Supporting Information for "Power and Pathways: Exploring robustness, cooperative stability and power relationships in regional infrastructure investment and water supply management portfolio pathways"

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Contents

1 Objective Functions

This section presents the details of the objective formulation for the Sedento valley planning problem. These objectives were first formulated for the Sedento Valley by Trindade et al., (2020).

1. *Reliability* (f_{REL}): The reliability objective calculated as the fraction of considered states of the world which may cause the combined storage level of a utility to drop below 20% of its maximum capacity in any given week (failure condition):

$$\text{maximize } f_{REL} = \underset{j}{min}\left[\underset{y}{min}\left(\frac{1}{N_r}\sum_{i=1}^{N_r} g_{i,j}^{y}\right)\right] \quad (1)$$

where,

$$g_{i,j}^{y} = \begin{cases} 0 & \forall w \ : \ \frac{x_{s,i,j}^{w,y}}{C_j} \geq S_c \\ 1 & \text{otherwise} \end{cases}$$

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where $g_{i,j}^{y} = 0$ if there was a week in a given year of a particular realization where the combined storage of utility j falls below S_c of capacity (20% in this study), and 1 otherwise, N_r is the number of realizations in one function evaluation, y is the simulation year, N_{ys} is the number of years in the project horizon, i is the simulation realization index.

2. *Restriction Frequency* (f_{RF}): Restriction frequency represents the fraction of years across all realizations in which water use restrictions were enacted in at least one week:

$$\text{minimize } f_{RF} = \max_{j} \left[\frac{1}{N_{ys} \cdot N_r} \sum_{i=1}^{N_r} \sum_{y=1}^{N_{ys}} h_{i,j}^{y} \right] \tag{2}$$

where,

$$h_{i,j}^{y} = \begin{cases} 0 & \forall w \ : \ x_{srof,i,j}^{y,w} \leq \theta_{rt,j} \\ 1 & \text{otherwise} \end{cases}$$

where $h_{i,j,y} = 0$ if there was a week in a given year of a given realization in which water use restrictions were enacted, and 1 otherwise.

3. *Infrastructure Net Present Cost* (f_{NPC}): The average net present cost of all new infrastructure build across all realizations:

$$\text{minimize } f_{NPC} = \frac{1}{N_r} \sum_{i=1}^{N_r} \sum_{y=1}^{BM} \frac{PMT}{(1+d)^y} \tag{3}$$

where BM is the bond term, d is the discount rate (5%), y is the year of the debt service payment PMT since the bond was issued, with PMT being calculated as (assuming a level debt service bond):

$$PMT = \frac{P\left[BR(1+BR)^{BM}\right]}{\left[(1+BR)^{BM}-1\right]} \tag{4}$$

where P is the principal (construction cost), BR is the interest rate to be paid to the lender BT is the bond term. The stream of payments is then discounted to present values.

4. *Peak Financial Cost* (f_{PFC}): The average cost objective represents the expected yearly cost of debt plus all non-infrastructure water portfolio assets used to manage droughts over the planning horizon. These costs are revenue losses from restrictions, transfer costs, contingency fund contributions, third-party insurance con-

tract costs, and debt repayment:

$$\text{minimize } f_{AC} = \max_j \left[\frac{1}{N_{ys} \cdot N_r} \sum_{i=1}^{N_r} \sum_{y=1}^{N_{ys}} SYC_{i,j}^y \right] \tag{5}$$

where,

$$SYC_{i,j}^y = \frac{\sum_{c \in C_j} PMT_{i,j,c} + \theta_{acfc,j} \cdot ATR_{i,j}^y + IP_{i,j}^y + ATR_{i,j}}{ATR_{i,j}^y}$$

where IP is the insurance contract cost in a given year y, $PMT_{i,j,c}$ is the debt payment for infrastructure option c if it belongs to the set C_j of infrastructure options to be built by utility j and is built in realization i, and ATR is the total annual volumetric revenue. All these variables are dollar values.

5. *Worse First Percentile Cost* (f_{WFPC}): The worse case cost objective represents the 1% highest single-year drought management costs observed across all analyzed SOWs over the planning horizon:

$$SYC_{i,j}^y = \frac{max(RL_{i,j}^y + TC_{i,j}^y - \theta_{acfc,j} \cdot ATR_{i,j}^y - YIPO_{i,j}^y, 0)}{ATR_{i,j}^y} \tag{6}$$

where IP is the insurance contract cost in a given year y, RL is the revenue losses from water use restrictions, TC is the transfer costs, $YIPO$ is the total insurance payout over year y, CF is the available contingency funds, and ATR is the total annual volumetric revenue. All these variables are dollar values. The worse case cost objective is then:

$$\text{minimize } f_{WCC} = \max_j \left\{ \underset{i \in N_r}{quantile}(SYC_{i,j}, 0.99) \right\} \tag{7}$$

S2 Runtime Diagnostics

For reliable search with a MOEA, it is important to run multiple instances of the algorithm to overcome any biases in search generated by the initial population (Salazar et al., 2016). For each defection scenario, four random seeds were run for each utility. The true Pareto set for this problem is not known, so to assess the convergence convergence we measure relative hypervolume (Zitzler et al., 2007), which compares performance of the approximate Pareto sets discovered at set checkpoints within search to the final "reference set", which contains non-dominated solutions across all seeds. If the relative hypervolume is found to plateau, we conclude that the algorithm has converged to a satisfactory approximation of the true Pareto set.

Runtime diagnostics for all defection optimizations are shown in Figure S1. There was very little variance across seeds, and the hypervolume of all defection optimizations plateaued after around 20,000 function evaluations.

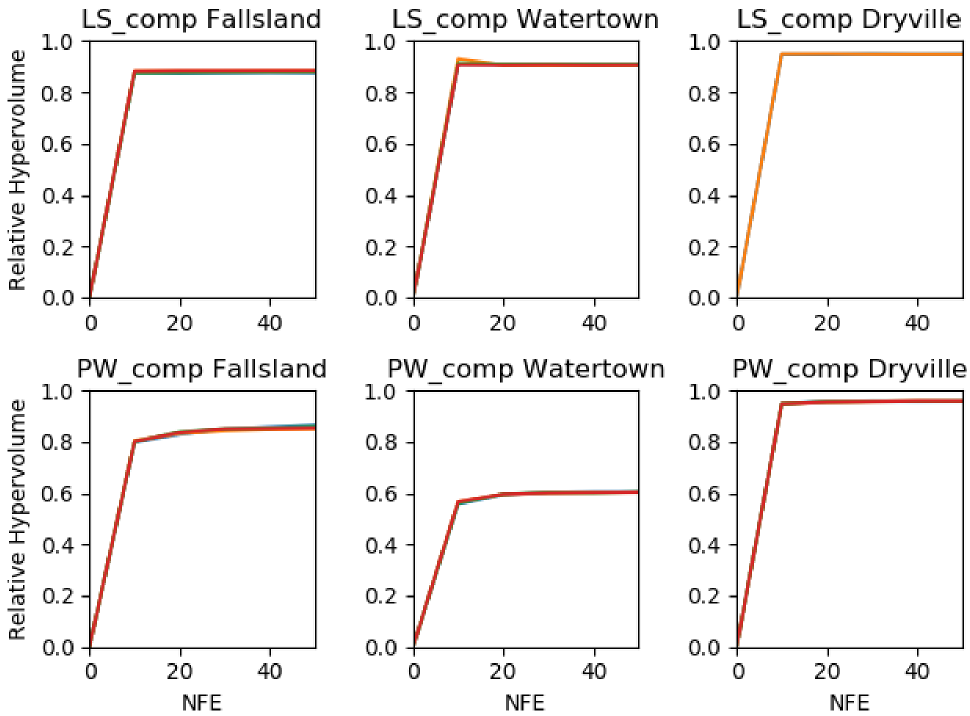

Figure S1. Runtime diagnostics for the individual optimization runs. The plateau of hypervolume across all seeds for all formulations indicates that number of function evaluations (NFE) were enough to achieve maximum attainable convergence.

S3. Robustness of defection alternatives

Figures S2-S4 show the top 30 defection alternatives for each utility under the least squares compromise selection (Social planner's compromise). The robustness of each alternative is plotted on the vertical axes, and the ranking of the solution is plotted on the horizontal axis. The solutions highlighted in black were used to generate the scenario discovery results shown in Figure 10 of the main text.

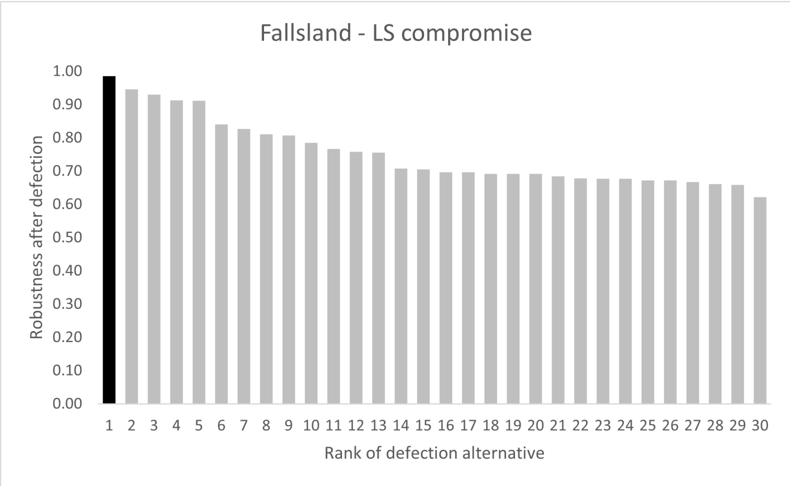

Figure S2. Robustness of defection alternatives for Fallsland under the LS compromise selection.

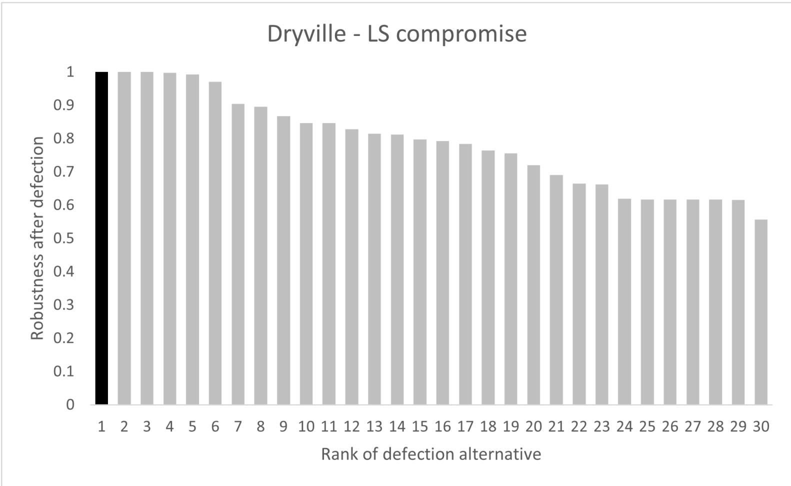

Figure S3. Robustness of defection alternatives for Dryville under the LS compromise selection.

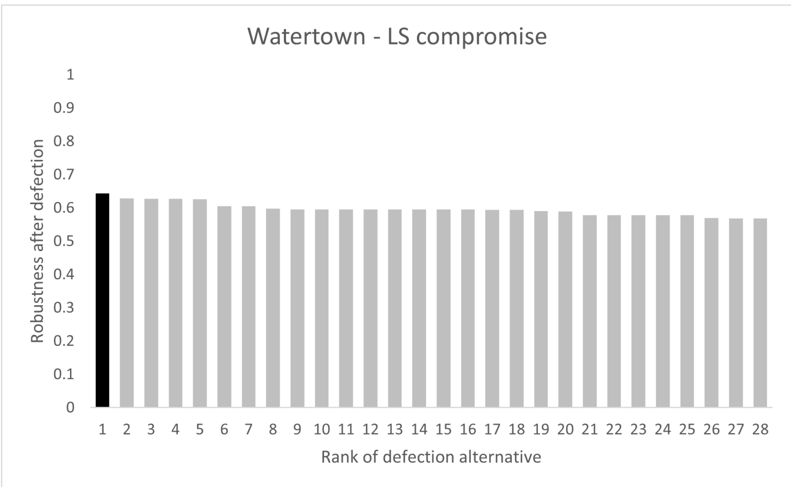

Figure S4. Robustness of defection alternatives for Watertown under the LS compromise selection.

Figures S5-S7 show the top 30 defection alternatives for each utility under the power index compromise selection (pragmatist's compromise). The robustness of each alternative is plotted on the vertical axes, and the ranking of the solution is plotted on the horizontal axis. The solutions highlighted in black were used to generate the scenario discovery results shown in Figure 10 of the main text.

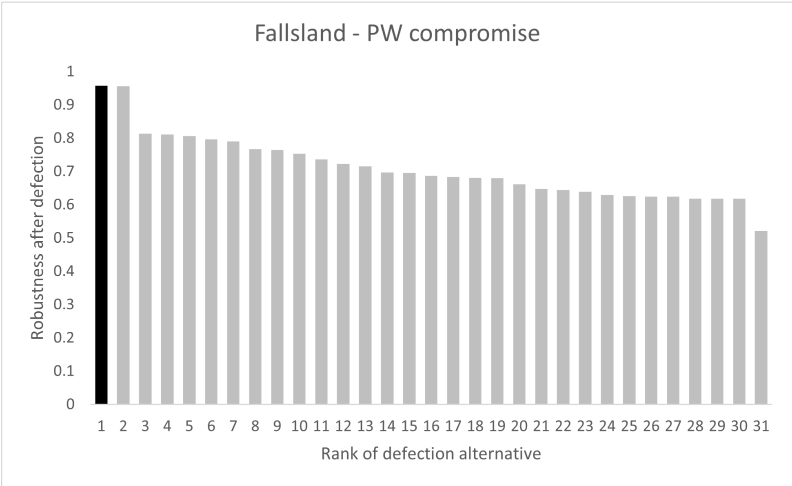

Figure S5. Robustness of defection alternatives for Fallsland under the PW compromise selection.

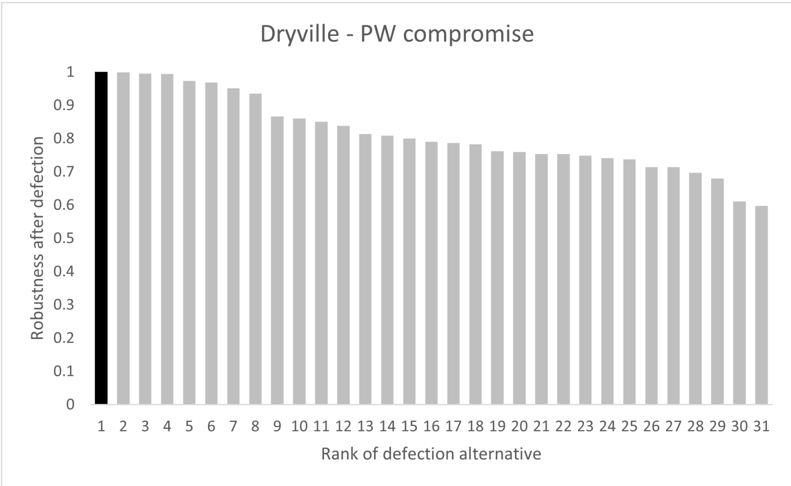

Figure S6. Robustness of defection alternatives for Dryville under the PW compromise selection.

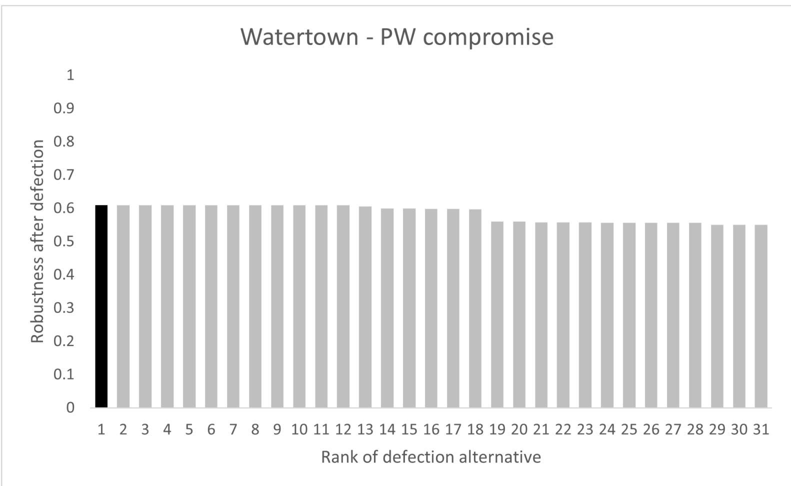

Figure S7. Robustness of defection alternatives for Watertown under the LS compromise selection.

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