remains the highest priority for determining reservoir releases. The priority of other operating objectives varies by reservoir and circumstance. Federal reservoir managers follow a "rule curve" that guides daily decisions for capturing and releasing water, rules that reflect multiple objectives and legal requirements taking into account flood risk, downstream water uses, boating and summer reservoir recreation, fish habitat, navigation, and pollution attenuation. Beginning in April, reservoir managers are required to manage water releases in order to meet ESA-mandated minimum instream flows at various control points downstream. The lowest (downstream) aggregated flow point is in the mainstem Willamette at Salem. In years when spring inflows into the reservoirs are very low, reservoir managers may be unable to continue to fill the reservoirs (which impinges on summer recreational uses) while at the same time releasing water downstream to meet demands by farmers and cities, and maintain ESA-mandated minimum instream flows. Reservoir managers effectively mediate water shortages in such a way that reservoir fill and potentially instream flow requirements will be the uses that go unmet. Federal law also includes protections under the Endangered Species Act (ESA) of four threatened or endangered fish species. This involves maintaining minimum instream flows at various control points in the main stem and major tributaries. From April to September, the ESA mandated flows normally total 3.75 MAF. These flows are managed via upstream dam operations whereby reservoir management rules require the release of water to satisfy the prescribed flows.[21] Federal laws also interact in complex ways with state law [22]. For example, the federal ESA-mandated minimum instream flows have led regulators to place a limit on the amount of reservoir stored water that can be allocated under contracts with irrigators to 6% of the total stored volume.[21]

The 13 reservoirs are jointly operated as a system. To guide them in this task, the US Army Corps of Engineers (USACE) uses a reservoir operations model (ResSim) to perform rule-based calculations that are constrained by operational goals, regulatory targets, and priorities. The reservoir operations model implemented within the WW2100 model (ResSim Lite) is based closely on the 2012 version of the USACE's ResSim model, including the 2009 Biological Opinion (BiOp) flow targets and releases [21].

Each reservoir has operational zones (Supplementary Table 1), which are based on pool elevation on a particular date (Supplementary Figure 4) and rules sets (Supplementary Table 2) associated with it. The rule set is prioritized within each zone and across reservoirs, such that the model calculates release quantities and locations (i.e., powerhouse, regulating outlet, and spillway) at each time step to meet the highest priority rule. These rules are organized into a rule priority table for each reservoir, which contains a list of constraints, from lowest priority on top to highest priority on the bottom, for each operation zone within the reservoir. The model attempts to meet all of the priority rules that are physically possible for all reservoirs.

Flows at downstream control points are used to establish reservoir releases. Many reservoirs can be influenced by a single control point (e.g. Minimum Flow at Salem) and many control points can be influenced by a single reservoir

In addition to flood regulation at control points, a number of other constraints including the BiOp flow targets (Supplementary Tables 3 and 4) are implemented within the modelled and actual system. The BiOp flow targets vary based on the type of water year (Supplementary Table 5). The water-year type is established in the WW2100 model on 20 May, when the volume of water stored in all of the reservoirs is summed.

Within the WW2100 model, each reservoir has one data object that stores eight variables: time, pool elevation, rule curve elevation, inflow, outflow, powerhouse flow, regulating outlet flow and spillway flow. The combined set of rules, constraints, priorities, and current conditions are queried at each time step to establish releases, as summarized in the following series of functions:

i. *Update elevation and rule curve information and set desired release.* The current pool elevation is obtained and maximum gate outflows are updated based on the current pool elevation. The desired release is the amount of water needed to be released to take the pool elevation back to the target pool elevation in one timestep. If a reservoir is below the target pool elevation, then the desired release is set to 0. If the reservoir is a re-regulating reservoir (used to smooth releases from an upstream reservoir), inflow is set equal to outflow and the rule process is skipped.
ii. *Define the operations zone.* The operations zone defines which rules are to be used to determine outflow. The operation zone is defined by the current pool elevation with respect to the rule curve (conservation curve in Supplementary Figure 4). Once the operating zone is determined, constraints are applied in order, determined by their place in the rule priority table.

iii. *Apply constraints, prioritized within each zone.* Constraint values are obtained from lookup tables for each individual rule. If the constraint value applies (e.g. the outflow is greater than a maximum, less than a minimum, etc.), then the actual release is adjusted to conform to the constraint. The constraints are applied in order of priority, from lowest to highest. The logic describing release decisions is explained in detail in Section 11.4.1 of the HEC-ResSim User's Manual[23]. A number of constraints may be implemented in any given time step. Max and Min constraints set upper and lower boundaries on outflow. Increasing rate and decreasing rate rules govern the allowed rate of change of flow releases (ramping rates). The control point constraints adjust outflow based on current conditions at the control point. After application of all the rules, outflow is checked to see if it is below the allowed minimum flow. Each time a constraint changes the outflow value, the name of the constraint is stored as the "active rule." The final constraint applied, and thus the constraint controlling the outflow value, is stored for output.

iv. *Assign Reservoir Outlet Flows.* Once the outflow for a particular reservoir has been determined, the outflow is split between the outlets, which can be power plant outlets, regulating outlets, or spillway gates. Outlets are subject to physical and operational constraints, and all the reservoirs in the model are prioritized in the same way, with outflows being routed first to the penstocks for those that have a powerhouse, followed by regulating outlets, and finally to the spillways.

The following values are collected at each time step (daily) for each reservoir modelled and recorded in Willamette Envision: pool elevation, rule curve elevation, inflow, outflow, powerhouse flow, regulating outlet flow, spillway flow, and the active rule.

4. Water Allocation with water rights and regulatory discretion

For both out-of-stream and instream water rights Oregon water law operates according to the "prior appropriations doctrine" used in most western states [24]. The water rights system allocates water according to water right priority date (first date of use historically). Under Oregon law, all water is publicly owned, so that irrigators, municipalities or other users must obtain a permit from the Oregon Water Resources Department (OWRD) to obtain a usufructuary right. Further, the law requires that surface or groundwater be put to a "beneficial use without waste." Final certificates of water rights define the timing of use, the maximum rate of diversion, and the annual volume allowed under the water right. When conflicts arise due to shortage, the more senior water right is given priority and more junior water right holders are required to curtail their water use if it conflicts with the appropriation of water by the senior water right holder. Water rights may be transferred between points of use under Oregon law when transactions are arranged by parties and approved by the OWRD [25]. Each instream flow water right has a seniority date and is prioritized along with out-of-stream water rights when not all water demands can be met.

5. Water rights model input data

The water rights model requires a detailed input data set to represent the irrigation, municipal, and instream water rights in the basin, with specific details about the locations (point of use and point of diversion), allowed use, priority date, start date, end date, and maximum rates and duties (maximum amount diverted annually). The input data were obtained from the Oregon Department of Water Resources (WRD) Water Rights Information System http://www.oregon.gov/owrd/pages/wr/wris.aspx). This data centre includes GIS and tabular data for each water right in the state. These data were intersected with the model's IDU parcels and stream layer. Overlaps between Point of Use (POUs) and Point of Diversion (PODs) were approximated to achieve a high correspondence between the modelled and the actual water rights in terms of size, location and other characteristics. The input data set includes 15,413 irrigation water rights, 1,024 municipal water rights, and 93 instream water rights. Of the irrigation water rights, 8,678 are surface water (232,720 acres) and 6,735 are groundwater (228,800 acres). A parcel of farmland cannot have more than one "primary" irrigation water right (that can be used if there is sufficient water available).

Because the vast majority of irrigation water rights in the WRB have identical start dates (March 1), end dates (Oct. 31), maximum rates (1/80th cfs per acre) and duties (2.5 acre-feet per acre), these values were applied uniformly in the model. For municipal and instream water rights, specific rates (max or min) were applied to each water right.

In the case of municipal water rights, most large cities have multiple water rights, including surface and groundwater rights, utilizing more than one point of diversion. Use of these water rights is prioritized on the basis of multiple criteria including costs, water quality, and seasonal availability. It is therefore impossible to predict which water right will be used, or used first, based solely on the water right priority date. To replicate the priorities and sequencing observed in the basin's major cities, water use reports for recent years were used to apportion the urban water demand to the water rights that have been used most frequently by each city.

The water right sources, types of storage, and forms of conveyance for municipal water supply represent a complex, capital-intensive supply system. Municipalities, for example, buy and sell water among neighbouring cities. Portland's main water supply is an out-of-basin source and the city currently sells about one-third of the imported water to other municipalities within the Metro area. The AltWaterMaster model operates on the basis of the expectation that cities within the Portland Metro region will buy and sell water among themselves as needed, and will continue to rely on the major surface water sources used currently. As demand grows, the model allows for additional water to be made available by utilizing sources of water from the mainstem of the Willamette River, which is in fact what is currently being developed by the Tualatin Valley Water District to the southwest of Portland's city centre.

G. Policy scenario and responses

For each of three types of policy mechanisms a set of modelled actions are designed to conserve water and mitigate the drought scenario shortage which is manifested in a 520,000 AF shortfall in ESA mandated minimum flows for fish habitat in the mainstem Willamette River. The three types of mechanisms and the scale of interventions (in terms of stringency) are described here:

i. Urban water pricing: residential and industrial price increases are introduced at 40%, 80%, 120%, and 160%.

ii. Irrigated agriculture is assessed a fee per acre when irrigated. The four levels of fees are $10, $20, $30, and $40 per acre.
iii. Federal reservoir management rules are altered to enable more water to be stored for subsequent release to meet the BiOp flow requirements In sum, we evaluate four increasingly robust interventions: 1) halve buffer storage, 2) eliminate buffer storage, 3) start refill one week early and eliminate buffer storage, and 4) start refill one week early, fill faster, and eliminate buffer storage.

For each of these policy interventions the modelled amount of conserved water (reduced diversions in the case of urban and agriculture; reduced shortages in the case of reservoir operations) are summarized in Supplementary Table 6. And the net impact on the drought-induced shortage (in mainstem flows) is indicated in Supplementary Table 7. When policies are combined, we might expect the overall mitigation effect to be somewhat less than the sum of the individual policies due to double counting or substitutability for amounts of water conserved. Indeed, in Supplementary Table 7 we see that at each policy level, the mitigation impact of the combined policies are about 7% less than the sum of the impacts of the individual polices.

H. Computational methods

The WW2100 model is archived in a publicly readable subversion repository at Oregon State University. The code and data for the research reported here is accessible at: at http://inr.oregonstate.edu/ww2100/data. The Willamette Envision model version used in the current analysis (v4.3) is updated from the version (v3.0) used in prior analysis.[1]

The modelled simulations for our analysis were initiated with the AltWW2100.envx file. Each scenario was simulated for the 10 years 2010-2019, using CMIP5 MIROC climate data downscaled to a 2.5 arc-minute grid (~4 km). The representation of a "normal year" were based on the 2010-2019 averages; the drought scenario results are based on the 2019 simulations. Results for each policy were generated by post-processing output from runs of model. Urban and reservoir policy scenarios were based on model version 4.1. Agricultural policy scenarios were based on version 4.2. Combination policy scenarios and 90-year runs of the reference and "high climate change" scenarios were based on version 4.3.

Daily control point flows at Salem, Oregon are a key indicator of drought impacts. These outputs are reported in text files with file names beginning with "HBV_Flows_(m3_s)_" and ending with "_Run0.csv." The infix or middle of the file name references the individual scenario run. For the reference scenario this is FlexRespRef, for the urban price policies these are FlexUrb40, FlexUrb80, FlexUrb120, and FlexUrb160; for irrigation fees they are FlexIRP10, FlexIRP20, FlexIRP30, and FlexIRP40; and for the reservoir operations scenarios they are FlexBuff1, FlexBuff0, FlexRes21, and FlexRes41. The four combined policy scenarios are Combo1normal, Combo2normal, Combo3normal, and Combo4normal. The "high climate change" scenario is FlexRespHighClim.

References

1. Jaeger, W. K. *et al.* Finding water scarcity amid abundance using human–natural system models. *Proc. Natl. Acad. Sci.* **114,** 11884–11889 (2017).
2. Envision. (2014). Available at: http://envision.bioe.orst.edu/. (Accessed: 21st September 2018)
3. Halofsky, J. E., Creutzburg, M. K. & Hemstrom, M. A. *Integrating social, economic, and ecological values across large landscapes. Gen.Tech. Rep. PNW-GTR-896. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 206 p.* **896,** (2014).
4. Oregon State University. Integrated Landscape Assessment Project. (2014). Available at: https://inr.oregonstate.edu/ilap. (Accessed: 21st September 2018)
5. Kennedy, R. E. *et al.* Spatial and temporal patterns of forest disturbance and regrowth within the area of the Northwest Forest Plan. *Remote Sens. Environ.* **122,** 117–133 (2012).
6. Kennedy, R. E., Yang, Z. & Cohen, W. B. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr — Temporal segmentation algorithms. *Remote Sens. Environ.* **114,** 2897–2910 (2010).
7. Ohmann, J. L. *et al.* Mapping change of older forest with nearest-neighbor imputation and Landsat time-series. *For. Ecol. Manage.* **272,** 13–25 (2012).
8. US Geological Survey. National Gap Analysis Program: USGS Core Sciences Analytics and Synthesis. (2014). Available at: https://gapanalysis.usgs.gov/. (Accessed: 21st September 2018)
9. US Geological Survey (USGS). National Hydrography Dataset. (2014). Available at: http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php. (Accessed: 21st September 2018)
10. EPA, U. S. Community water system survey 2000 Volume 1: Overview. (2002).
11. EPA, U. S. Water Supply and Use in the United States. **2008,** 7367 (2008).
12. Sheffield, J. & Wood, E. F. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Clim. Dyn.* **31,** 79–105 (2008).
13. Coleman, E. A. A Comparison of Demand-Side Water Management Strategies Using Disaggregate Data. *Public Work. Manag. Policy* **13,** 215–223 (2009).
14. Ferraro, P. J. & Price, M. K. Using Nonpecuniary Strategies to Influence Behavior: Evidence from a Large-Scale Field Experiment. *Rev. Econ. Stat.* **95,** 64–73 (2013).
15. Brent, D. A., Cook, J. H. & Olsen, S. Social Comparisons, Household Water Use, and Participation in Utility Conservation Programs: Evidence from Three Randomized Trials. *J. Assoc. Environ. Resour. Econ.* **2,** 597–627 (2015).
16. Bennear, L. S., Lee, J. M. & Taylor, L. O. Municipal Rebate Programs for Environmental Retrofits: An Evaluation of Additionality and Cost-Effectiveness. *J. Policy Anal. Manag.* **32,** 350–372 (2013).
17. Mini, C., Hogue, T. S. & Pincetl, S. The effectiveness of water conservation measures on summer residential water use in Los Angeles, California. *Resour. Conserv. Recycl.* **94,** 136–145 (2015).
18. Wichman, C. J., Taylor, L. O. & von Haefen, R. H. Conservation policies: Who responds to price and who responds to prescription? *J. Environ. Econ. Manage.* **79,** 114–134 (2016).

19. Mansur, E. T. & Olmstead, S. M. The value of scarce water: Measuring the inefficiency of municipal regulations. *J. Urban Econ.* **71,** 332–346 (2012).
20. Olmstead, S. M. The Economics of Managing Scarce Water Resources. *Rev. Environ. Econ. Policy* **4,** 179–198 (2010).
21. U.S. Fish and Wildlife Service (USFWS). *Biological Opinion on the Continued Operation and Maintenance of the Willamette River Basin Project and Effects to Oregon Chub, Bull Trout, and Bull Trout Critical Habitat Designated Under the Endangered Species Act*. (U.S. Fish and Wildlife Service, 2008).
22. Amos, A. L. Developing the Law of the River: The Integration of Law and Policy into Hydrologic and Socio-economic Modeling Efforts in the Willamette River Basin. *U. Kan. L. Rev.* **62,** 1091 (2013).
23. U.S.A.C.E. HEC-ResSim Reservoir System Simulation: User's Manual. (2013). Available at: http://www.hec.usace.army.mil/publications/. (Accessed: 15th October 2018)
24. Amos, A. Freshwater Conservation in the Context of Energy and Climate Policy: Assessing Progress and Identifying Challengesin Oregon and the Western United States. *U. Denv. Water L. Rev.* (2008).
25. Getches, D., Zellmer, S. & Amos, A. *Water Law in a Nutshell, 5th*. (West Academic, 2015).
26. NMFS, N. M. F. S. *Willamette River Basin Project Biological Opinion*. (2008).

Supplementary Table 1. Reservoir zones in ResSim Lite model

Zone	Description
Top of dam	Where overtopping would occur.
Flood control	Max pool available for flood regulation.
Conservation	The "Rule Curve" which includes minimum and maximum conservation pools.
Buffer	Acts like an interim draft limit to keep pool from drafting too low below minimum conservation pool.
Inactive	The lowest pool that can access outlets.

Supplementary Table 2. Operating rule types

Rule type
Minimum
Maximum
Increasing rate
Decreasing rate
Control point
Power plant rule (gate specific)
Regulating outlet rule (gate specific)
Spillway rule (gate specific)

Supplementary Table 3. Biological Opinion minimum flow objectives for Willamette River at Salem.

Time period	Weekly average minimum flow (cubic feet per second)	Instantaneous minimum flow (cubic feet per second)
April 1-15	17,800	14,300
April 16-30	17,800	14,300
May 1-21	15,000	12,000
June 1-15	13,000	10,500
June 16-30	8,700	7,000

Source [26].

Supplementary Table 4. Congressionally authorized minimum flow objectives, Willamette River at Salem and Albany.

Time period	Average flow at Albany (cfs)	Average flow at Salem (cfs)
June 1-30	4,500	N/A
July 1-31	4,500	6,000
August 1-15	5,000	6,000
August 16-31	5,000	6,500
September 1-30	5,000	7,000
October 1-31	5,000	7,000

Source [26].

Supplementary Table 5. Water year types based on total volume stored in all federal reservoirs (million acre-feet).

Water Year Types	Abundant	Adequate	Insufficient	Deficit
May 20th storage:	≥ 1.48	1.20 to 1.47	0.90 to 1.19	< 0.90

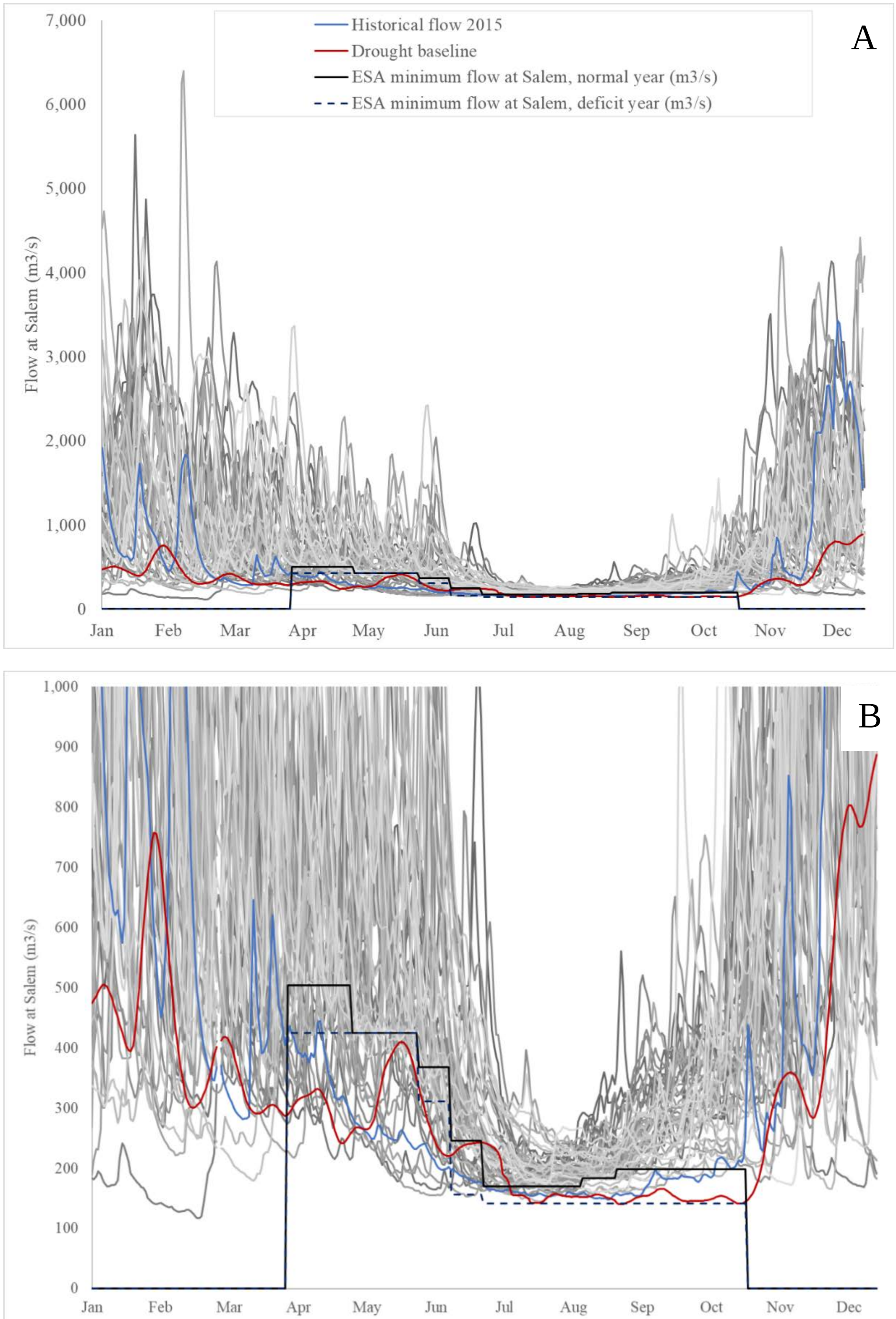
Source [26].

Supplementary Table 6. Potential water conservation by policy type and stringency

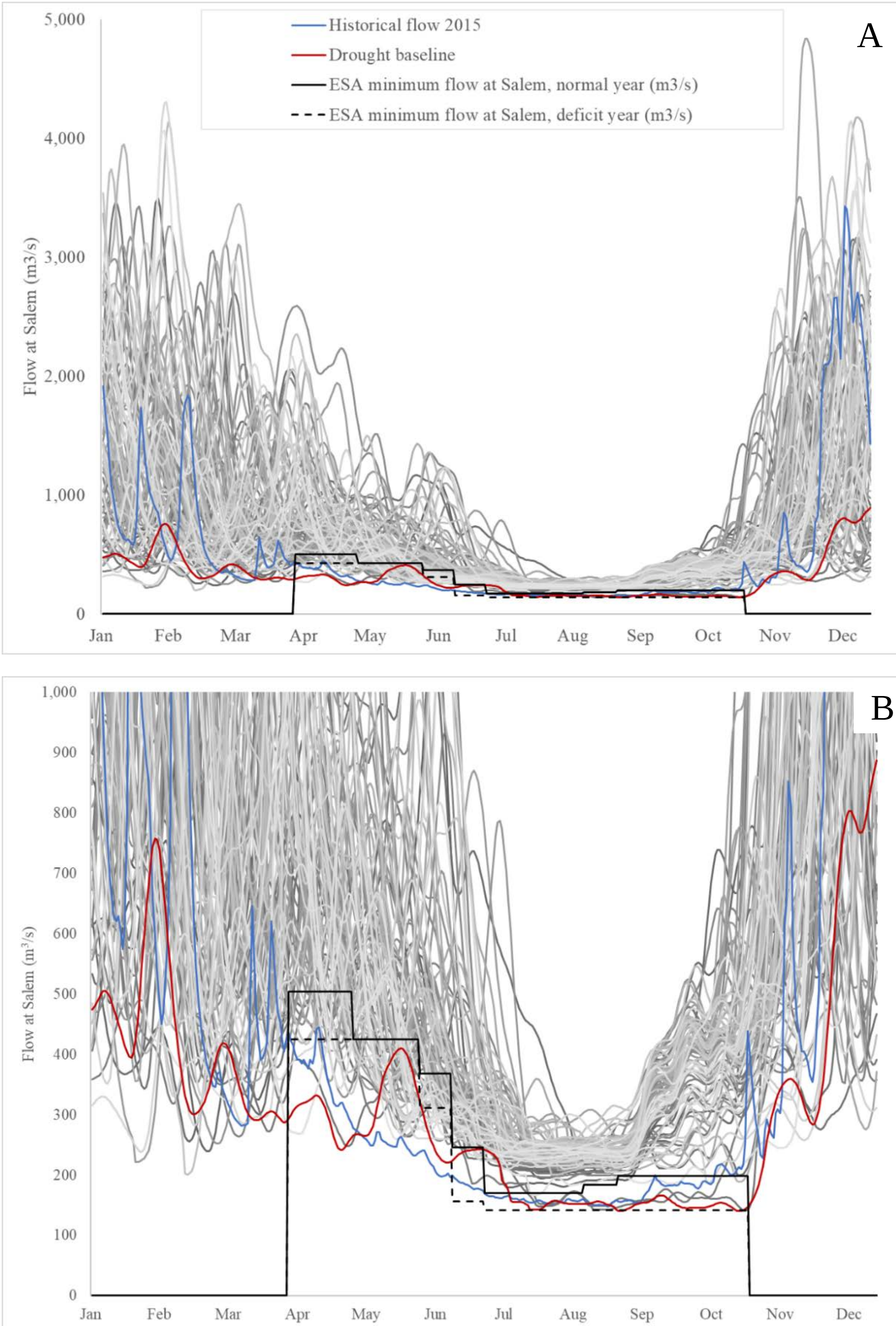
Conserved water by level of policy stringency (acre-feet)	Level 1	Level 2	Level 3	Level 4
Urban water price increases	26,271	44,061	57,259	67,596
Irrigation water fee (per acre)	14,532	62,903	153,207	250,222
Reservoir management changes	22,063	35,186	60,539	101,669
Total	62,866	142,150	271,006	419,486

Supplementary Table 7. Potential mitigation of drought-induced shortage

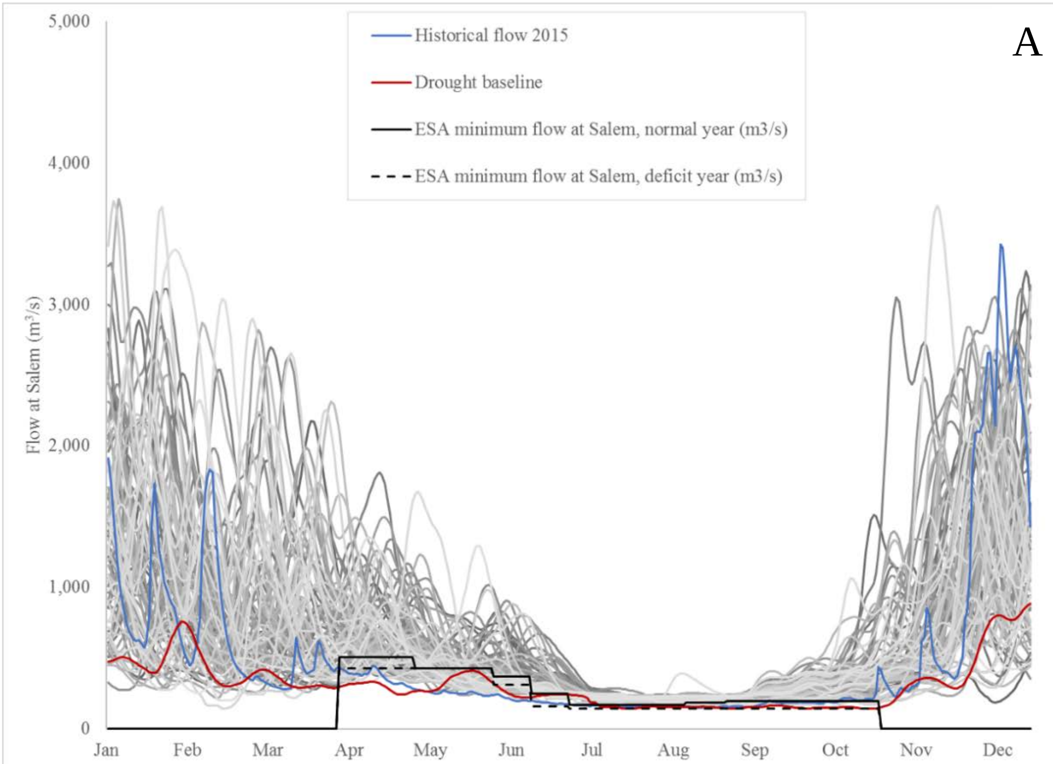
Conserved water by level of policy stringency (acre-feet)	Level 1	Level 2	Level 3	Level 4
Urban water price increases	965	2,100	2,974	3,720
Irrigation water fee (per acre)	(1,321)	4,270	14,451	20,438
Reservoir management changes	22,063	35,186	60,539	101,669
Sum of individual policies	21,707	41,555	77,965	125,827
Policy combinations	20,424	38,763	72,404	116,390

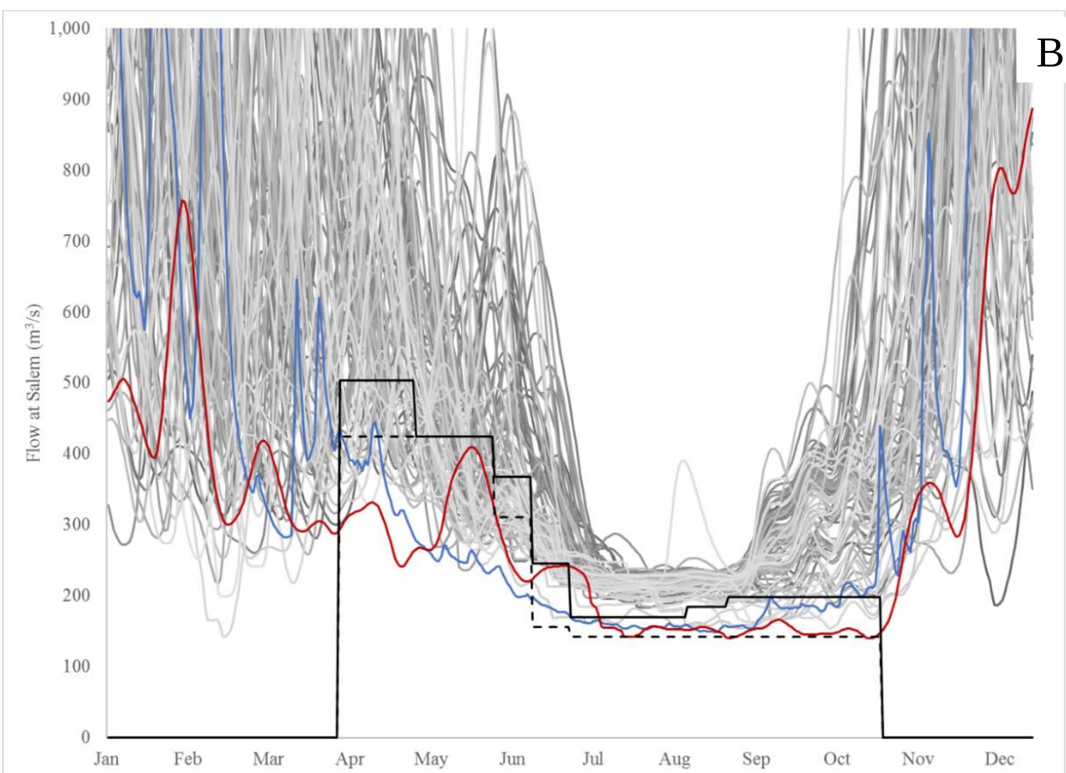


Supplementary Figures 1A and 1B. Historical flows at Salem 1969-2018, simulated drought baseline, ESA minimum flows, and 2015 actual flows (with full and truncated vertical scales).

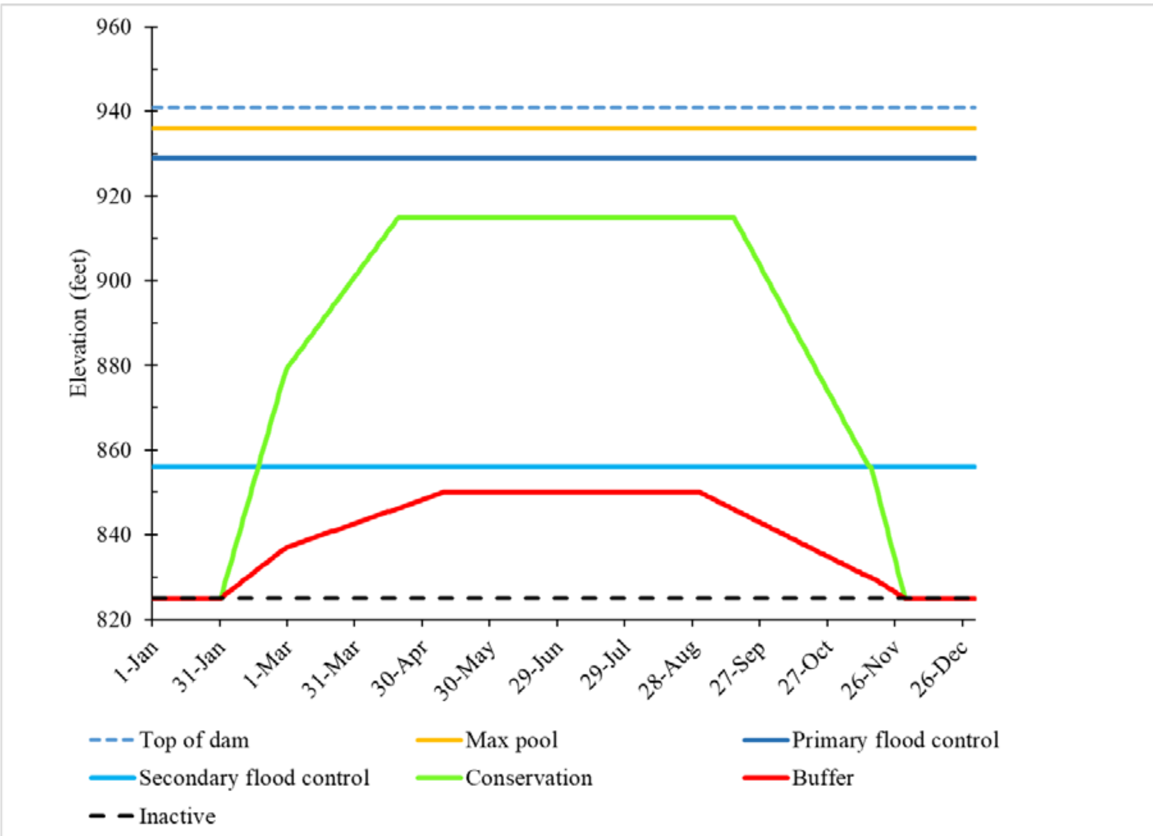


Supplementary Figures 2A and 2B. Modelled flows for scenarios for years 2010-2099, simulated drought baseline, ESA minimum flows, and 2015 actual flows (with full and truncated vertical scales).





Supplementary Figures 3A and 3B. Modelled flows for the "high climate change" scenario for years 2010-2099, ESA minimum flows, and 2015 actual flows (with full and truncated vertical scales).



Supplementary Figure 4. Reservoir operating zones (based on Lookout Point Reservoir).

Notes: The conservation curve (green) is the primary rule curve. The zone above the rule curve is the Flood Control Zone, while below the curve is the Conservation Zone. If the pool elevation is above the elevation demarcating the primary flood control zone (horizontal dark blue line), the zone is labelled Top of Dam Zone. If the pool elevation falls below the red line, the zone is labelled the Buffer Zone. There also exists an alternative flood control zone in this case, when the pool elevation is above the rule curve but below the secondary flood control line (in light blue).