PROBABILISTIC POLITICAL VIABILITY: A METHODOLOGY FOR PREDICTIVE POLITICAL ECONOMY

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ABSTRACT. Currently available political economic tools are not very useful for predicting the outcomes of real-world policy problems. Researchers have limited information on which to assign parameters to the mappings from policies to outcomes to utilities or to represent the political process adequately. We present a method for evaluating the viability of political alternatives in complex settings and apply it to an ongoing California water policy debate. Certain options would be "robustly politically viable" if stakeholder groups trusted that they would be implemented as negotiated. Once we incorporate institutional mistrust into the model, none of the alternatives are robustly politically viable.

KEYWORDS: Pareto Optimality, Delta, California, Political Economy, Deep uncertainty, Robust decision making, Modeling uncertainty

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1. Introduction

This paper introduces a novel methodology for analyzing the political viability of alternative resolutions to complex policy problems. To illustrate our approach, we examine in detail a particular natural resource management controversy. In principle, our methodology could be applied to a much larger class of problems, such as climate change, health-care, etc. Typically, in such contexts, much more is known about the scientific, engineering, institutional and economic aspects of the problem than about the complex, relatively unstructured political terrain within which conflicts will have to be resolved. For this reason, our methodology exploits the detailed information available about the former aspects, while adopting a minimalist approach to the latter aspect. Rather than imposing a specific political structure on the problem, we assess the political viability of policy options by examining whether or not they satisfy a rather weak criterion that is a necessary condition for a broad class of solution concepts.

The probabilistic political viability methodology is designed to analyze specific, one-time policy negotiations, involving tradeoffs between economic and environmental objectives, market and non-market valuations, and private and public goods. In such contexts, the problems associated with constructing a model are particularly challenging. The complexities really matter: it is important to model the interconnected economic, social, and ecosystem impacts of the various policy options under consideration. Our approach must be more fine-grained than models that use econometric techniques to identify broad regularities linking processes to outcomes; the more we abstract from the idiosyncratic details of a problem, the less credible will be the model's probabilistic predictions. This leads to models that are too complex to be solved analytically. As a result, the methodology uses simulation methods to predict outcomes and conduct comparative statics analysis. Moreover, trying to predict exactly what policy will emerge is too ambitious a goal; instead, we seek to identify policies that meet a coarser "political viability" criterion. Finally, when modeling complex, unique policy debates, it is virtually impossible to assemble a database rich enough that econometric techniques can be used to estimate model parameters. Since we cannot have confidence in any particular parameterization of the model *and* must utilize numerical rather than analytical comparative statics methods, we study the properties of the model under the widest possible range of plausible parameter specifications. We then assess the likelihood that any particular policy option will be politically viable based on a specified viability criterion.

We apply this methodology to the debate over the future of California's Sacramento-San Joaquin Delta. At present, this debate centers around two critical questions: first, how much water can be exported from the Delta watershed without violating the economic and ecological integrity of the Delta, and second, should the state build a conveyance structure that would deliver water from the Sacramento River directly to diversion pumps, avoiding the Delta entirely? Opinions are sharply divided, and stakeholder groups have different concerns. Agricultural and urban users of exported water are concerned about the economic impacts of reduced supplies. Many environmentalists are focused on ecological effects, including the implications for threatened and endangered species. Delta residents and growers are concerned about its economic and ecological integrity. Some policymakers have expressed concern regarding the potential costs for taxpayers. The diversity of stakeholder interests is not the only challenge for reaching agreement. Water policy in California has had a long and tangled history, including many failed attempts to obtain consensus and form institutions to implement agreements. Consistent with this history, one of the obstacles to reaching a solution regarding water exports and the Delta is that key stakeholder groups have expressed serious mistrust in the institutions that would implement any solution.

We investigate the political viability of possible solutions to the Delta crisis and the impact of institutional mistrust on that viability. There has been extensive analysis of the environmental and economic consequences of various Delta alternatives (Lund *et al.*, 2007, 2008; Cooley *et al.*, 2008) and some rankings of these alternatives based on a variety of financial and non-financial criteria (Lund *et al.*, 2008). Hanemann & Dyckman (2009) and Madani & Lund (2011b) conclude that stakeholders are unlikely to agree on an alternative in the absence of credible government intervention or a substantial worsening of the current situation. Although Madani & Lund (2011a) conclude that the construction of a conveyance facility to convey water exports around the Delta *might* emerge as an equilibrium, their analysis strongly suggests that parties may be unable to agree upon a solution, in which case the status quo will prevail.

The paper is organized as follows. Section 2 develops our probabilistic political viability methodology. Section 3 presents the details of the Delta application and constructs a formal model of that political process, which is then embedded within the probabilistic political viability methodology. Section 4, presents the results and discusses their significance for both the Delta application and our methodology. It first establishes that for the range of parameterizations of the Delta problem that we consider, certain alternatives would be "robustly politically viable," if all stakeholder groups trusted that these alternatives would be implemented in accordance with negotiated guidelines. It then examines how the political viability of these alternatives changes as institutional mistrust increases. Section 5 concludes.

2. THE PROBABILISTIC POLITICAL VIABILITY METHODOLOGY

This section introduces the Probabilistic Political Viability methodology (PPV). The methodology begins with a predictive political economic model that has four basic components: a set of *policy options*; a set of *stakeholders* or participants in the process; a political prediction mapping from *policy options* via *outcomes* to stakeholder expected utilities; and a *prediction concept*. The prediction concept selects policy options that meet a certain political viability criterion, based on the expected utilities that stakeholders assign to these options. Subsection 2.2 formally specifies the components of a predictive political economic model. The PPV methodology then incorporates the researcher's lack of information about how to parameterize the model, as described in later subsections.

2.1. **Exogenous variables.**

Each exogenous variable in our model is classified either as a parameter, a state-dependent variable or a policy. The term *parameter* refers to any exogenous variable whose value is known by stakeholders. We denote by $\mathbb{Z}$ the space of all parameter vectors, with generic element $\mathbf{z}$. Conventionally, *a state of the world* refers to a "move by nature" (Rasmusen, 2007, p.54). Here we use the term "state of the world" very broadly to encompass any component of the model about which stakeholders are uncertain, including ones that are not usually thought of as being determined by nature, such as certain random aspects of the mapping from policies to outcomes and the default outcomes.[1] The set of possible states of the world is given by $\mathbb{S} \subset \mathbb{R}$, with generic element s. For every model variable classified as state dependent, we specify a probability distribution $f(s; \mathbf{z}^s)$ over the states of the world that represent stakeholders' uncertainty about it. The parameters governing these distributions are given by a subvector $\mathbf{z}^s$ of $\mathbf{z}$. Finally, there is a policy space $\mathbb{X} \subset \mathbb{R}^2$, with generic element $\mathbf{x}$, consisting of a set of possible policy options.

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[1] Stakeholders face unpredictability in the traditional sense, i.e., Knightian risk: they know the probability distributions over which they must take expectations. In reality, however, there is no bright line distinction between Knightian risk and uncertainty. Rather, these concepts should be thought of as extreme points of a conceptual continuum, along which our stakeholders' unknowns are dispersed.

2.2. **A Political Prediction Mapping.** Stakeholders derive expected utilities not from a particular policy *per se*, but from the range of possible *outcomes* that might be induced if this policy were implemented. We thus define a mapping from $\mathbb{Z} \times \mathbb{S} \times \mathbb{X}$ to the outcome space $\mathbb{Y} \subset \mathbb{R}^m$. An element $\mathbf{y} \in \mathbb{Y}$ is called an *outcome vector*, while the components of $\mathbf{y}$ will be referred to simply as *outcomes*. The specification of this mapping includes a number of *outcome parameters*, whose values are given by the subvector $\mathbf{z}^{\mathbf{y}}$ of $\mathbf{z}$. The outcome of policy $\mathbf{x}$ conditional on state of the world s and outcome parameter vector $\mathbf{z}^{\mathbf{y}}$ is denoted by $\mathbf{y}\left(\mathbf{x}; s, \mathbf{z}^{y}\right)$.

Each participant in the political process has a utility function defined over outcomes; $\mathbf{z}^u$ is a subvector of *utility parameters* specifying stakeholders' preferences. The vector $\mathbf{u}\left(\mathbf{y}\left(\mathbf{x}; s, \mathbf{z}^{y}\right); \mathbf{z}^{u}\right)$ enumerates the utilities of all stakeholders resulting from policy in state s, given parameter subvectors $\mathbf{z}^y$ and $\mathbf{z}^u$. Stakeholders maximize expected utility, taking expectations over possible states of the world. A composite vector $\mathbf{z} = \left(\mathbf{z}^y, \mathbf{z}^u, \mathbf{z}^s, \mathbf{z}^d\right)$ includes the three parameter subvectors, plus a fourth, $\mathbf{z}^d$, defined below. The vector of stakeholders' expected utilities is given by

$$\mathbf{Eu}\left(\mathbf{x}; \mathbf{z}\right) = \int \mathbf{u}\left(\mathbf{y}\left(\mathbf{x}; s, \mathbf{z}^{y}\right); \mathbf{z}^{u}\right) f\left(s; \mathbf{z}^{s}\right) ds. \tag{1}$$

A predictive political economic model is represented by a *political prediction mapping* $\mathbf{W} : \mathbb{Z} \to \mathbb{X}$. Given a parameterization $\mathbf{z} \in \mathbb{Z}$ of the model, $\mathbf{W}(\mathbf{z})$ is the model's prediction of which element (or elements) from $\mathbb{X}$ are "politically viable," in a sense to be described below.

The typical approach to political economic modeling is to isolate an alternative or set of alternatives that *solves* the model using the specified solution concept. However, a starting point for this paper is the infeasibility of isolating a single model that best represents a given complex real-world political process. Therefore, the political prediction correspondence maps not to the outcome identified by applying any one particular solution concept, but rather to a set of policies that satisfy some criterion for political viability. For the purposes of this paper we use a relatively weak criterion: Pareto dominance. Given a "default outcome" that will be implemented if the participants in the political process cannot negotiate an agreement, $\mathbf{W}\left(\mathbf{z}\right)$ is the set of alternatives that Pareto dominate this outcome when the model is parameterized by $\mathbf{z}$. This criterion is a necessary condition for a large class of political economic solution concepts; in any model requiring consensus among some set of players, Pareto dominance is a necessary condition for a policy to be a solution.[2]

The default outcome is denoted by $\mathbf{y}^d\left(s;\mathbf{z}^d\right)$, where $\mathbf{z}^d$ is a subvector of parameters that relate to this outcome. The dependence of $\mathbf{y}^d$ on s reflects the possibility that stakeholders may be uncertain about what will happen in the absence of an agreement. The vector of expected default utilities is:

$$\mathbf{Eu}^d(\mathbf{z}) = \int \mathbf{u}\left(\mathbf{y}^d\left(s;\mathbf{z}^d\right);\mathbf{z}^u\right) f\left(s;\mathbf{z}^s\right) ds. \tag{2}$$

Note that by definition this vector is independent of every non-default policy $\mathbf{x}$ in $\mathbb{X}$. The Pareto dominance political prediction mapping is specified as:

$$\mathbf{W}(\mathbf{z}) = \left\{\mathbf{x} \in \mathbb{X} : Eu_i(\mathbf{x};\mathbf{z}) \geq Eu_i^d(\mathbf{z}) \text{ for all } i\right\}. \tag{3}$$

2.3. **Probabilistic Political Viability.** Each realization $\mathbf{z} \in \mathbb{Z}$ corresponds to a specific parameterization of the model in which stakeholders have uncertainty only about the realized state of the world; the associated political prediction of the model is $\mathbf{W}(\mathbf{z})$. While stakeholders know the value of $\mathbf{z}$, the modeler does not. To incorporate this lack of knowledge into our methodology, we model the components of $\mathbf{z}$ as stochastic; we define a random vector $\tilde{\mathbf{z}} \in \mathbb{Z}$ with density function $h(\tilde{\mathbf{z}})$, representing epistemic uncertainty about the true value of $\mathbf{z}$. We use the term *modeling uncertainty* to refer to our lack of information about how best to model, and then parameterize, the political-economic environment that we wish to study.[3] This approach allows us to study the sensitivity of our political prediction mapping, $\mathbf{W}(\cdot)$, to the particular parameterization of the problem.

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[2] As a criterion for political viability, Pareto dominance has an obvious shortcoming: each stakeholder in the model is assumed to have veto power over the decision-making process. In this respect, our notion of political viability is a flawed representation of virtually every actual political process: either it endows some modeled stakeholders with more power than they actually have, or it excludes from the model stakeholders who, though lacking veto power, may have considerable political influence. In the former instance, the set of politically viable options will be underestimated; an option can fail to meet our criterion because it is unacceptable to some stakeholder that in the real world would lack the political clout to block it. In the latter instance, the set will be overestimated; it will include policy options that are acceptable to all of the stakeholders with veto power, but in the real world would not survive the combined opposition of multiple stakeholders, none of whom had the political power to veto the outcome unilaterally. It is nonetheless a helpful exercise to identify the Pareto dominant set. In particular, as we shall demonstrate in section 3 below, it can be especially instructive to learn that certain highly publicized possibilities fail to satisfy even this relatively modest selection criterion.

[3] The very similar term "model uncertainty" is widely associated with the work of Hansen & Sargent (2001), which builds on work by Gilboa & Schmeidler (1989) and others. Gilboa *et al.* (2008) provides an accessible overview. This literature is motivated by a problem very similar to the one that we confront: how to deal with situations where probabilities are unknowable. However, they focus on the question of how to optimize an objective function in this context; we eschew optimization altogether, instead attempting to isolate potential solutions that satisfy a weak necessary condition for optimality.

To study the role of modeling uncertainty, we define a *probabilistic political viability function* $V : \mathbb{X} \rightarrow [0,1]$, where $V(\mathbf{x})$ is the probability computed over possible realizations of modeling uncertainty that policy $\mathbf{x}$ satisfies our viability criterion, i.e., Pareto dominates the default. Formally,

$$V(\mathbf{x}) = Pr_{\mathbb{Z}}(\mathbf{x} \in \mathbf{W}(\mathbf{z})) \tag{4}$$

We partition the policy space into "more likely" and "less likely" regions to summarize the information provided by our viability function. Formally, for some K, we specify a K-vector ρ of probability threshholds, where $0 = \rho_1 < \rho_k < \rho_K < 1$, and for each k, define a "more likely" region $\mathbb{C}_k^+ = \{\mathbf{x} \in \mathbb{X} : V(\mathbf{x}) > \rho_k\}$ and a "less likely" region $\mathbb{C}_k^- = \{\mathbf{x} \in \mathbb{X} : V(\mathbf{x}) \leq \rho_k\}$. $\mathbb{C}_k^+$ and $\mathbb{C}_k^-$ are, respectively, the upper- and lower-contour sets of Vcorresponding to ρ_k. Under Pareto dominance, $\mathbb{C}_k^+$ contains all policies that Pareto dominate the default for some fraction exceeding ρ_k of possible realizations of modeling uncertainty. We will say that a policy in the "highest" upper-contour set $\mathbb{C}_k^+$ is *robustly politically viable*; for a policy with this designation, we can have a high degree of confidence that its political viability is not highly sensitive to specific model parameterizations. Conversely, a policy in the "lowest" lower-contour set $\mathbb{C}_1^-$ will be called *never politically viable;* we can be highly confident that a policy in this category will not survive the political process, regardless of specific model parameterizations.

Our approach is closely related to the "robust decisionmaking" approach developed to evaluate problems characterized by "deep uncertainty." Deep uncertainty refers to situations where the researcher or affected parties cannot agree on how to characterize the problem in question in one or more of the following ways: the appropriate set of conceptual relationships defining the problem and potential solutions, the probability distributions that represent uncertainty about key relationships and parameters, and/or the desirability of alternative outcomes (Lempert, 2002).[4] In robust decisionmaking, computer simulations are used to generate a large ensemble of outcomes, each based on a specific model. Rather than interpreting the results using summary statistics of realized outcomes, as one would in a Monte Carlo setting, the results are interpreted as representing modeling uncertainty. If a potential solution performs well for a substantial share of the simulations, then it is deemed robust. Lempert (2002) argues that robust decisionmaking does not need to be based

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[4] Deep uncertainty is closely related to the distinction between situations of "risk" and of "uncertainty" introduced to economists by Frank Knight.

on a model known to make reliable forecasts. Rather, the model must be capable of identifying key players, relationships, and potential states of the world well enough to identify which potential strategies are likely to fare well under a wide range of specifications. At the same time, the potential values of the individual elements of each specification are limited to realistic ranges (Lempert, 2002). These ranges can be defined using expert opinion or other information.[5]

Our probabilistic political viability approach follows the same logic. In our political economic context, just as in a decision-theoretic context, the value of a single optimal solution based on a single model specification is less useful, the more sensitive is the model outcome to uncertainty regarding the model specification (Lempert *et al.* (2006)). In complicated problems, an appropriate model may be sufficiently complex that a single specification cannot be useful because the effects of the many assumptions it incorporates cannot be disentangled from each other. Furthermore, probabilities play two distinct roles in both approaches; first, the conventional one of representing the likelihood of realizations of states of the world, or known uncertainty; second, the provision of a framework for summarizing information about the effect of modeling uncertainty on the performance of specific policies according to specific criteria (Lempert *et al.*, 2004).

Our approach is related as well to the "robust control" and the "info-gap" literatures, although less closely. Robust control is a means of modeling ambiguity-averse preferences (Hansen & Sargent, 2001). Due to the limits of knowledge regarding the factors driving species survival, among other considerations, robust control is a natural choice for modeling many natural resource problems, including extractive fisheries and water allocation (Shaw & Woodward, 2008). Info-gap theory is designed to identify policies that decisionmakers can be confident will meet an acceptability criterion (Ben-Haim, 2006). In both literatures, the goal is to identify a single policy that meets an optimality criterion designed to address the well-known problems associated with decisionmaking under Knightian uncertainty (See Ellsberg, 1961; Gilboa & Schmeidler, 1989). Our stakeholders face unpredictability in the traditional sense, i.e., Knightian risk: they know the probability distributions over which they must take expectations.[6] Because of this, the issues associated with Knightian uncertainty —ambiguity aversion, etc.; seeGilboa *et al.* (2008) for a summary—do not arise.

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[5] Methodologically, robust decisionmaking is very closely related to multi-model analysis and perturbed physics analysis, which have been used extensively to model climate change, among other applications (For examples of this literature, see Murphy *et al.* (2004); Piani *et al.* (2005); Stainforth *et al.* (2005); Rougier (2007); Dessai *et al.* (2009)).

[6] There is no bright line distinction between Knightian risk and uncertainty. Rather, these concepts should be thought of as extreme points of a conceptual continuum, along which our stakeholders' unknowns are dispersed.

2.4. **Simulation Approach.** For complex policy problems it is virtually impossible to express in tractable analytical form the key elements of the predictive political model, in particular, $\mathbf{y}(\cdot)$, $\mathbf{W}(\cdot)$ and $V(\cdot)$. Accordingly, we assign specific functional forms to $\mathbf{y}(\cdot)$ and $\mathbf{u}(\cdot)$ and to the distributions over $\mathbb{S}$ and $\mathbb{Z}$. We define the parameter space $\mathbb{Z}$ to be a hypercube. Lacking any basis on which to rank the relative likelihoods of alternative parameterizations, we invoke the principle of insufficient reason (Sinn, 1980) and assume that the elements of the random parameter vector $\tilde{\mathbf{z}}$ are independently and uniformly distributed. That is, for each dimension of $\tilde{\mathbf{z}}$ we specify an interval wide enough to include all values of the component that we consider to be plausible, and then assume that each value in that interval is equally likely to be realized. Let $f(\cdot)$ denote the (constant) density defined on $\mathbb{Z}$. For each realization of $\tilde{\mathbf{z}}$ with distribution parameter subvector $\mathbf{z}^s$, the distribution over states of the world has density $h(\cdot;\mathbf{z}^s)$. Once again, we assume that $h(\cdot;\mathbf{z}^s)$ is a constant; the subvector $\mathbf{z}^s$ determines the supports of the various random variables. Now, for each $\mathbf{z} \in \mathbb{Z}$ (the "outer loop"), we compute players' payoffs for each policy in $\mathbb{X}$ and for the default outcome for each realization $s \in \mathbb{S}$ (the "inner loop"). We then take expectations over $\mathbb{S}$ to identify the PD set for the realization $\mathbf{z}$. This approach provides a comprehensive picture of political viability across the entire spectrum of plausible parameter configurations through the probabilistic viability function $V(\cdot)$ and its associated upper and lower contour sets $\mathbb{C}_k^+$ and $\mathbb{C}_k^-$,. In the following two sections, we apply this methodology to a specific policy problem, and study $\mathbf{W}(\cdot)$ and $V(\cdot)$ in that context.

3. THE DELTA APPLICATION

The case study in this section illustrates the PPV methodology developed in Section 2. This case study presents all of the issues discussed in the introduction. The problem is exceedingly complex and multi-faceted. There is a diverse set of stakeholders whose conflicting, non-comparable interests cannot be balanced against each other using conventional utilitarian principles. The issues that arise involve market and non-market goods, privately owned and common-pool resources, and an intricate mix of economic, environmental and engineering objectives. There is a great deal of exogenous uncertainty. The scientific relationships between key variables are imperfectly understood. For these reasons, it is appropriate to search among potential resolutions for ones whose political viability is robust with respect to a wide array of possible characterizations of the political situation.

3.1. The Sacramento-San Joaquin Delta.

The Sacramento-San Joaquin Delta is the confluence of two large river systems draining California's Central Valley: the Sacramento in the north and the San Joaquin in the south.Settlement has changed the Delta from a marshy region of shifting channels and salinity to a series of levee-protected islands surrounded by fixed channels. The vast majority of San Joaquin River water is diverted upstream. Large quantities of Sacramento River water are also diverted upstream. A substantial portion of the water that does reach the Delta is then pulled south, against natural flow patterns, to large pumping plants and exported to agricultural users in the San Joaquin Valley and urban users in Southern California and the Bay Area. The salinity of the Delta is carefully regulated to protect the quality of water exports.

Today, the Delta is widely acknowledged to be in crisis. The region serves two critical needs for California: ecosystem services and water infrastructure. While there has always been some tension between these goals, the conflict between them has intensified in recent years. Fish populations have crashed, and five species are listed as threatened or endangered. Lawsuits filed under the Endangered Species Act (ESA) have led to dramatic cuts in water exports(United States District Court, 2007), which in turn have contributed to rising unemployment rates in many agricultural regions reliant on the Delta for water.

The Delta also faces a substantial risk of levee failure. The aging levees protecting Delta islands are at risk from isolated failures and catastrophic simultaneous failures perhaps due to earthquakes on the region's faults. In the event of massive failure, water would rush in to fill the levee lined islands and saline water from San Francisco Bay would be drawn into the Delta, making its water unfit for drinking, agricultural production, and important fish species. The consequences for California's residents would be enormous; nearly two-thirds of the state's residents rely on the Delta for drinking water. A major levee breach is predicted to cost between \$8 and \$15 billion (Lund *et al.*, 2008).

3.2. Proposed solutions.

Several independent studies have considered how the state should respond to this crisis (Bay Delta Conservation Plan, 2007, 2009; Blue Ribbon Task Force, 2007, 2008; Cooley *et al.*, 2008; Delta Vision Committee, 2008; Lund *et al.*, 2007, 2008). The Lund *et al.* (2008) report has been particularly influential and our analysis draws heavily on it. Its authors argue that there are four basic strategies available to the government: stop exporting water from the Delta altogether, invest in reinforcing the Delta's levees and continue exporting water through it, build a canal or other isolated conveyance system to carry exports around the Delta, or combine the last two alternatives in a dual conveyance system where some water is exported through the Delta and some around it in a canal.

The first strategy, stopping all exports, would have sweeping consequences. Agricultural and urban interests currently reliant on the Delta for water would need to reduce their water use, find alternate sources of supply, or do some of both. Water conservation, land fallowing, wastewater recovery, and desalination would all likely play major roles in the adaptation. Each of these responses would be extremely costly; Lund *et al.* (2008) estimate that stopping all water exports through the Delta would cost between \$1.5 and \$2.5 billion per year. While this strategy would likely be the best option from an ecosystem prospective, it is important to recognize that even stopping all exports would not **guarantee** the recovery of endangered fish populations.

The second strategy is to reinforce the levee structure in the Delta while continuing to export water through it. This strategy is appealing in that it does not require the construction of new conveyance infrastructure, which would have a high price tag and might not resolve the Delta's problems. Water managers would continue policies designed to keep the Delta's salinity below specified targets. Given the current risk of levee failure, a through-Delta strategy would require substantial investments in levee upgrades. However, most engineers believe that it would be impossible to eliminate the risk of catastrophic levee failure. As a result, choosing a through-Delta strategy implies accepting some degree of failure risk. Moreover, most ecologists believe that such a system is likely to be the worst of the four alternatives from an ecosystem perspective.

The third strategy is to build a canal, tunnel or other isolated conveyance system around the Delta. For brevity we use "canal" to represent an isolated conveyance structure, whatever its form.[7] Today, all the water that reaches the lower end of the Sacramento River flows into the Delta. By exporting water around the Delta instead of through it, only water not destined for export would flow into the Delta. A canal would insulate the state's water supply from the risk of levee failure. It would be expensive to construct, but water users have pledged to pay for it in exchange for the security it offers. Although controversial, many biologists believe that such a system would be better for

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[7] The idea of a tunnel (or pair of tunnels) rather than a surface canal is a relatively recent one *(Bay Delta Conservation Plan, 2010, p. 35).* While there are important differences between the two systems, they are second order relative to the considerations discussed in this paper. In what follows, we use the word "canal" as shorthand for "some surface or underground conveyance system that is isolated from the Delta itself."

the region's ecosystem than the status quo, despite the lower quantities of fresh water that would flow into the Delta. Several ecosystem impacts would be reduced under this strategy. In particular, it would eliminate the "flow reversals" that occur when the export pumps draw water against its natural flow patterns and would probably reduce the impact of ESA restrictions on pumping at certain times of the year. It would also eliminate the need to regulate the salinity of the Delta as water would enter the canal upstream from the Delta. However, in-Delta interests are worried about the impact of these lower inflows on Delta water quality. Moreover, many groups, particularly in-Delta interests and some environmental groups have expressed concern that the institutions charged with managing the conveyance system might eventually bow to political pressure to renege on agreed upon limits on canal usage.

The final strategy is to combine the previous two: export some water through a canal and some through the Delta. Many believe that this strategy, known as "dual conveyance," could represent the best of both worlds: maintaining inflows to the Delta and therefore maintaining its water quality, providing the flexibility to route exports in the least harmful fashion at any particular point in time, and providing a secure export option in the event of levee failure. Others fear that it could be the worst of both worlds: expensive to construct and not guaranteeing either ecosystem health or water supply reliability by failing to separate these functions.

Opinions about how to proceed are varied. Supporters of a canal and/or dual-conveyance option include Arnold Schwarzenegger and Jerry Brown, California's past and present governors, an independent group of experts, many water export users, the Bay-Delta Conservation Plan committee, and the Nature Conservancy. Opponents include farmers, local residents and recreational users within the Delta (henceforth referred to collectively as "in-Delta interests") and some Northern California residents. Many environmental groups are withholding judgment but have indicated that if appropriate safeguards were guaranteed a canal might be part of a workable solution. The main source of concern among environmental groups is that the canal will not be operated in accordance with environmental protection laws and the Endangered Species Act (ESA). These groups have expressed a fundamental lack of trust in existing water management institutions, noting that these are the same institutions that failed to prevent the current crisis. The situation is evolving rapidly as analysis of the various options and plans continues. (See, for example, National Research Council

(2011).) We construct a probabilistic political viability model of the political debate over the future of the Delta in order to assess the political viability of the various options on the table.

3.3. **A Probabilistic Political Viability Model of the Delta.** This subsection embeds a computable model of the policy options facing California into the framework introduced in Section 2. Given the complexity of the choices, the full specification is quite detailed. This section provides a sketch of the entire model and focuses on the features that are critical for the results. The technical appendix, available on request, provides a complete description of the model's functional forms and parameter specifications.

Following Lund *et al.* (2008), we focus on two policy choices: how much water to export and how to convey it. Our model includes five broadly specified stakeholder groups: urban users of exported water, the agricultural regions of the San Joaquin Valley that rely on exported water, environmentalists, state taxpayers, and in-Delta interests. These groups have conflicting concerns about the financial, ecological, and employment impacts of the possible options available to the government. Politically, it would be very difficult to impose a solution to the Delta's problems over the vigorous objections of any one of them.[8] To the extent that each of these groups possesses some degree of veto power over the final solution, our political viability criterion—Pareto dominance—is a necessary condition for a solution to be sustainable.[9] Indeed, *Sacramento Bee* political reporter Dan Walters has commented on the "unwritten rule" that "any major policy decree must have virtually unanimous support from every stakeholder group or it will ultimately fail because opponents have so many political ways to kill it" (Walters, 2010).

3.3.1. *Policy Choices.* A policy in our model is represented by a pair $(x_{\mathrm{ex}}, x_{\mathrm{shr}}) \in \mathbb{X} \subset \mathbb{R}^2_+$, where x_{ex} is the total amount of water exported and x_{shr} is the share of exports routed around the Delta through a canal. We let x_{ex} vary from zero to 7.5 million acre feet (maf)[10] and let x_s vary from zero to one. Prior to the court mandated cutbacks, exports averaged approximately 6 maf; we refer to this as the pre-2007 export level. The size of the canal constructed is not a a policy choice in

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[8] There is another interest group that has some degree of veto power: agricultural users upstream of the Delta. We have omitted them because of lack of data. It is less clear that the in-Delta interests have real veto power over Delta solutions, but they are certainly a vocal interest group exerting substantial influence over the process.

[9] In their analysis of the Delta, Madani & Lund (2011a) consider six game-theoretic solution concepts: a necessary condition for a policy to solve any one of their games is that it (weakly) Pareto dominates the status quo.

[10] Lund *et al.* (2008) identify 7.6 maf as the maximum level of exports consistent with minimum flow constraints on the Sacramento River.

Table 1. Costs of Various Export Regimes and how they are allocated

Cost	Allocation	Dependence on Export Regime
Reduced exports	Agricultural and urban water users	Increases as total exports decline
Water treatment	Agricultural and urban water users	Increases as total amount of water exported through Delta increases
Levee maintenance	Primarily taxpayers; also agricultural and urban water users	Increases as total amount of water exported through Delta increases
Repair	Taxpayers	Constant, but only paid if no canal is built, either initially or after disaster
Canal Construction	Mostly water users; also taxpayers	Constant for any level of canal exports; also paid if canal is built following collapse
Collapse	Water users and taxpayers	Constant, but only paid if no canal is built

our model; we assume that if constructed, a canal will be sized based on engineering considerations as recommended by Lund *et al.* (2008). Each of the solutions identified in Lund *et al.* (2008) can be represented as a specific point in $\mathbb{X}$. Our parameterization is self-explanatory for each of the strategies except the dual-conveyance alternative. Because the report does not include a precise description of how a dual-conveyance plan would allocate exports between the canal and through-Delta pumping, we represent the dual conveyance alternative by dividing exports evenly between the two; other values of x_{shr} would correspond to different dual conveyance alternatives.

3.3.2. *Outcomes.* Each policy vector is mapped to a stochastic outcome vector which represents the payoff-relevant consequences of implementing that vector. Many of these outcomes are financial. Different export regimes impose different types of costs that are shared among three of our stakeholder groups: agricultural users and urban users that rely on Delta exports for some of their water, and the taxpayers. The model includes five specific costs: costs due to reduced water exports, water treatment costs, levee maintenance costs, repair costs following a major collapse, and costs associated with a major collapse of the levee system.[11] Table 1 summarizes the allocation of these costs and the key pathways through which the policy vector $\mathbf{x}$ influences them. Several of the costs are borne only in the event that a canal either is or is not constructed. As a result, our mapping from policies to outcomes is discontinuous as we move from $x_{\text{shr}} = 0$ to $x_{\text{shr}} > 0$. This discontinuity induces discontinuities in stakeholder preferences that are discussed in section 4.

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[11] The costs included in the cost of a levee collapse are the costs of a sudden disruption of water supplies during the transition period until either the levees are repaired or a canal is constructed. They do not cover all potential consequences of a collapse, most importantly the costs to in-Delta interests of a catastrophic collapse. In-Delta concerns about costs associated with levee collapse are captured by including levee maintenance in their utility function as described in subsection 3.3.5.

There are also non-financial outcomes that affect stakeholder utilities, including agricultural employment in the San Joaquin Valley, inflows to the Delta, and the possibility of fish extinction. The the role they play in stakeholder utility is discussed in subsection 3.3.5.

3.3.3. *Stakeholder Uncertainty.* All of the outcomes defined above are contingent on the state of the world s, which incorporates all of the uncertainty that stakeholders confront. This uncertainty is due to the inherently stochastic nature of the linkages between policy decisions and their ultimate impacts. One source of this uncertainty is scientific controversy among experts, such as disagreement about how fish populations will respond to changes in water export regimes. Another source of uncertainty is that certain payoff-relevant events will not occur until the future: these include the occurrence and timing of a major levee collapse, whether fish species will recover, and whether exports will be cut at some future time to aid the species' recovery. The technical appendix presents a detailed description of each of the components of our model that vary across states of the world and their assumed distributions.[12]

There is one last source of uncertainty that plays a critical role both in the real-world policy debate and in our model: how, exactly, will future export regimes be implemented? Here we distinguish between the negotiated policy choice $\mathbf{x}$ that emerges from the political process—we call this the *declared policy*—and the *actual export regime in a particular state of the world.* The actual export regimes may in some states deviate from the declared policy for one of three reasons. First, reductions in exports may be required in order to comply with the ESA. For instance, if the political process agreed upon a thru-Delta solution with pre-2007 levels (around 6 maf), fish populations would quite likely continue their rapid decline. In some states of the world, the judicial system would then intervene, mandating a significant cut in exports. In these states, actual exports would diverge from the declared policy. Second, the institutions responsible for water management may fail to implement the declared export policy for reasons that will be discussed in subsection

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[12] Our approach is related to the one taken by Madani & Lund (2011a). Their Monte Carlo analysis draws from a distribution similar to our distribution over states of the world. A key distinction between their analysis and ours is that every draw from their distribution resolves all payoff-relevant uncertainty: their two stakeholders face no uncertainty in the games that they play; there is, however, uncertainty about which solution concept best represents the true political situation (stakeholders' behavior). By contrast, the five stakeholders in our model compare policy alternatives to the default outcome on the basis of expected utility computations across possible states of the world. A second, even more fundamental difference is that we undertake this exercise for a large number of draws from the set of possible values for all variables subject to modeling uncertainty.

3.4. Finally, if a major levee collapse occurs, the post-disaster export regime may differ from the pre-disaster export regime.

To model this relationship between declared export policy and the realized export regime, we define the function $\mathbf{g}\left(\mathbf{x}; s, \mathbf{z}_y\right)$, representing the actual export regime that results in state s from a policy choice $\mathbf{x}$**,** given the outcome parameter vector $\mathbf{z}^y$. As noted above, stakeholders' utilities depend on the outcome vector $\mathbf{y}$, which depends in turn on the *realized export regime*: $\mathbf{y}\left(\mathbf{g}\left(\mathbf{x}; s, \mathbf{z}^y\right); s, \mathbf{z}^y\right)$. Thus s can affect the outcome vector both directly, through state-contingent values such as the relationship between a particular export level and water supply costs, and indirectly, through its influence on the actual export regime.

3.3.4. *The Default Outcome.* The default outcome in our model has deterministic and random components. If stakeholders cannot agree on a policy alternative in $\mathbb{X}$ then no major policy change will be implemented. As a result, no canal will be built and no money will be spent on maintaining the levees, so the probability of a massive levee failure will increase. The issue of primary concern to stakeholders under the default outcome is the level of water exports in the absence of a massive levee failure. This level is uncertain. As in the case of agreement, the actual level of default exports will depend on whether or not fish populations show signs of recovery and whether export reductions are imposed if not.

Default exports are dependent on the future state of the world, and hence unknown to both stakeholders and the modeler. The distribution describing stakeholder uncertainty is subject to modeling uncertainty. Specifically, we model default exports as state-contingent and treat the parameters governing the distribution of the relevant state as components of modeling uncertainty. To reflect stakeholder uncertainty, we write the default export regime as $\mathbf{g}^d\left(s, \mathbf{z}^d\right)$ and the default outcome as $\mathbf{y}^d\left(\mathbf{g}^d\left(s, \mathbf{z}^d\right); s, \mathbf{z}^d\right)$. As always, we assume that stakeholders know the value of $\mathbf{z}^d$ but not the realization of the state of the world s; as usual, $\mathbf{z}^d$ is a component of modeling uncertainty.

3.3.5. *Stakeholder Utility.* The following list introduces the arguments of each stakeholder group's utility function. The two letter code after each group's title will be used as shorthand to identify groups when we present our results. With the exception of environmentalists, each stakeholder group has a CES utility function defined over the components of the outcome vector that we assume affects its utility. Each group's preferences over outcomes induce preferences over policy variables, although the linkages are not immediately transparent. Environmentalists are a special case. For tractability, they are concerned exclusively about the survival of two fish species, Delta smelt and salmon. Because fish survival is a binary variable, the CES specification we use for other groups is inappropriate for environmentalists. Further discussion of the induced policy preferences is provided in subsection 4.1.1 below.

State taxpayers (Tp): Taxpayers are concerned with reducing the government's total expenditure liability and are risk neutral. The two major (variable) determinants of the government's liability are the cost of levee maintenance, which increases with the amount of water exported through the Delta, and the costs of a major collapse, borne only if a canal does not exist. Thus Tp's utility is increasing in x_{shr}, decreasing in x_{ex}, and jumps up as we move from $x_{\text{shr}} = 0$ to $x_{\text{shr}} > 0$.

Urban users (Ur): This group is an aggregate of urban interests in Southern California and the San Francisco Bay Area. It is concerned with minimizing the cost of meeting its water supply needs. Delta exports are cheaper than alternatives, so urban user utility increases with x_{ex}. Moreover, both water treatment costs and the probability of cutbacks for ecosystem protection increase as water exports are shifted from a canal to the Delta, so Ur's utility also increases with x_{shr}.

Agricultural users(Ag): This group includes farmers in the San Joaquin Valley who rely on water exported through the Delta. The two arguments in Ag's utility function are farming profits and the level of agricultural employment. Ag's preferences are very similar to those of Ur, although Ag's utility decreases faster than Ur's as x_{ex} falls since Ag's profits and agricultural employment both decline.

In-Delta interests: (Dt) This group is a composite of local residents, farmers, and recreational users within the Delta. The two arguments of Dt's utility function are Delta inflows and levee maintenance. The first argument proxies the quality of water in the Delta, which is highly correlated with Delta inflows. In the absence of a canal, Delta inflows are determined by factors exogenous to our model—hydrological variables and upstream diversions. If a canal were built, then any water exported through it would reduce inflows into the Delta. The second argument, levee maintenance, is a function of the amount of water exported through the Delta: any agreed-upon policy package will allocate funds for levee maintenance according to a formula that increases with through Delta exports. Both impacts imply that Dt's utility decreases with x_{shr}. The impact of increasing x_{ex} depends on the value of x_{shr}. At high values of x_{shr} increasing exports reduces Dt's utility due to reduced inflows; at low values of x_{shr}, Dt's utility increases with exports due to increased levee maintenance.

Environmentalists (Ev): Ev is concerned exclusively with the survival of two fish species: Delta smelt and salmon. We define four state-dependent utility levels for Ev, similar to Woodward & Shaw (2008). If both species survive, its utility is 1; if neither survive it is zero. If only one of the two species survive, its utility is some number between 0 and 1, depending on which species survives. Ev's expected utility thus increases as the probability of survival increases and hence decreases with x_{ex}. The impact of x_{shr} is more complex and is discussed in detail in section 4.

Following the approach in Section 2, the vector of expected utilities resulting from policy $\mathbf{x}$ is

$$\mathbf{Eu}\left(\mathbf{x};\mathbf{z}\right)=\int\mathbf{u}\left(\mathbf{y}\left(\mathbf{g}\left(\mathbf{x};s,\mathbf{z}^{y}\right);s,\mathbf{z}^{y}\right);\mathbf{z}^{u}\right)h\left(s;\mathbf{z}^{s}\right)ds$$

and the expected default utility vector is

$$\mathbf{Eu}^{d}\left(\mathbf{z}\right)=\int\mathbf{u}\left(\mathbf{y}^{d}\left(\mathbf{g}^{d}\left(s,\mathbf{z}^{d}\right);s,\mathbf{z}^{d}\right);\mathbf{z}^{u}\right)h\left(s;\mathbf{z}^{s}\right)ds.$$

3.3.6. *Modeling Uncertainty.* The elements of the parameter space $\mathbb{Z}$ that are components of *modeling uncertainty* include parameters specifying the distribution over the states of the world that relate to the default outcome, the environmentalists' payoffs when only one species survives and, for each of the other groups, its level of risk aversion, its elasticity of substitution, and the relative weights that it assigns to different objectives. The remaining components of $\mathbb{Z}$ are parameters known to both stakeholders and the researcher, which are modeled as degenerate random variables. A list of these is provided in the technical appendix. Table 2 lists each non-degenerate element of $\mathbb{Z}$ and the upper and lower bounds on the interval of values considered plausible for each one. Since we have no basis for specifying an informative prior over these intervals, the principle of insufficient reason dictates that each element should be independently and uniformly distributed over the interval we specify as its support.

Table 2. Elements and Distribution of Modeling Uncertainty

Variable	Lower Bound	Upper Bound
Weight on jobs vs money in Ag utility	0.2	0.8
Weight on maintenance vs inflows in Dt utility	0.2	0.8
Constant in Dt utility	0.05	0.15
Ag elasticity of substiution	0.5	1.5
Dt elasticity of substitution	0.5	1.5
Ag risk aversion coefficient	0.2	1
Dt risk aversion coefficient	0.2	1
Ur risk aversion coefficient	0.2	1
Ev utility if only smelt survive*	0.25	0.75
Ev utility if only salmon survive*	0.25	0.75
Spread of default export distribution above and below mean (maf)	0	2

* Ev utility is scaled so that 0 represents the utility if neither species survives and 1 represents the utility if both survive.

3.3.7. *Probabilistic Viability of Delta Solutions.* Section 2 (equations 3 and 4 respectively) defined $\mathbf{W}(\mathbf{z})$, the Pareto dominant set (PD) given a particular realization $\mathbf{z}$ of $\tilde{\mathbf{z}}$, and $V(\mathbf{x})$, the probability with respect to modeling uncertainty that the policy $\mathbf{x}$ belongs to the Pareto dominant set. Note that for any given $\mathbf{z}$ the payoff-relevant characteristics of each policy alternative $\mathbf{x}$ are uncertain because the state of the world is unknown. There are two sources of randomness. First, as discussed in subsection 3.3.3, the total level of exports and the share flowing through the canal are state-dependent. Second, for any realized level of exports, there is uncertainty about how this level will map into payoff relevant outcomes. However, for any given $\mathbf{z}$ the PD set itself is deterministic—a policy is either dominated in expectation by the default for at least one player or it is not.

3.4. **Institutional Mistrust.** As noted in subsection 3.2, many groups, including in-Delta interests and some environmentalists, have repeatedly expressed concerns that if the total capacity available for exports were increased by building a canal, this entire capacity would be maximally utilized, regardless of the declared level of exports.[13] This concern has been exacerbated by calls from engineers to choose its capacity to match engineering constraints rather than to implement any particular export level. The engineering reasons for this approach are compelling: a large canal

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[13] Blogger Dan Bacher voices a widely held view: "Although the Delta Vision Task Force's report recommended that less water be exported out of the Delta to help the estuary's collapsing ecosystem, canal opponents note that the construction of a canal with increased water export capacity would inevitably be used to export more water out of the system.... I have repeatedly asked canal advocates to give me one example, in U.S. or world history, where the construction of a big diversion canal has resulted in less water being taken out of a river system. I have also asked them to give me one example, in U.S. or world history, where the construction of a big diversion canal has resulted in a restored or improved ecosystem. None of the canal backers have been able to answer either one of these two questions." Bacher (2009)

would provide maximum flexibility to time export flows during the least environmentally damaging time periods. However, the approach would build in substantial excess capacity, fueling fears of exports greater than those agreed upon.

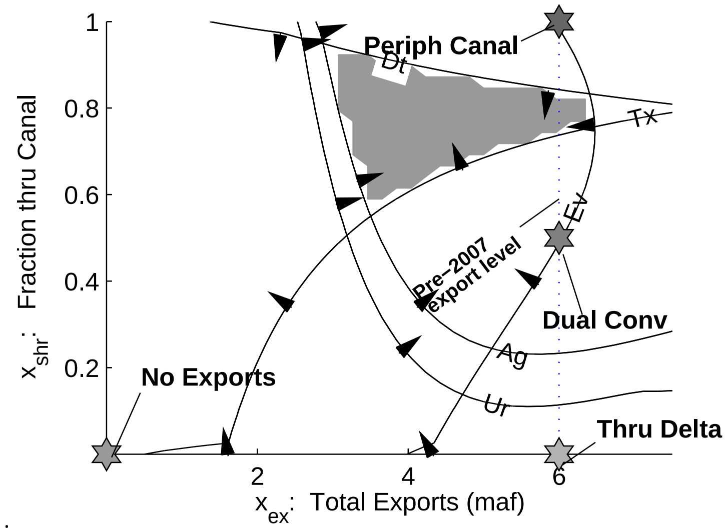
We model the impact of institutional mistrust on the political process in a stylized way by introducing an additional state-dependent variable: with probability $\lambda \in [0,1]$, water users will convince regulators to fill the canal to its capacity level at all times; with probability $1-\lambda$, the canal will be operated in accordance with the declared policy $\mathbf{x}$. As with any other component of s, stakeholders take expectations over the possibility that export level commitments are not honored; the magnitude of λ is another component of the distribution parameter $\mathbf{z}^s$, which is known by stakeholders. Section 4 considers the comparative statics effect on political viability of increasing the value of λ. More precisely, it examines how the upper and lower contour sets of $V(\mathbf{z};\cdot)$ vary as the degree of mistrust increases.

4. RESULTS

The first set of results focuses on the set of policies that Pareto dominate the default outcome for one particular realization of modeling uncertainty, namely the expected value $\bar{\mathbf{z}} = \int_{\mathbb{Z}} \mathbf{z} f(\mathbf{z}) d\mathbf{z}$ of the random variable $\tilde{\mathbf{z}}$ with respect to modeling uncertainty. For this parameterization, we increase mistrust λ, and examine the changes in size and location of the Pareto dominant (PD) set, $\mathbf{W}(\bar{\mathbf{z}};\lambda)$ (see eq. 3). We then introduce modeling uncertainty into the analysis, and examine the probabilistic properties of the PD set over a wide range of alternative parameterizations by classifying policies according to the probability with respect to modeling uncertainty that they dominate the default outcome. We use graphical methods to summarize our results and illuminate the relationship between our probabilistic set measures and institutional mistrust.

4.1. **One realization of modeling uncertainty.** Having fixed the parameterization vector $\bar{\mathbf{z}}$, we use Monte Carlo methods to identify the PD set. We draw a large sample from the space $\mathbb{S}$ of states of the world in accordance with the distribution $h(\cdot;\bar{\mathbf{z}}^s)$. For each policy vector $\mathbf{x}$ in a fine grid of points in the policy space $\mathbb{X}$ and each realized state s in the sample, we compute stakeholder group k's utility $u_k(\mathbf{x};s,\bar{\mathbf{z}})$ from $\mathbf{x}$ given s, and conditional on the parameter vector $\bar{\mathbf{z}}$. We then average $u_k(\mathbf{x};\cdot,\bar{\mathbf{z}})$ over our sample to obtain the expected utility $Eu_k(\mathbf{x};\bar{\mathbf{z}})$ that k derives from $\mathbf{x}$.

FIGURE 1. The PD set with perfect trust conditional on $\bar{\mathbf{z}}$



We repeat this approach to compute k's expected utility, $Eu_k^d(\bar{\mathbf{z}})$ from the default outcome. This exercise identifies the PD set $\mathbf{W}(\bar{\mathbf{z}})$.

4.1.1. *Perfect Trust.* Initially, we analyze the PD set assuming institutions are perfectly trusted by stakeholders, i.e. that $\lambda = 0$, and identify $\mathbf{W}(\bar{\mathbf{z}}; \lambda = 0)$, which is the shaded area in Figure 1. The boundaries of Figure 1 coincide with the boundaries of the policy space. Moving from left to right in the diagram, the total amount of water exports, x_{ex}, increases; moving from the bottom to the top, the percentage of the exports flowing through the canal, x_{shr}, increases.[14] The filled circles in the figure are stylized depictions of the four policy alternatives discussed in detail in the PPIC report.

Each contour line depicted in Figure 1 represents the participation constraint for one of the stakeholder groups, i.e., the set of policy options which yield that group an expected utility level equal to its expected utility from the default outcome. The arrows attached to each constraint line are gradient vectors, pointing into the region of the policy space which the stakeholder group prefers to the default.

The shapes of the participation constraints in Figure 1 reflect the preferences of the various stakeholder groups. Ag and Ur will veto policies that involve low levels of exports. Both groups will trade

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[14] Note that the volumetric distinction between vertically differentiated points shrinks to zero as their horizontal location moves to the left of the diagram: in the limit, obviously, there is no distinction between different fractions of zero.

slightly smaller total exports for larger shares through the canal, but are concerned primarily with achieving a high base level of exports; consequently, their participation constraints slope steeply downward. They will also veto policies with very low shares through the canal, because they will not find it worth the cost of constructing the canal.Tp will veto policy vectors in the lower right corner of the space, since it is in this region that the levels of exports through the Delta, and hence expenditures on levee maintenance, will be the highest. Ev will veto policies that involve high levels of exports, although this group is more willing to accept exports if they are routed at least partially through the canal. This reflects the conclusion in Lund *et al.* (2008) that fish populations are more likely to recover under either a dual conveyance or pure peripheral canal option than if exports are pumped exclusively through the Delta. The precise shape of Ev's participation constraint is due to the specification of the fish survival probabilities and the assumption that the dual conveyance option splits exports equally between the canal and the Delta. For Dt, the two outputs which matter—freshwater inflows to the Delta and expenditures on levee maintenance—both decrease with exports through a canal; hence Dt will veto policies in the uppermost region of the policy space. Dt will accept even very high levels of x_{ex}, provided x_{shr} is sufficiently low because levee maintenance expenditures increase with total exports. As x_{ex} increases, there is a decline in the maximum level of x_{shr} that is acceptable to Dt. It is surprising that Dt is willing to accept such a large fraction of the available alternatives, since Delta interests have always vociferously opposed a canal. The reason is that these alternatives are being compared to a default outcome that is extremely unsatisfactory in expectation: unless some kind of agreement is negotiated, expenditures on levee maintenance will be minimal, increasing the probability of a major levee collapse, which would be devastating to Dt.

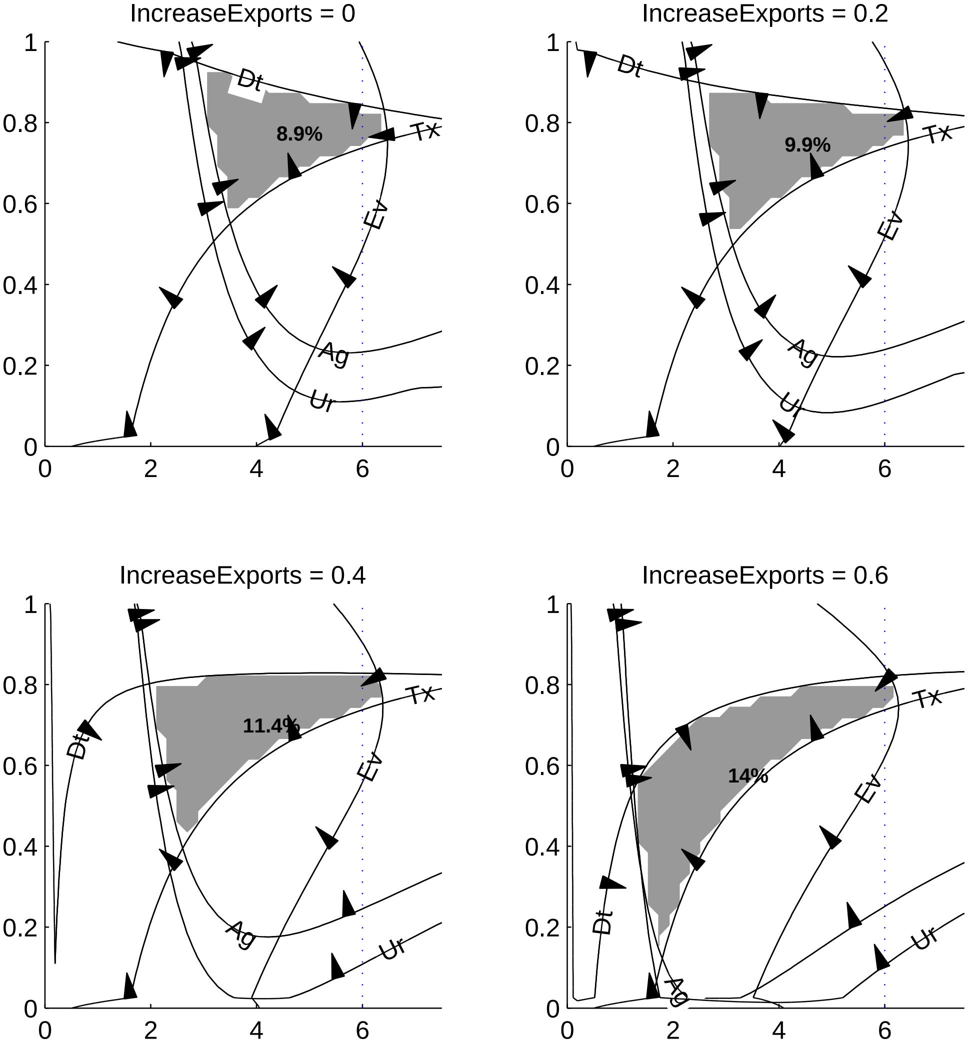
As noted in subsection 3.3.2, there is a discontinuity in the mapping from policies to expected utilities when $x_{\text{shr}} = 0$. We assume that if a canal exists, all exports will be routed through it in the event of catastrophic damage to Delta levees. Thus the state-contingent costs and benefits of a canal change discontinuously at $x_{\text{shr}} = 0$. This reflects an important discontinuity in the real-world political-economic landscape: if a canal is built, it will have a very high option value, even if $x_{\text{shr}} \approx 0$. Moreover, the size of the canal that will be constructed is independent of x_{shr} provided that $x_{\text{shr}} > 0$. In the absence of an alternative conveyance option, a major levee collapse will lead to one of two outcomes: either a canal will be built or extensive levee repairs will be undertaken.

The high cost of these emergency response options implies that the maximum level of x_{ex} (and thus the maximum level of regular levee maintenance expenditures) that Tp will accept falls when $x_{\mathrm{shr}} = 0$. The possibility of rebuilding the Delta levees and continuing through Delta exports also creates a discontinuity for Ev. For any given level of x_{ex}, fish survival probabilities are lowest when the realized share through the canal is zero (i.e., all exports flow through the Delta). We assume that if $x_{\mathrm{shr}} > 0$, all exports would with probability one be shifted exclusively to a canal following a disaster; in contrast, if $x_{\mathrm{shr}} = 0$, exports will, with positive probability, continue to be routed exclusively through the Delta, with strong negative implications for fish survival probabilities. In short, even if a canal would be used only in the event of a disaster, its existence would contribute significantly, in expectation, to fish survival probabilities. For this reason, the maximum level of x_{ex} that Ev will accept falls discontinuously when $x_{\mathrm{shr}} = 0$.

The shaded region in Figure 1 is the PD set at the mean level $\bar{\mathbf{z}}$ of modeling uncertainty. Note first that this set is nonempty, i.e., there do exist policies that Pareto dominate the default. This suggests that that if the model, when parameterized by $\bar{\mathbf{z}}$, is a reasonable stylization of the actual political process, then we cannot rule out the possibility that *some* negotiated solution will emerge from the political process. Moreover, for this parameterization, two necessary conditions for a policy to be acceptable to all stakeholders are that total exports will not exceed the pre-2007 level of 6 maf, and no more than half of all exports will flow through the Delta. Finally, under this parameterization at least three of the four options identified by the PPIC report would be vetoed by some group. Whether or not the fourth option—dual conveyance—would be vetoed depends on how the option would be implemented.

4.1.2. *Impact of Mistrust.* This subsection evaluates the consequences of institutional mistrust by comparing the PD sets, $\mathbf{W}(\bar{\mathbf{z}}; \lambda)$, for four levels of $\lambda \in \{0, 0.2, 0.4, 0.6\}$, representing the probability that the canal will be filled to capacity. We restrict our attention to just one parameterization of the model, $\bar{\mathbf{z}}$. Figure 2 is the analog of Figure 1 for all four levels of mistrust. The first panel replicates Figure 1. The percentage number printed inside of each set $\mathbf{W}(\bar{\mathbf{z}}; \lambda)$ indicates the size of this set relative to the entire policy space. The location of each number roughly indicates the center of the corresponding set.

FIGURE 2. Impact of mistrust on the location of PD set with parameterization $\bar{\mathbf{z}}$



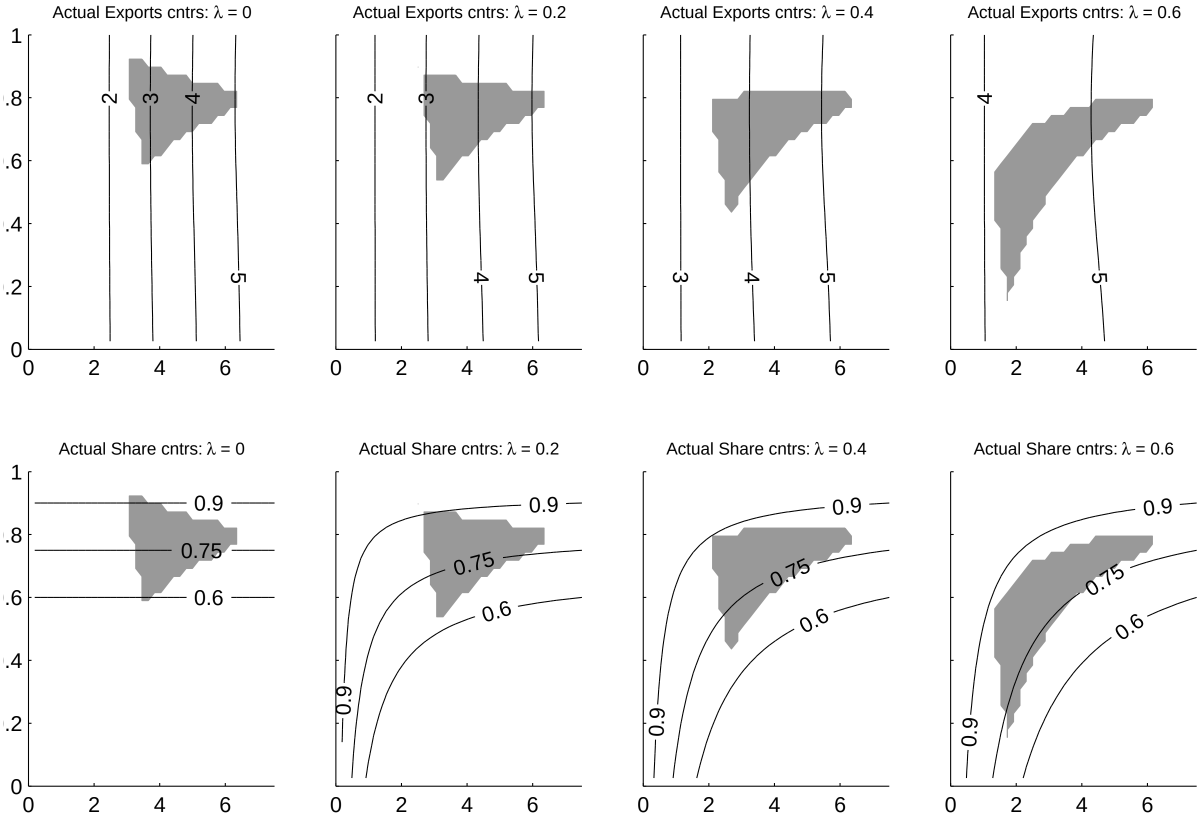
All of the costs for which Tp is responsible are independent of the level of mistrust, so the group's participation constraint is independent of the level of mistrust. The successive increases in mistrust induce shifts in all other stakeholders' participation constraints, and, hence the location and size of the PD set. At higher levels of mistrust, Ag and Ur are willing to accept lower levels of declared total exports because the expected actual level of exports (and shares through the canal) will increase. Ev's participation constraint moves to the left for the same reason. It also exhibits an increase in curvature that is dependent on the specific functional form for fish survival and has little impact on our results. The shift in Dt's participation constraint as mistrust increases is particularly dramatic. The change in its curvature between $\lambda = 0.2$ and $\lambda = 0.4$ can be traced to the change in the shape of the contours of the expected actual share routed through a canal. Canal exports lower

Dt's expected payoff because the water is diverted upstream, thus lowering Delta water quality by reducing freshwater inflows.

Due to the combined impacts of these shifts, the location and size of the PD set changes as mistrust increases, as shown in Figure 2. As noted above, the participation constraints for Ag, Ur and Ev all move to the left, causing the PD set to move left. At the same time, the *size* of the PD set increases monotonically with mistrust, from 8% to 14% of the entire space. This result seems counter-intuitive at first glance: one could interpret its size as a summary measure of the prospects for a successful negotiation, and one would certainly expect that these prospects would be diminished in the presence of mistrust. But this intuition does not take into account that there are gainers as well as losers from mistrust. As mistrust increases, the constraints of the mistrusted groups slacken, while those of the mistrusters tighten; the former are more willing to come to an agreement upon which they may be able to renege; the latter are less willing to agree, because the agreement may be reneged upon. The increase in size is caused by three factors. First, Ag's and Ur's constraints are shifting left at a significantly faster rate than Ev's, increasing the width of the PD set. The second effect plays the more significant role. The interaction between Tp's and Dt's participation constraints causes the PD set to be much narrower at its right-hand edge than at its left-hand edge. That is, at high levels of total exports, the interval of export shares that are acceptable to all parties is much smaller than at low levels of total exports. As a consequence, even if Ev's and Ag and/or Ur's constraints were to shift left with mistrust at the same rate, the PD set would increase in size: a "short" column would be eliminated from the set, while a "tall" column would be added. Finally,Dt's constraint increasingly limits the set of possible agreements. When trust is not an issue, Dt is a relatively obliging negotiating partner: the fraction of possible alternatives that this group is willing to accept is clearly higher than that of any other group. But once the probability of a trust violation reaches 0.6, the fraction of alternatives that Dt will accept is particularly small. The model thus suggests that a critical factor driving Dt's highly publicized opposition to the canal is its strong belief that agreed upon restrictions on exports are unlikely to be honored in practice.

In addition to depicting the impact on the size of the PD set, Figure 2 illustrates that as mistrust increases, the PD set moves down and to the left; the acceptable policies are characterized by fewer total exports and a smaller share of those exports through the canal. The downward shift is driven primarily by the shift in Dt's constraint; the leftward shift by the shifts in Ag's, Ur's and Ev's

FIGURE 3. Expected export configurations for parameterization $\bar{\mathbf{z}}$



constraints. The shift toward lower exports is not surprising, but this figure tells only part of the story, i.e., what happens to the levels *of declared* water exports in the PD set. As mistrust increases, so does the probability that water exports will fill the canal to capacity. Hence the reduction in *expected actual* exports associated with alternatives in the PD set is less than the figure would suggest Indeed, expected actual exports could increase.

Figure 3 illustrates this point. It depicts how mistrust affects the mapping from negotiated policies to expected actual export configurations.[15] Each panel in Figure 3 is a contour plot: each solid line is a locus of policy vectors for which the expected level of actual exports (top row) or actual share through the canal (bottom row) is the labeled amount. Included as a reference, the solid area in each panel is the PD set corresponding to λ, i.e. the set $\mathbf{W}(\bar{\mathbf{z}};\lambda)$. With perfect trust, the contours for expected actual exports in the top row of Figure 3 are nearly vertical lines; however, each *declared* level implies a lower *expected actual* level because of the possibility of fish-mandated

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[15] Throughout this discussion of the mapping, we take expectations over only those states of the world for which a major levee collapse does *not* occur.

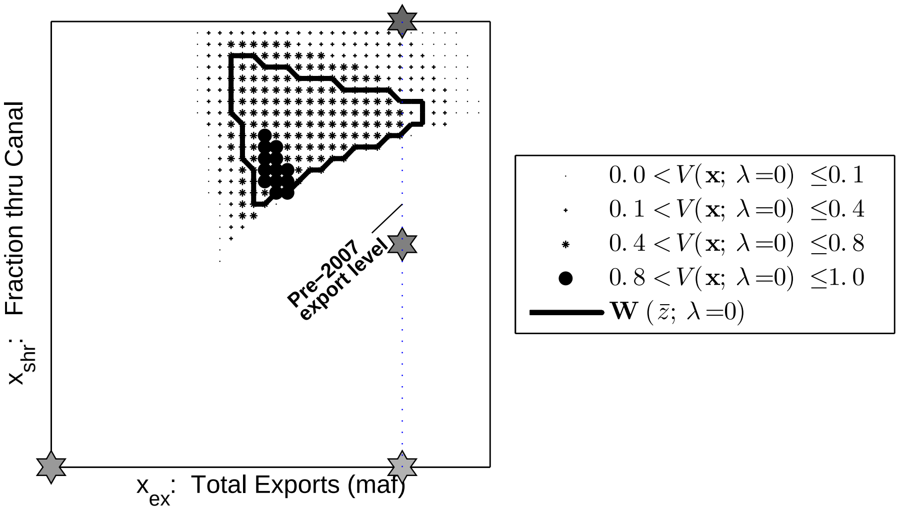
cutbacks. For any declared policy such that $x_{\text{shr}} > 0$ and $x_{\text{ex}} > 0$, the corresponding expected level of actual exports increases with mistrust; in the last column, expected actual exports are expected to be nearly half the pre-2007 level even when the declared export level is almost zero.

Now consider the second row of Figure 3. With perfect trust, the contours are perfectly horizontal and the declared and actual expected shares coincide. However, the actual share through the canal increases considerably as mistrust increases because any exports exceeding negotiated levels would flow through a canal. To see this, note that at low levels of declared total exports, very small amounts would flow through the Delta, whether or not commitments are honored; on the other hand, if water users succeed in lobbying regulators to increase actual exports, large quantities of water will flow through the originally nearly empty canal, dramatically increasing the actual share of total exports that flows through it.

4.2. **Probabilistic Pareto dominance.** The preceding subsection examined the properties of the model under one particular parameterization of modeling uncertainty. Many of these properties, however, are determined by the interplay among a large number of parameters. To illustrate, recall how in Figure 2 the size of the PD set increases monotonically with mistrust. Trends such as this one depend on interactions between components of modeling uncertainty. A natural next step, then, is to compile statistical information about the impact of mistrust based on a large sample of possible model parameterizations. Accordingly, this subsection summarizes the data generated by repeating the analysis in subsection 4.1 for 1,000 draws from the space of modeling uncertainty, $\mathbb{Z}$. We first assume perfect trust ($\lambda = 0$) and evaluate the probabilistic political viability function, $V(\cdot; \lambda = 0)$, at each element of the policy space, $\mathbb{X}$. We then repeat this process for the other three levels of mistrust.

4.2.1. *Perfect Trust.* Figure 4 partitions $\mathbb{X}$ into regions depending on the probability that each policy belongs to the PD set. A policy is termed *robustly politically viable* (RPV) if it Pareto dominates the default for at least 80% of the realizations of modeling uncertainty; such policies are marked in the figure with the largest solid circles. Policies that are politically viable for at least one parameterization are referred to as *possibly politically viable* (PPV). The PPV set includes all of the points identified with some marker in the figure. Finally, policies in the white (unmarked)

Figure 4. Probability of Pareto dominance with perfect trust



region are said to be *never politically viable* (NPV).[16] The solid line is the boundary of the PD set for the parameterization $\bar{\mathbf{z}}$. The figure is in some sense similar to Figure 1; both suggest that most of the policies that have some chance of emerging from the political process involve export levels less than pre-2007 levels, which are routed primarily but not exclusively through the canal. Yet Figure 4 contains far more information than Figure 1.

One critical difference between the two figures is the interpretation of the unmarked regions of the policy space. Policies in the unmarked region of Figure 1 are Pareto dominated by the default for the single parameterization $\bar{\mathbf{z}}$. By contrast, NPV (i.e., unmarked) policies in Figure 4 are Pareto dominated by the default for *all* realizations of modeling uncertainty in our sample. A striking property of the figure is that all four policies singled out by Lund *et al.* (2008) are NPV. In particular, *all* points on the graph's left edge (corresponding to ceasing all exports) and its bottom edge (corresponding to routing all exports through the Delta) are NPV. Lund *et al.* (2008) were similarly skeptical of all no-canal alternatives, noting that despite its environmental benefits, a policy of stopping all exports is simply too expensive for the state, while continuing to rely exclusively on through Delta exports carries unacceptable risks to both water supply reliability and the ecosystem. Moreover, our analysis suggests all points on the top edge of the graph (corresponding to pure canal alternatives) are *also* NPV. These alternatives are always vetoed by at least one stakeholder. If

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[16] Using the terminology defined in subsection 2.3, our vector of probability thresholds is given by $\rho = (0.0, 0.1, 0.4, 0.8)$.The RPV set corresponds to $\mathbb{C}_4^+$; the PPV set corresponds to $\mathbb{C}_1^+$, and the NPV set corresponds to $\mathbb{C}_1^-$.

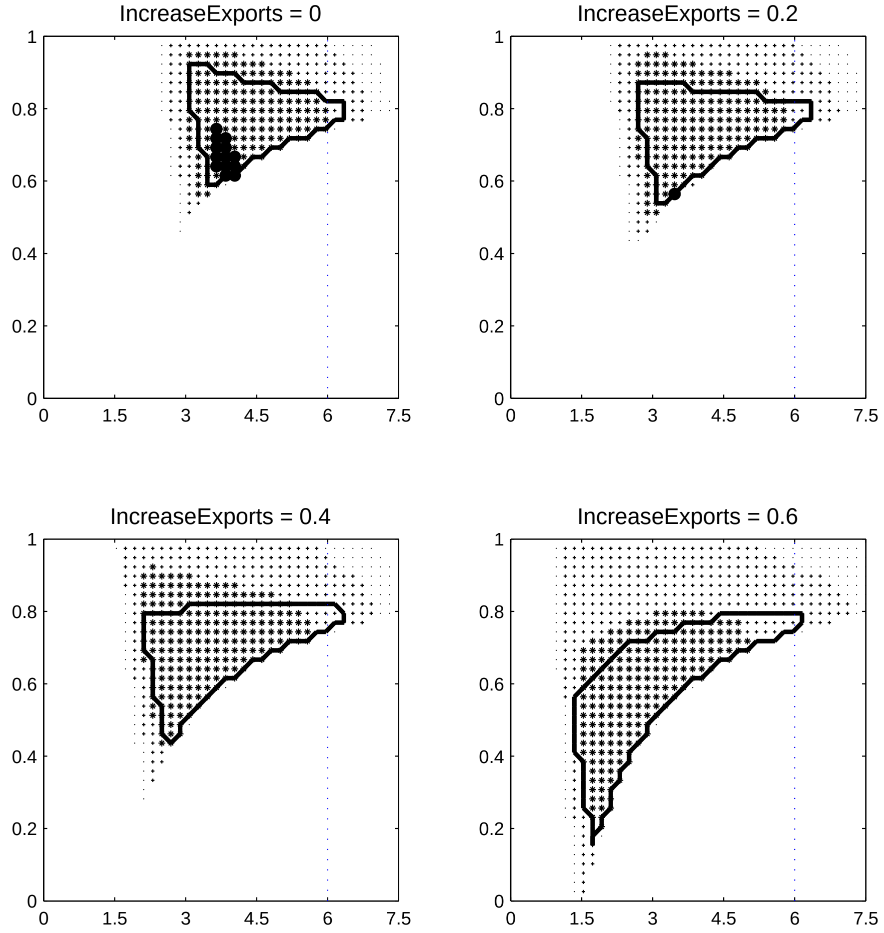
export levels are too low to justify the cost of construction, water users are unwilling to pay for a canal. On the other hand, if export levels are too high, Dt will veto any pure canal alternative because reduced Delta inflows cause two negative consequences: water quality in the Delta will decline relative to the default and expenditures on levee maintenance will remain at zero. Finally, our analysis suggests that a dual-conveyance alternative with pre-2007 exports evenly split between a canal and the Delta is NPV, although other dual-conveyance configurations are PPV.

The set of robustly politically viable policies in Figure 4 is considerably smaller than the shaded set $\mathbf{W}(\bar{\mathbf{z}};0)$ depicted in Figure 1, and bounded by the solid line in this figure. While just under 9% of the policy space belongs to $\mathbf{W}(\bar{\mathbf{z}};0)$, less than 1% of the policy space is robustly politically viable. Put another way, less than 10% of the policies inside the solid line are RPV, although almost all of them satisfy the Pareto criterion with probability at least 40%. There is no policy which Pareto dominates the default for more than 85% of the realizations of $\mathbf{z}$. These data illustrate the obvious point that inclusion in the PD set for the mean realization of modeling uncertainty is no guarantee of robust political viability.

4.2.2. *Impact of Mistrust.* The first panel of Figure 5 replicates Figure 4; the remaining panels show the impact of increasing mistrust. Legends for these figures are the same as for Figure 4. In each panel, we overlay for reference the boundaries of the shaded set $\mathbf{W}(\bar{\mathbf{z}};\lambda)$ in the corresponding panel of Figure 2. As mistrust increases, the set of PPV policies increases; this effect is driven primarily by slackenings in the participation constraints for Ag and Ur. As discussed in subsection 4.1.2, the more likely it is that the canal will be utilized to capacity, the more willing Ag and Ur will be to accept somewhat lower values of x_{ex} and x_{shr}. The size of this effect depends on how their utility functions are parameterized. On the other hand, the set of robustly politically viable policies shrinks dramatically, virtually disappearing even for $\lambda = 0.2$. The first effect is also apparent in Figure 2, but the latter effect contrasts with the increasing size of the PD sets in Figure 2.

Using modified box-and-whisker plots, Figure 6 demonstrates that the shrinking RPV sets are caused by increased variation in the size and location of the PD sets. It summarizes for different levels of mistrust the distribution of three measures of the PD set across modeling uncertainty: the size of the set and the locations of its horizontal and vertical midpoints. The latter two measures are, respectively, the means of the declared levels of exports and shares through the canal that

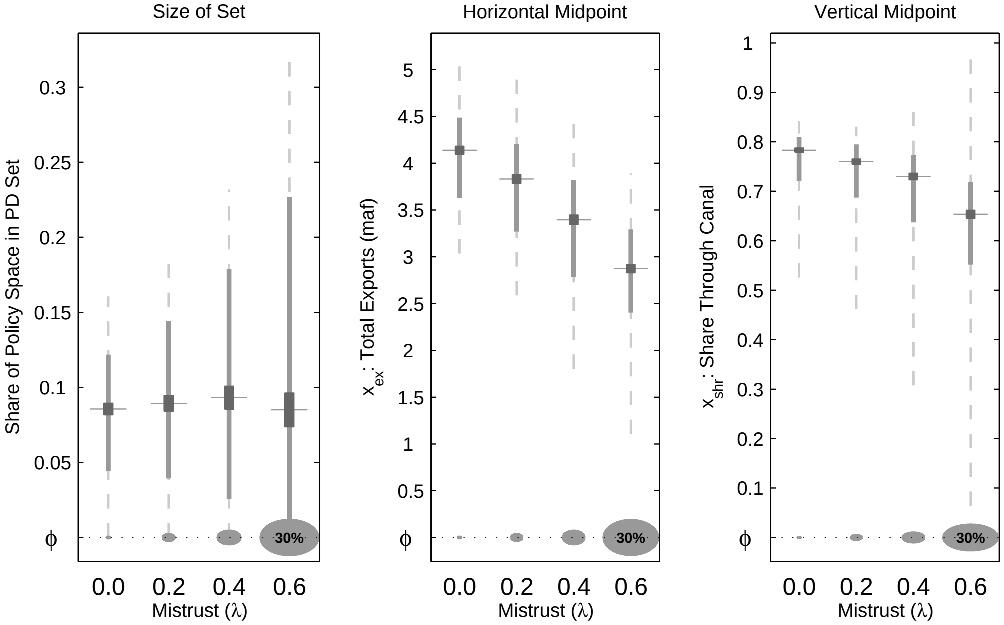
Figure 5. Impact of mistrust on the probability of Pareto dominance



satisfy the Pareto criterion for each vector $\mathbf{z}$. In each panel, for each value of λ the solid horizontal line indicates the median value across our sample from $\mathbb{Z}$ for the measure being plotted. The thick, squat rectangles denote 95% confidence intervals for the population medians. The thin, elongated rectangles denote the interquartile ranges of the sample data, and the whiskers (thin, dashed lines) indicate the support of the sample data. At the bottom of each panel, the filled ovals corresponding to each λ indicate the probability that the PD set is empty; the area of the oval is proportional to the percentage of parameterizations for which the PD sets are empty, given that level of mistrust.

As the left panel of Figure 6 illustrates, the median size of the Pareto set $\mathbf{W}(\cdot;\lambda)$ varies insignificantly with λ, while both the inter-quartile range and the support of the entire sample increase dramatically. Obviously, the size variable is censored at zero, so the support cannot continue to move down in later panels. Instead, there is a striking increase in the percentage of parameterizations for which the PD set is empty. These fractions are negligible for low levels of λ, but increase dramatically for

FIGURE 6. Distribution of set measures across modeling uncertainty



higher levels, reaching 30% when $\lambda = 0.6$. Because the PD set is empty for such a high percentage of parameterizations at this level of mistrust, a policy would fail the RPV criterion even if it belonged to the PD set for *every* realization of modeling uncertainty. To summarize, the data strongly indicate that the increased variation in the size of the PD set contributes significantly to the evaporation of the RPV set seen in Figure 5.

The remaining two panels in Figure 6 confirm that the increased variation in the location of the PD sets also plays a role. The trends in each locational median are large, negative and significant, reflecting the shift down and to the left of the PPV sets in Figure 5; however, these changes do not influence the size of the PD set. Moreover, in the middle panel, we see that mistrust has little impact on the horizontal dispersion of the PD sets; the lengths of the interquartile ranges and the sample data support remain more or less constant as mistrust increases. However, in the right panel, we see that the vertical dispersion of the PD sets increases with mistrust, especially at high levels. This increasing vertical dispersion also plays a role in reducing the size of the RPV set. Because the PD sets are located at increasingly varied vertical positions, it becomes harder for a given policy to be in the PD set for a large number of draws.

5. CONCLUSIONS

In this paper we develop a new methodology for predictive political economy modeling. The approach is designed to analyze complex, one-of-a-kind, real-world political negotiations. Our ultimate goal is to make assessments about which policy outcomes might emerge from the political process. In this context, economists face uncertainty about many critical components of the analysis, and have no clear basis for selecting one particular model of the decision-making process. Our response to this challenge is to analyze a large, parameterized family of models, and seek to identify outcomes which are robustly political viable over a wide variety of possible specifications. Lacking sufficient knowledge to specify which game-form best captures the real-world political process we are modeling, we adopt a minimal predictive criterion—Pareto dominance—rather than impose any one specific game-theoretic solution concept.

We illustrate our approach by applying it to the current debate regarding the future of California's Sacramento-San Joaquin Delta. This application is particularly suited to our mode of analysis. It is characterized by a variety of the problems that plague political economists, including public goods, missing markets, and tradeoffs between noncomparable objectives. Commentators agree that a political compromise cannot be implemented without the approval of a broad spectrum of stakeholders; moreover, it is possible to conceive of a range of possible ways that the future may unfold if a compromise cannot be reached. For these reasons, Pareto dominance is a well-defined concept, and is indeed a necessary condition for a solution to the problem. Finally, a small number of potential solutions that have been identified as focal points of the policy debate. It is instructive to use our methodology to assess the viability of these candidate solutions.

Our specific results regarding the policy debate are consistent with the conventional wisdom. Many experts agree that there is no hope that a consensus solution can be reached. Our analysis strongly supports this wisdom: none of the most widely discussed options Pareto dominate the default for any of the model specifications considered. Moreover, only a very small number of policy options meet the criterion of robust political viability. In contrast to the conventional wisdom, the analysis identifies a broad range of options that do meet the standard for political viability for at least a minority of the model specifications considered. Under the conventional wisdom, an important inhibitor of a consensus solution is stakeholders' mutual mistrust. Our analysis illustrates that mistrust dramatically reduces the set of robustly politically viable policy options, although it also increases the set of options which are viable with low probability. In particular, the impact of mistrust is to reduce the political viability of solutions involving high levels of water exports, transported primarily through a new conveyance that bypasses the Delta. Thus, our analysis highlights the importance of designing Delta governance institutions, which could potentially improve welfare by reducing or limiting the extent of mistrust.

Our analysis also contributes to the broader political economy methodology literature. Researchers in a wide range of fields are concerned with how to address Knightian uncertainty. In contexts characterized by this kind of uncertainty, there is little benefit to be gained from seeking to identify the "right" model or the "right" solution. As we illustrate, it is potentially more productive to identify a reasonable family of models and a set of candidate solutions that are robust with respect to a wide range of model specifications. Moreover, our approach illustrates the usefulness of complex, yet still stylized, computable political economy models by demonstrating that they can aid in identifying which model components are critical drivers of the model's results, and which ones leave its conclusions relatively intact.

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