

## Dividing the waters: An empirical analysis of interstate compact allocation of transboundary rivers

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Received 8 July 2010; revised 14 February 2011; accepted 18 March 2011; published 15 June 2011.

[1] Legal scholars and jurists have identified several criteria (e.g., hydrology, climate, population, and historical water use) to guide equitable allocation of transboundary rivers among riparian claimants. Are these criteria used in practice, such that a quantitative pattern emerges from actual water-sharing agreements regarding factors affecting allocations? To address this, we study interstate compacts, the principal mechanism for allocating the waters of transboundary rivers within the United States. We develop a georeferenced data set and construct variables representing conditions in state-based watersheds of 14 rivers at the times of compact ratification. A state's water allocation share of a compact serves as the dependent variable, and a set of explanatory variables is derived from legal and political theories. We estimate allocation shares using both ordinary least squares (OLS) and bootstrap regressions, and we apply two alternative specifications of the factors affecting compact allocations, one with and one without political variables. Estimated coefficients on variables for land area, population, prior water use, riparian position, and Congressional committee chair are statistically significant in the OLS regressions. The preferred OLS specification, which includes political variables, provides a good fit ( $R^2 = 0.84$ ). We also find that OLS and bootstrap regressions have a similar ability to predict state allocation shares. We discuss how the results could be used as a reference point in negotiations over new compacts or international river treaties and as a basis to identify existing compacts with statistical outliers.

**Citation:** Katz, D. L., and M. R. Moore (2011), Dividing the waters: An empirical analysis of interstate compact allocation of transboundary rivers, *Water Resour. Res.*, 47, W06513, doi:10.1029/2010WR009736.

### 1. Introduction

[2] Water in rivers is a classic common pool resource. Allocation of river water and other shared water resources is an increasingly important geopolitical issue as populations grow, lifestyles change, and the planet's climate changes. Over 260 of the world's rivers cross national boundaries, and over the past 2 centuries, over 450 international water agreements have been signed in an attempt to manage these shared resources, including over 100 that deal with quantitative allocations of water [Wolf, 1999; Transboundary Freshwater Dispute Database, <http://www.transboundarywaters.orst.edu/database>, accessed 26 January 2010]. In the United States, states have aggressively contested water resources from rivers that cross or form state boundaries ("transboundary" rivers) for over a century. Interstate compacts, negotiated agreements between or among the competing states, are the primary mechanism to resolve these conflicts. To date, over 50 water-related compacts have been negotiated, with over 20 that primarily address issues of water allocation, especially in the arid West [Sherk, 2000].

[3] International bodies such as the International Law Association (ILA) and the United Nations have proposed criteria for consideration in transboundary water allocation [ILA, 1967; United Nations General Assembly, 1997]. These criteria include factors such as hydrology, climate, population, and historical water use. In response to disputes between states over rights to transboundary river waters, the U.S. Supreme Court defined a similar set of factors to consider when determining interstate water allocations [State of Nebraska versus State of Wyoming, 1945; Sherk, 2000, 2008]. While both international law and U.S. judicial rulings seek to achieve an equitable allocation of water, neither proposed any specific weights or numerical formulas to guide negotiators in applying their respective allocative criteria. The U.S. Supreme Court, in fact, explicitly refused to devise a quantitative prescription based on these factors, stating that each situation should be evaluated on its own merits such that "the effort always is to secure an equitable apportionment without quibbling over formulas" [State of New Jersey versus State of New York, 1931].

[4] While much has been written about criteria for transboundary water allocation (see section 2), most of the previous research has involved qualitative, normative assessment of these criteria. Relatively little work has been empirical, and even less has analyzed allocative criteria in a quantitative manner. This study seeks to address this gap in the literature by providing a positive statistical analysis of U.S. interstate compacts. We address the question of whether an allocation formula is implicit in actual compacts

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by evaluating whether or not a quantitative pattern emerges regarding the factors that affect state-level water allocations of rivers.

[5] To undertake this study, we develop a unique georeferenced data set with 33 state-level observations over 14 interstate river compacts. Data reflect the primary criteria outlined in international and U.S. legal theory, including state- and compact-based water allocation shares, land area, average virgin water supply, precompact water use, average temperature, population, and income. Variables are constructed from the data to represent conditions found in state-based watersheds of the rivers at the time of (or near the time of) compact passage. To address the possible influence of political factors not included in equitable allocation criteria, we also include variables covering riparian position on the river, state population, and representation on Congressional committees that dealt with water resource management. Two main statistical analyses are undertaken. First, we estimate ordinary least squares (OLS) regressions to assess the statistical performance of the explanatory variables as determinants of state-level water allocations of interstate rivers. Second, we estimate bootstrap regressions as a robustness check for the OLS regression results. The bootstrapping technique accounts for lack of independence of values both in the dependent variable (water allocation share) and in some of the explanatory variables, which could introduce bias in the OLS regressions. By running repeated regressions using sampling with replacement, the bootstrap regressions also compensate for limitations in OLS due to the small number of observations in the data set.

[6] The study of interstate water compacts addresses the need for research on U.S. water institutions [*National Research Council*, 2001]. Specifically, our research on governance of common pool rivers in a comparative mode across compacts relates to two of the National Research Council's recommendations: "understand issues related to the governance of water where it has common pool and public good attributes" and "conduct comparative studies of water laws and institutions" [*National Research Council*, 2001, p. 4]. As such, the analysis combines priority research and practical policy relevance.

[7] In terms of practical relevance, this study contributes to a knowledge base for understanding conflicts on two types of interstate rivers, those with compacts and those without compacts. In the western United States, existing compacts are being strained by population growth and environmental demands. While interstate water markets may resolve some of these tensions, legal scholars agree that compact allocations are likely to be revisited, and revised, to address contemporary basin-wide issues [*Sax et al.*, 2000; *Tarlock*, 2001; *Sherk*, 2005; *Muys et al.*, 2007]. Indeed, precedent exists for compact revision. The Bear River Compact and Costilla Creek Compact were amended subsequent to their original signing, and *Hundley* [2009] reports on a 2007 amendment to the Colorado River Compact when assessing tensions among signatory states to that compact.

[8] In the eastern United States, water scarcity is emerging as a problem in formerly water-rich regions because of population growth and economic development. To resolve transboundary water conflicts, these regions will require better understanding of interstate allocative criteria and negotiation principles [*Abrams*, 2002]. Evidence for the need of such can be seen in the unsuccessful attempts by

states to develop mutually acceptable water allocation formulas as part of compacts over the Apalachicola-Chattahoochee-Flint and the Alabama-Coosa-Tallapoosa river basins and in the dispute between Maryland and Virginia over use of the Potomac River, which the U.S. Supreme Court eventually decided in 2003.

[9] This study also informs the setting of transboundary international rivers and other shared water resources, where conflicts continue to arise despite numerous treaties and a growing body of international water law. (For recent reviews of transboundary water conflicts, negotiations, and management, see *Wolf* [2007], *Dinar* [2008], and *Zawahri and Gerlak* [2009].) In lieu of established norms, factors other than equitable apportionment criteria, factors such as regional balance of power, may dominate international agreements to divide waters [*Zeitoun and Warner*, 2006; *Dinar*, 2009]. The scope of negotiated compact settlements is narrower in the United States, however, since states retain the option to appeal to the U.S. Supreme Court's equitable apportionment process or to a Congressional apportionment process, rather than the compact process. States do not have a guarantee of access to such alternative processes; the Court is not obligated to accept a request for equitable apportionment and, in fact, has expressed its reluctance to do so [*Sherk*, 2005], and Congress has intervened in interstate allocations only on rare occasion. However, this potential would likely increase if the Supreme Court or Congress were to determine that one or more negotiating partners was not negotiating in good faith on the basis of equitable apportionment criteria.

[10] Because of the potential availability of these two alternatives to compacts guided by principles of equitable apportionment, such principles may be adhered to more closely in compact allocations than in international agreements. Thus, compact-based water allocation provides an important model for equitable sharing that may be informative for negotiations of international transboundary river negotiations, where alternative mechanisms to determine allocations are not available, as well. In this regard, our study provides a positive perspective on the normative question of equitable interstate water allocation.

[11] This paper continues by developing the institutional context for transboundary river allocation and describing related research in section 2. Section 3 describes the data on interstate water compacts, the variables formed from the data, and the statistical methods applied in the study. Section 4 reports the results of the statistical analyses. Section 5 draws conclusions and offers potential directions for future research.

## 2. Background and Related Research

### 2.1. Background and Study Rationale

[12] The International Law Association's Helsinki Rules on the Uses of the Waters of International Rivers prescribes a list of 11 factors to be considered in any transboundary water allocation decision [*ILA*, 1967]. These factors are geography, hydrology, climate, past utilization, economic and social needs, populations dependent on waters, comparative costs of alternative means of satisfying the economic and social needs, availability of other resources, avoidance of unnecessary waste in utilization, practicability of compensation to one or more of the cobasin states, and

the degree to which the needs of a basin state may be satisfied, without causing substantial injury to a cobasin state. The Helsinki Rules marked the first general attempt to formalize standard factors to consider for “reasonable and equitable” water allocation in an international context. The Helsinki Rules remained a set of broad recommendations, never achieving the status of an international agreement. Thus, perhaps not surprisingly, they were never applied directly to international treaties or other water allocation decisions [Wolf, 1999]. Their importance, instead, lies in placing the issue of standard criteria for transboundary water allocation on the international agenda and in serving as a basis for subsequent work in this field.

[13] Some 30 years after the Helsinki Rules, the international community reached broad agreement on principles for equitable sharing of transboundary waters in the United Nations’ (UN) Convention on the Law of the Non-Navigational Uses of International Watercourses, which was adopted by the UN General Assembly (21 May 1997). This work was based largely on a consolidated version of the Helsinki Rules, although it was expanded to include some factors not considered earlier, such as ecological concerns. Despite broad endorsement (the 1997 General Assembly vote on the convention produced 103 in favor, 3 opposed, and 27 abstentions), the convention remains controversial. It has yet to come into force. As of early 2011, only 21 nations had ratified, accepted, acceded, or approved the agreement.

[14] One reason that the convention has yet to be widely adopted and remains controversial is the lack of means to prioritize between its competing allocation principles and criteria. Both the Helsinki Rules and the UN convention were normative in nature, yet both explicitly avoided placing weights on the factors they identified, leaving that to the policymakers and negotiators of specific agreements. The 1997 UN convention, for instance, provided the vague directive that “the weight to be given to each factor is to be determined by its importance [emphasis added]” and that “all relevant factors are to be considered together.” The Berlin Rules on Water Resources, an attempt by the ILA to update the Helsinki Rules, similarly stated that “the weight of each factor is to be determined by its importance in comparison with other relevant factors. In determining what is reasonable and equitable use, all relevant factors are to be considered together and a conclusion reached on the basis of the whole” [ILA, 2004, p. 21].

[15] In the United States, three approaches are available for resolving water disputes between or among states: interstate compacts, apportionment by the U.S. Supreme Court, and apportionment by the U.S. Congress [Sax et al., 2000]. Compacts have the status of federal law upon ratification of the U.S. Congress. If states cannot agree on a compact, they can appeal to the U.S. Supreme Court to issue an equitable apportionment decree that establishes state-level allocations. Three such decrees are in force; however, the Court has indicated a preference for states to resolve water disputes via compacts [Muys et al., 2007]. As noted in section 1, although the Court defined criteria for guiding allocations, U.S. legal doctrine also provides little direction on how to prioritize among competing factors. The option of Congressional apportionment flows from the power to regulate interstate commerce. The U.S. Congress has acted only twice to apportion rivers. *Sherk* [2005] highlights the advantages of Congressional apportionment in light of com-

plications created by federal laws and regulations applicable to interstate water resources.

[16] In the absence of international institutions to effect equitable water allocation, factors other than the equitable apportionment criteria, such as regional balance of power, may dominate international allocation agreements [e.g., *Conca et al.*, 2006; *Zeitoun and Warner*, 2006; *Wolf*, 2007]. In the case of U.S. compacts, however, one might expect recommended factors for equitable apportionment to play a prominent role in allocations due to the U.S. Supreme Court serving as a potential arbiter of last resort. Through analysis of U.S. compact allocations, we thus also seek to provide insight for the context of international water allocation.

## 2.2. Related Research

[17] Prior research on allocation of transboundary river water has been conducted in several academic fields, including law, economics, political science, geography, and history. Much of the work on allocative criteria, especially in the legal field, is normative in nature. Most of the empirical studies are qualitative case studies. While useful for hypothesis development, case study approaches, especially qualitative case studies based on individual basins, can be of limited value in terms of comparative analysis and testing of theories [George and Bennett, 2005; Dinar, 2008].

[18] Several authors have summarized legal issues associated with interstate water allocation in the United States. The work by *Muys* [1971] is the most comprehensive legal analysis of interstate compacts, and *Sherk* [2000] presents an updated study of the same nature. Summary treatments of the topic are covered in legal texts on U.S. water law [e.g., *Grant*, 1996; *Sax et al.*, 2000; *Tarlock*, 1991]. *Muys et al.* [2007] describe a recent effort by experts to devise an “ideal” interstate water compact. *Mandarano et al.* [2008] present a qualitative comparative analysis of alternative interstate water management institutions, including compacts. In addition, many historical narratives describe the development of individual compacts or adjudications; some of these provide commentary on the motivations of negotiators and their individual priorities and strategies [e.g., *McCormick*, 1994; *Hall*, 2002; Z. L. McCormick, Oklahoma State University, The use of interstate compacts to resolve transboundary water allocation issues, unpublished manuscript, 1994]. This literature, however, provides little on which to base comparative assessments.

[19] Several studies use economic theory and reasoning to examine interstate water allocation. *Bennett et al.* [2000] apply economic theory to the analysis of interstate compacts. They derive conditions for the “universally optimal” compact. Using this as a benchmark, they compare two commonly used compact allocation methods, fixed quantities and fixed percentages. Several other studies assess the economics of interstate water allocation. These studies take compact-based state-level allocations as given without assessing the process that created the allocations. The majority of these studies use theoretical or empirical models for three related purposes: to identify optimal allocations, to demonstrate inefficiencies in current allocation mechanisms, and to recommend water markets as a decentralized mechanism to induce efficiency [e.g., *Burness and Quirk*, 1979, 1980; *Howe*, 1985; *Booker and Young*, 1994]. *Howe et al.* [1986] present six criteria for evaluating methods of

allocation, including flexibility, reliability, and predictability. However, these are structural guidelines, not allocative criteria; that is, they do not represent the factors that legal experts define as essential for allocating water from transboundary rivers.

[20] A few studies conduct statistical analysis of compacts and compact implementation. *Bennett and Howe* [1998] develop a model of compact enforcement and assess incentives for noncompliance. They conduct a comparative assessment of the South Platte River and the La Plata River and find empirical evidence that both the frequency and level of noncompliance tend to be larger under a fixed allocation rule relative to a percentage allocation rule. *Schlager and Heikkila* [2009] compile data from a study of 14 interstate river compacts to assess the view of compacts as rigid, inflexible governance structures that cannot respond to water conflicts. They find that compact governments and related water agencies are capable of responding to conflicts, and they further identify the types of conflict solutions adopted. Our research differs from these two studies by focusing on compact formation, not compact implementation.

[21] In the literature on international water allocation, our research is most similar to that by *Dinar* [2008], who seeks to find general patterns in treaties: what issues are addressed, how the issues are resolved (in terms of consequences to different nation-states), and what factors explain the features of a resolution? Similar to our study, water allocation is addressed as a treaty issue, and several explanatory variables are created, such as riparian location on the watercourse and relative economic output of the nation-states. The treaties do not provide enough data to support regression methods of statistical analysis, so results from *Dinar's* study and our study are not directly comparable.

[22] Other research on international water allocation consists primarily of historical case studies of individual river basins or compilations of such studies [*Dinar and Dinar*, 2003; *Zawahri and Gerlak*, 2009]. Few studies, however, address the role of allocative criteria in any comprehensive manner. The study by *Wolf* [1999] is an exception, giving a broad historical overview of the development of international allocative criteria. *Wolf's* treatment, however, does not provide a quantitative analysis of actual implementation of these criteria. In fact, with the exception of work on conflict over shared water resources, relatively little quantitative empirical work exists covering international water allocation.

[23] Several studies develop theoretical analyses of proposed normative criteria for international river allocation [e.g., *van der Zaag*, 2002]. Like their counterparts for interstate rivers in the United States, these studies generally apply an economic efficiency criterion and stress the importance of considering the economic value of water in allocation decisions. Other studies emphasize the potential for water markets to play a useful role in resolving international water disputes [e.g., *Dinar and Wolf*, 1994; *Easter et al.*, 1999; *Perry et al.*, 1997; *World Water Commission*, 2000; *Fisher and Huber-Lee*, 2005]. Finally, a few theoretical studies address general allocation issues from a game theoretic perspective [e.g., *Rogers*, 1997; *Ambec and Sprumont*, 2002; *Just and Netanyahu*, 2004; *Carraro et al.*, 2005; *Wu and Whittington*, 2006; *Eleftheriadou and Mylopoulos*, 2008]. *Dinar et al.* [2007] develop an integrated approach to the

study of conflict over transboundary international water resources, applying theory from international relations, economics, and international law, as well as the quantitative tools of river basin modeling and game theory.

[24] In terms of empirical assessments of international transboundary allocations, *Hamner and Wolf* [1998] present summary data, although no statistical analysis, of international water agreements in the Transboundary Freshwater Dispute Database. While some allocation characteristics are mentioned, allocative criteria were not a focus of this study. *Conca et al.* [2006, p. 263] conduct a principled content analysis of international river agreements, seeking to find out “whether governments are converging on common principles for governing shared river basins and whether the effort to create a global normative framework for shared rivers has shaped the principled content of basin-level international accords.” Though this study is a positive statistical analysis, rather than addressing allocation principles, it focuses on the extent to which treaties include common institutional and governance mechanisms, such as provision for information exchange, prior notification, or dispute resolution. *Drieschova et al.* [2008] also undertake a quantitative analysis of governance mechanisms in international river treaties, but they focus on whether or not agreements contain rigid or flexible allocation mechanisms and not on the allocative criteria themselves.

[25] Two empirical studies seek to identify factors that lead to the formation of international water treaties [*Espey and Towfique*, 2004; *Song and Whittington*, 2004]. Both articles conduct logit analyses of the probability of treaty formation between countries, using somewhat different vectors of social and geographic characteristics as explanatory variables. Neither article, however, attempts to identify the factors used to establish treaty-based water allocations.

[26] In sum, the majority of the literature on transboundary water allocation develops qualitative legal analysis, theoretical economic analysis, or normative policy analysis. Empirical analyses of interstate water compacts largely examine compact implementation, not compact formation. Empirical analyses of international river treaties largely focus on factors leading to the formation of international agreements, rather than on factors affecting the division of waters in the treaties.

### 3. Methodology

#### 3.1. Preliminary Motivation of the Model

[27] This study seeks to understand the factors that affect state-based water allocations under interstate compacts. In order to compare across river basins of different sizes, the dependent variable, AllocationShare, is a state's share of the total water allocated by a compact. We develop a set of explanatory variables that include many of the normative criteria for fair allocation, as posited by legal studies and judicial rulings, as well as some political factors posited by political and international relations theory. We included variables representing all legal criteria for which we could obtain data. Some criteria, e.g., “avoidance of unnecessary waste in utilization of waters of the basin” or “practicability of compensation to one or more of the co-basin States” (Helsinki Rules), were not included in the analysis. Proxy variables were utilized for some criteria that were vaguely

**Table 1.** Compacts in Data Set

Compact	Signatory States	Year Signed
Arkansas River Compact	Colorado, Kansas	1948
Bear River Compact	Idaho, Utah, Wyoming	1958 (amended 1980)
Belle Fourche River Compact	South Dakota, Wyoming	1943
Big Blue River Compact	Kansas, Nebraska	1971
Caddo Lake Compact	Louisiana, Texas	1979
Cheyenne River Compact	South Dakota, Wyoming	1950 <sup>a</sup>
Colorado River Compact <sup>b</sup>	Arizona, California, Colorado, Nevada, New Mexico, Utah, Wyoming	1922
Costilla Creek Compact	Colorado, New Mexico	1945 (amended 1963)
La Plata River Compact	Colorado, New Mexico	1922
Republican River Compact	Colorado, Kansas, Nebraska	1942
Sabine River Compact	Louisiana, Texas	1953
Snake River Compact	Idaho, Wyoming	1949
Upper Colorado River Compact	Arizona, Colorado, New Mexico, Utah, Wyoming	1948
Yellowstone River Compact	Montana, Wyoming, North Dakota <sup>c</sup>	1950

<sup>a</sup>The Cheyenne River Compact never went into effect. It was included in the study because the original draft was agreed upon by both states but rejected by Congress because of Native American water rights issues. Subsequent attempts at a compact were unsuccessful.

<sup>b</sup>The Colorado River Compact was signed by the seven states indicated but allocated water between the upper and lower basins, rather than by state. For the purposes of this study, each basin was treated as a unit of analysis.

<sup>c</sup>The Yellowstone River Compact does not allocate water directly to North Dakota, and as such, this study only evaluates the allocation between Montana and Wyoming.

defined, e.g., “climate” and “economic and social needs” (Helsinki Rules).

[28] We estimate regression equations of the general form

$$\text{AllocationShare}_{sc} = \alpha + \mathbf{X}_{sc}\beta + u_{sc}, \quad (1)$$

where  $\text{AllocationShare}_{sc}$  is the share of total water allocated to state  $s$  in compact  $c$ ,  $\mathbf{X}_{sc}$  is a vector of explanatory variables,  $\alpha$  and  $\beta$  are parameters to be estimated, and  $u_{sc}$  is an error term. With this simple motivation, we turn to describing the data and variables.

### 3.2. Data and Variables

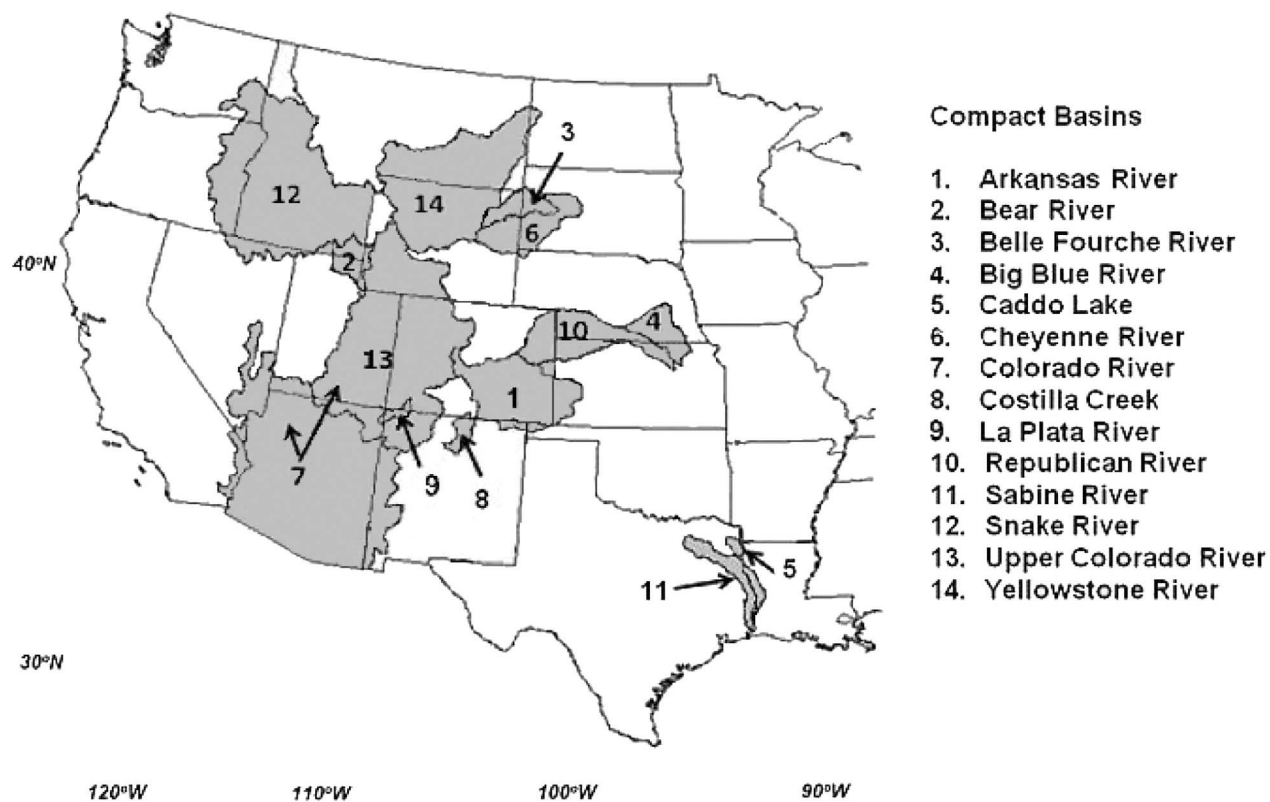
[29] The dependent variable,  $\text{AllocationShare}_{sc}$ , is a state’s water allocation share under a compact. Data on allocations were obtained directly from compact texts. Of over 20 compacts that address quantitative allocations, we succeeded in identifying or calculating 33 state shares of water allocated under 14 compacts. While some compacts explicitly write allocation in terms of percentage of flows (e.g., the Colorado Compact and the Belle Fourche Compact), others are less straightforward, indicating fixed amounts from various tributaries or amounts contingent on time period, flow conditions, storage levels, and so on (e.g., Upper Colorado Compact and the Republican River Compact). In cases in which shares were calculated, they were done so on the basis of historical average streamflow data [*U.S. Geological Survey*, 1995]. The Yellowstone River Compact provides an illustration. The compact text allocates Montana and Wyoming shares of four tributaries of the Yellowstone. (As the Yellowstone River Compact does not allocate water directly to North Dakota, we only evaluate the allocation between Montana and Wyoming.) We took average streamflows for the tributaries at stream gauges for all years prior to (and including) the year of compact signing, 1950. The shares were multiplied by the streamflows to derive tributary allocations to each state. The tributary allocations were summed to obtain an aggregate measure of allocations and, finally, allocation shares: 68% to Montana and 32% to Wyoming.

[30] The 14 compacts included in this study are listed in Table 1, along with the signatory states and the year of

compact signing. Figure 1 displays a map of the basins covered by these compacts.

[31] We develop 11 explanatory variables, all of which are categorized by state and compact and thus carry the  $sc$  subscript. Eight variables represent allocative criteria defined by U.S. or international legal doctrine. They include (1)  $\text{LandShare}_{sc}$ , the share of total land area in a river basin, among compact signatories, (2)  $\text{RelativePrecip}_{sc}$ , the relative precipitation within a basin (a proxy for relative contribution to natural flow), (3)  $\text{NonCompactPrecipShare}_{sc}$ , the share of rainfall outside of a basin (a proxy for available alternative sources of water in a state), (4)  $\text{MeanTemperature}_{sc}$ , the mean temperature for counties within a basin during the irrigation season, April–September, (5)  $\text{PopulationShare}_{sc}$ , the share of population in counties within a basin, (6)  $\text{PopulationGrowth}_{sc}$ , the growth rate of population in counties within the basin for the 20 year period covering the decennial census in the decade before and after the census closest to compact signing (a proxy for anticipated future needs), (7)  $\text{RelativeIncome}_{sc}$ , a relative measure of per capita income in counties within the basin (a proxy for economic need and/or economic power), and (8)  $\text{PriorWaterShare}_{sc}$ , a measure of historical water use for irrigation in counties prior to compact signing.

[32] Political variables may have affected compact allocations even though the compact process is intended to achieve equitable allocation. For instance, water negotiation theory stresses the geographical advantage of upstream nations [e.g., *Frey and Naff*, 1985; *Wolf*, 2007; *Dinar*, 2008] and the advantage that politically stronger parties may have because of their ability to impose punitive measures on negotiating partners via issue linkage in forums outside of water negotiations [e.g., *Zeitoun and Warner*, 2006; *Dinar*, 2008, 2009; *Daoudy*, 2009; *Zawahri and Gerlak*, 2009]. Riparian position may also imply specific legal obligations or limitations on usage. For instance, both U.S. and international law often carry provisions requiring states not to cause significant harm (e.g., UN Convention on the Law of the Non-Navigational Uses of International Watercourses, Article 7), an obligation that primarily affects upstream or border riparians. Last, research in U.S. political economy emphasizes the ability of Congressional committee chairs to



**Figure 1.** Map of compact basins included in this study.

influence outcomes related to their oversight functions [Weingast and Moran, 1983]. We therefore include three additional explanatory variables: (1) *RiparianPosition<sub>sc</sub>*, a binary variable indicating whether the state was the most upstream state in the compact, (2) *StatePopulation<sub>sc</sub>*, the share of total population of basin states within a compact (a proxy for political power), and (3) *CommitteeChair<sub>sc</sub>*, a binary variable indicating whether a state had a representative who chaired a Congressional committee with jurisdiction over interstate river compacts in the Congressional session during or prior to compact signing.

[33] The raw data for many of the explanatory variables are county-level data, for example, county-level data on income or population. For the variables based on these data, counties were included if some part of the county fell within

the river basin boundary. The county-level data are typically aggregated on a “river basin” basis within the state, not on an “entire state” basis. That is, the data are summed over counties in the river basin within each state. Last, several of the variables are constructed as a share (percentage), with the numerator a value for a particular state and the denominator a summed value over all states in the compact. In terms of time frame, the data sources represent the time period at or near the time of compact signing, unless otherwise indicated.

[34] Here we briefly describe the explanatory variables and underlying data sources. Table 2 provides summary statistics for the variables. Appendix A provides a complete description of data sources and methods of variable construction.

**Table 2.** Summary Statistics of Variables<sup>a</sup>

Variable	Observations	Mean	Median	SD	Minimum	Maximum
AllocationShare	33	0.424	0.5	0.258	0.005	0.960
LandShare	33	0.424	0.411	0.261	0.046	0.954
RelativePrecipitation	33	0.975	0.989	0.238	0.325	1.566
NonCompactPrecipShare	33	0.424	0.452	0.167	0.114	0.798
MeanTemperature	33	4.191	3.783	1.481	1.760	7.430
PopulationShare	33	0.424	0.404	0.251	0.065	0.917
PopulationGrowth	33	1.299	1.301	0.324	0.659	2.141
RelativeIncome	33	0.991	0.993	0.179	0.536	1.578
PriorWaterShare	33	0.424	0.369	0.347	0.002	0.982
RiparianPosition	33	0.394	0	0.496	0	1
StatePopulationShare	33	0.424	0.352	0.200	0.078	0.772
CommitteeChair	33	0.121	0	0.331	0	1

<sup>a</sup>The mean of all share variables equals 0.424, as follows. Shares sum to 1 within a compact, there are 14 compacts, and 14 divided by 33 observations equals 0.424.

[35] LandShare is a share variable ranging from 0.01 to 0.99 for each state and summing to 1.00 for each compact. River basin area was calculated using geographical information system (GIS) transects, with data from U.S. Geological Survey (USGS) watersheds, state boundaries, and county boundaries data layers.

[36] RelativePrecip is a measure relative to the basin mean, which is normalized to 1.00. Precipitation data were obtained from the USGS average annual precipitation data layer for the years 1961–1990. The data were weighted by land area when constructing the variable.

[37] NonCompactPrecipShare is a share variable ranging from 0.01 to 0.99 for each state and summing to 1.00 for each compact. Precipitation data were obtained from the USGS average annual precipitation data layer for the years 1961–1990. The data were weighted by land area when constructing the variable.

[38] MeanTemperature is based on categorical data indicating average temperature ranges on a scale from 1 to 9. Temperature data were obtained from NOAA's National Climatic Data Center (NCDC) climate maps for 1971–2000. Data for the variable were weighted by land area.

[39] PopulationShare is a share variable ranging from 0.01 to 0.99 for each state and summing to 1.00 for each compact. County and state population data were obtained from U.S. Census Bureau data for the census year closest to the year in which the compact was signed.

[40] PopulationGrowth is given in percent growth rate divided by 100. Population data sources are as for PopulationShare.

[41] RelativeIncome is a measure relative to the basin mean, which is normalized to 1.00. County and state income data were obtained from U.S. Census Bureau data for the census year closest to the year in which the compact was signed. County-level income data were available only for the years 1959, 1969, 1979, and so. For compacts ratified prior to 1959, 1959 income was used because county-level income data are not available for earlier years.

[42] PriorWaterShare is a share variable ranging from 0.01 to 0.99 for each state and summing to 1.00 for each compact. County-level irrigation data were obtained from the Census of Agriculture reports ([http://www.agcensus.usda.gov/Publications/Historical\\_Publications/index.asp](http://www.agcensus.usda.gov/Publications/Historical_Publications/index.asp)) from the year closest to the year of compact ratification for which data are available.

[43] RiparianPosition is a binary variable equal to 1 if the most upstream state in the compact and 0 otherwise.

[44] StatePopulation is a share variable ranging from 0.01 to 0.99 for each state and summing to 1.00 for each compact. Population data sources are described under PopulationShare.

[45] CommitteeChair is a binary variable equal to 1 if the state had a representative who chaired either the House of Representatives or the Senate committee with oversight over interstate river compacts during or immediately prior to the session in which the compact was signed and is 0 otherwise. Data on Congressional committee membership were obtained from Congressional reports [*U.S. House of Representatives*, 2002; *U.S. Senate*, 1989].

[46] As noted, proxy variables are used in some cases because of data limitations. Each state's relative contribution to the river's natural flow is not measured, so the variables for RelativePrecip and MeanTemperature serve as proxies

for the share of natural flow. The variable PriorWaterShare uses estimates of irrigation water use as a proxy variable for total water withdrawals, as the latter data are not available. This is a reasonable proxy given that irrigation accounted for the overwhelming majority of overall withdrawals. For population and income variables, values were for entire counties, even in cases in which only part of the county fell within the basin boundary. Use of proxy variables and imprecise data for some of the explanatory variables is justified, not only because of data limitations but also because the research objective is to understand the concerns and strategies of state negotiators, who would have faced similar limitations of available data. Thus, the data set should reasonably approximate the information available to compact negotiators and decision-makers.

### 3.3. Regression Methods

[47] The data set includes 33 observations of state-based compact water allocations and related explanatory variables. Of the 14 compacts, 10 allocate water between two states, 2 allocate among three states, 1 allocates among five states, and 1 allocates between two groups of states (the Colorado River Compact allocates between an upper basin group and a lower basin group) (Table 1).

[48] The states in an individual compact make up a cluster sample, so standard errors are adjusted for intracompact correlation. Formally, we estimate a particular version of equation (1), the cluster-specific random effects model [*Cameron and Trivedi*, 2005, p. 831]:

$$\text{AllocationShare}_{sc} = \alpha + \mathbf{X}_{sc}\beta + \nu_c + \varepsilon_{sc}, \quad (2)$$

where  $\nu_c$  is a random component specific to compact  $c$  and  $\varepsilon_{sc}$  is a residual error term. The random component captures the effect of any within-compact unobserved variables.

[49] We apply the OLS estimator to estimate two specifications of equation (2), both of which include AllocationShare as the dependent variable. Specification 1 contains only the eight variables associated with the legal criteria for water allocation: LandShare, RelativePrecipitation, Non-CompactPrecipShare, MeanTemperature, PopulationShare, PopulationGrowth, RelativeIncome, and PriorWaterShare. Specification 2 contains all 11 explanatory variables; that is, to specification 1, it adds RiparianPosition, StatePopulationShare, and CommitteeChair.

[50] We investigated multicollinearity in the regression estimates by computing variation inflation factors after each regression. The largest variance inflation factor is less than 5, which is well below the threshold level for harmful multicollinearity of 10 [*Kennedy*, 1992, p. 183]. Thus, multicollinearity is not a problem despite the small number of observations. To address heteroskedasticity, robust standard errors clustered by compacts are computed in the regressions.

[51] To supplement the OLS regressions, we conducted bootstrap regressions of the same two specifications. Bootstrapping involves repeated sampling from the observations with replacement, and various types of bootstrapping techniques are useful for addressing different shortcomings in data sets, such as small sample size or relative lack of variation in observed variables [e.g., *Stine*, 1989; *Hesterberg et al.*, 2006]. In this study, bootstrap regressions were estimated by randomly drawing one observation from each



**Table 3.** Regression Estimates for State Allocation Share of Interstate River Compact<sup>a</sup>

Independent Variable	OLS Regressions				Bootstrap Regressions			
	Legal Variables		All Variables		Legal Variables		All Variables	
	Coefficient	Standard Error	Coefficient	Standard Error	Coefficient	Standard Deviation	Coefficient	Standard Deviation
LandShare	0.201***	0.063	0.224**	0.085	0.180	0.151	0.185	0.270
RelativePrecipitation	0.009	0.108	0.121	0.100	-0.083	0.211	0.006	0.268
NonCompactPrecipShare	-0.009	0.146	0.278	0.188	-0.010	0.303	0.407	0.721
MeanTemperature	0.003	0.008	-0.011	0.011	0.011	0.045	-0.004	0.063
PopulationShare	0.432**	0.152	0.436***	0.116	0.491**	0.183	0.481*	0.285
PopulationGrowth	0.129	0.096	0.119	0.070	0.130	0.193	0.110	0.263
RelativeIncome	-0.023	0.164	-0.048	0.174	-0.113	0.331	-0.234	0.514
PriorWaterShare	0.353***	0.081	0.394***	0.078	0.380***	0.135	0.447**	0.234
RiparianPosition			-0.124***	0.041			-0.108	0.185
StatePopulationShare			-0.356	0.226			-0.458	0.617
CommitteeChair			0.114**	0.040			0.049	0.256
Constant	-0.158	0.261	-0.133	0.227	-0.041	0.540	0.117	0.701
R <sup>2</sup>	0.79		0.84					
Adjusted R <sup>2</sup>	0.70		0.75					
Observations	33		33					
Clusters	14		14					
Repetitions					1000		1000	
Strata					14		14	

<sup>a</sup>The dependent variable is AllocationShare. For ordinary least squares (OLS) regressions, robust standard errors, clustered by compact, are reported. For bootstrap regressions, coefficients represent mean values from bootstrap regressions, with standard deviations reported. Statistical significance was assessed using a bootstrap percentile confidence interval method. Legal variables indicates specification 1, and all variables indicates specification 2. Significance is indicated as follows: \*\*\*, significant at the 1% level; \*\*, significant at the 5% level; \*, significant at the 10% level.

compact and running an OLS regression with 14 observations. The value for each coefficient estimate was saved, and the regression was repeated with resampling 1000 times. After 1000 resamples, the distribution of the coefficient estimates for each variable approaches a normal distribution. The standard deviation of the coefficient estimates for a given variable then serves as a measure comparable to the standard error in an OLS regression. Confidence intervals, and therefore a form of statistical significance, can be estimated by eliminating the 1%, 5%, or 10% of observations at the tails of the distribution and assessing whether the remaining 99%, 95%, or 90% of the observations are either all above or all below zero.

[52] The bootstrap regressions serve as a valuable robustness check for the OLS regression results, which may have shortcomings for at least three reasons. First, several of the variables, including the dependent variable, are measured as shares that sum to 1 within a compact. As such, observations on a given variable are not independent of one other. For a two-party compact, for instance, once the allocation share of one state is known, the other is necessarily 1 minus this share. Potential problems created by this type of data are circumvented by sampling only one observation from each compact for each bootstrap regression. Second, given that the original data set is small, bootstrap regressions provide an alternative approach for evaluating confidence intervals for estimated coefficients based on a larger number of observations. Third, since the state is the unit of analysis in the OLS regressions, compacts with more than two states are overrepresented and thus may unduly impact study results. By sampling only one observation per compact, the bootstrapping technique also avoids giving extra weight to compacts with higher numbers of parties.

[53] A third regression method, censored least absolute deviations estimation, was also used to reflect the fact that the sum of the dependent (and of some of the independent)

variables is constrained to 1. The values did not differ substantially from the OLS values and are not reported.

## 4. Results

### 4.1. OLS Regressions

[54] OLS results are reported in Table 3 for the two specifications: (1) variables associated with the legal criteria for water allocation and (2) all variables, including political variables. Both specifications fit the data relatively well, with  $R^2$  values of 0.79 and 0.84. We conclude that specification 2 is the preferred specification for three reasons: its adjusted  $R^2$  is larger (0.75 to 0.70), two of the additional variables in the specification have estimated coefficients that are statistically significant, and the joint hypothesis that the three additional variables in specification 2 are equal to 0 is strongly rejected ( $F(3, 13) = 15.58, p = 0.0001$ ). The factors affecting interstate water allocation thus appear to include political variables in addition to the physical and socioeconomic variables prescribed by legal authorities and doctrines.

[55] The variables LandShare, PopulationShare, and PriorWaterShare are significant in both specifications and relatively stable in magnitude across specifications. Each of these variables takes on values between 0 and 1 to reflect the state's fraction of a multistate compact total for the respective variable. The estimated coefficients in specification 2 can be interpreted as follows: a 0.01 (1%) change in LandShare changes a state's expected water AllocationShare by 0.00224 (0.224%). A 1% change in PopulationShare changes a state's AllocationShare by 0.436%. A 1% change in PriorWaterShare changes a state's AllocationShare by 0.394%.

[56] Other variables under the legal criteria, including precipitation, population, and income measures, do not exert a statistically significant effect on a state's water AllocationShare. Population growth rate (PopulationGrowth)



approaches significance at the 10% level (11.5%) in specification 2.

[57] The upstream position on a watercourse is thought to strengthen a country's bargaining position in international water negotiations [e.g., *Frey and Naff*, 1985; *Wolf*, 2007; *Dinar*, 2008]. Yet the evidence in specification 2 suggests that the upstream state in interstate compacts (RiparianPosition = 1) is actually penalized, receiving a lower water share by 0.124 (12.4%). This may be because downstream parties often develop rivers earlier; however, one would expect most of such effects to be captured by the variables of PriorWaterShare and PopulationShare. They also may result from the legal requirement not to cause significant harm to downstream parties. Regardless of the cause, the results are consistent with findings that other factors may dominate the theorized upstream advantage [*Daoudy*, 2009; *Dinar*, 2009].

[58] Last, a state's water share increases by 0.114 (11.4%) if one of its representatives in the U.S. Senate or House was chair of a committee with jurisdiction over interstate river compacts (CommitteeChair = 1). This result provides quantitative evidence to supplement the historical research by *Hundley* [1992, p. 212], who wrote of states exerting influence over the Colorado River Compact through "their control of key congressional reclamation [water] committees."

[59] Considering a particular state and compact provides a useful perspective on the results. We consider Montana in the Yellowstone River Compact with Wyoming, in which Montana receives a 68% AllocationShare of the compact water. Montana has 52% of the area (LandShare for Montana = 0.518), 58% of the population at compact signing (PopulationShare = 0.576), and 48% of the water use in the basin at compact signing (PriorWaterUse = 0.478). On the basis of the estimated coefficients, Montana's predicted AllocationShare would increase by 0.224% if its LandShare increased by 1% to 53%. AllocationShare would increase by 0.436% if Montana's PopulationShare increased by 1% to 59%. AllocationShare would increase by 0.394% if Montana's PriorWaterShare increased by 1% to 49%. In addition, Montana is the downstream state in the compact, and Montana did not have a committee chair in the U.S. Congress. These two variables are binary (0, 1) variables. Thus, Montana's predicted AllocationShare would decrease by 12.4% if its riparian position were switched relative to Wyoming. Last, AllocationShare would increase by 11.4% if one or more of the Congressional water committees were chaired by a member from Montana.

[60] *Bennett and Howe* [1998] and *Bennett et al.* [2000] emphasize that three types of allocation formulas emerge from interstate river compacts: percentages of flow, fixed absolute quantities, or some combination of both. In light of these studies, we also estimated regressions that included dummy variables indicating if the compact was based on percentages of flow, fixed quantities, or a combination. The results did not differ significantly from the results without such variables and thus are not reported.

## 4.2. Bootstrap Regressions

[61] The distribution of estimated coefficients is roughly normal for most variables in the bootstrap regressions. Given the normality of the distribution of coefficient estimates,

inferences can be made as to statistical significance on the basis of coefficient means and distributions, and results can be compared to those from the OLS regressions. As each bootstrap regression utilizes only one randomly drawn observation from each compact (for  $N = 14$ ), the bootstrap regressions provide a stringent basis of comparison for the OLS regressions. For each variable, we report the mean and standard deviation of its estimated coefficients on the basis of the 1000 regressions (Table 3).

[62] A bootstrap percentile confidence interval method was used to assess the statistical significance of the bootstrap coefficient estimates. Confidence intervals are constructed in this method by arranging the bootstrap results in increasing magnitude and using the observations at the upper and lower  $\alpha/2$  percentiles as a measure of the  $\alpha$  significance level [*Efron and Tibshirani*, 1993; *Mooney and Duval*, 1993]. Thus, we note when 90%, 95%, or 99% of the 1000 estimates of a coefficient are greater than 0 for positive coefficients or less than 0 for negative coefficients. Only two variables, PopulationShare and PriorWaterShare, satisfy these criteria at different levels in both specifications of the bootstrap regressions.

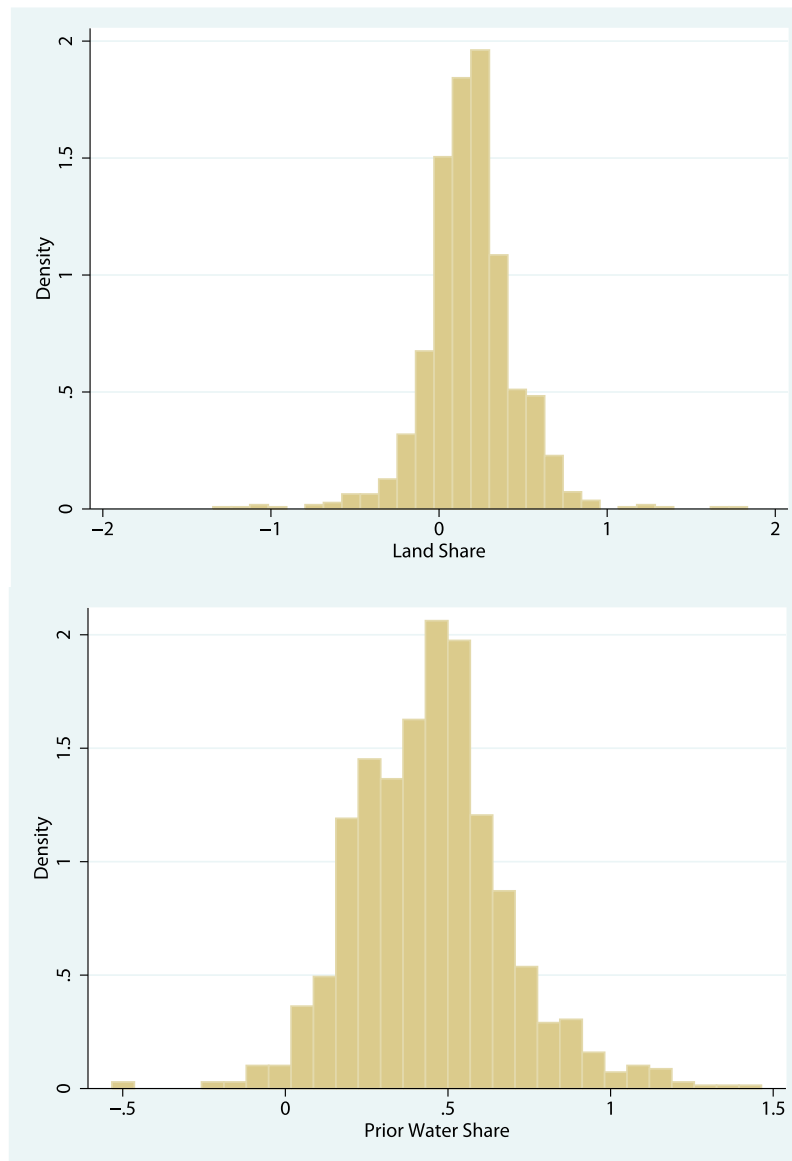
[63] For purposes of illustration, Figure 2 shows histograms of estimates for two variables in specification 2, LandShare and PriorWaterShare. For LandShare, although the mean was positive and close to the value found in OLS, many coefficient estimates were negative, and so one cannot claim with confidence that the mean is significantly different from zero. For PriorWaterShare, however, the mean is similar to that found in OLS, and more than 95% of the coefficient estimates are above zero, providing solid support that the coefficient is robust.

[64] The bootstrap regressions provide mixed support for the OLS results. Across the board, the mean values of the coefficient estimates from bootstrapping are very similar to the corresponding OLS coefficient estimates. However, for three variables, LandShare, RiparianPosition, and CommitteeChair, the distributions of coefficient estimates from bootstrapping raise a question about the statistical significance of these variables' coefficient estimates in the OLS regressions.

## 4.3. Predicted State Shares of Interstate Compacts

[65] Predicted compact shares provide additional perspective on the OLS and bootstrap regressions. We report actual shares and predicted shares on the basis of specification 2 (Table 4). Predictions based on the OLS results are straightforward to generate. For the bootstrap, we applied the equation  $\text{PredictedShare}_{sc} = \bar{\alpha} + \mathbf{X}_{sc} \bar{\beta}$ , where  $\bar{\alpha}$  is the mean value of the estimated constant and  $\bar{\beta}$  are the mean values of the coefficient estimates from the bootstrap regressions.

[66] The predicted shares are very similar across OLS and bootstrapping, just like the estimated coefficients are very similar; the predicted shares are typically closer to each other, in fact, than they are to the actual shares. On a case-by-case basis, the bootstrap prediction error (measured as actual share minus predicted share) is smaller in absolute value than the OLS prediction error in 16 of 33 cases, the OLS prediction error is smaller in 14 cases, and there are three ties (when rounded off to hundredths).



**Figure 2.** Histograms of coefficient estimates from bootstrap regressions.

[67] Mean absolute error (MAE), a common measure of forecast accuracy [Greene, 2008], is the average of the absolute value of the 33 prediction errors. The MAE is 0.079 for the OLS predictions and 0.083 for the bootstrap predictions in specification 2. For specification 1, the MAE is 0.092 for the OLS predictions and 0.094 for the bootstrap predictions. Thus, OLS outperforms the bootstrap on this basis, but only by a small margin.

[68] A second relevant concept is normalized predicted share of a compact. Within a compact, the actual shares are constrained to sum to 1; that is, the total water endowment gets allocated via the compact. The predicted shares are not subject to this constraint, such that predicted shares within a compact typically sum to greater than 1 or less than 1 and only rarely sum to 1. The Colorado River Compact provides an example of the predicted shares summing to greater than 1, while the Yellowstone River Compact illustrates the opposite case. The normalized predicted shares are adjust-

ments to the predicted shares to assure that shares sum to 1 within a compact.

[69] To derive the normalized predicted shares, we rescaled shares equiproportionately within a compact while constraining their sum to equal 1. The rescaling uses the factor  $(1/\sum_{s=1}^S p_s)$ , where  $p_s$  is the predicted share of state  $s$  within a particular compact. Predicted shares within a compact are each multiplied by this factor to derive the normalized predicted share. For example, if the predicted shares of a compact summed to 0.9, we multiplied each individual predicted share by  $(1/0.9)$  to obtain the normalized predicted shares. Rescaling by this common factor assures that the shares sum to 1. Thus, the rescaling is a contraction if  $\sum_{s=1}^S p_s$  is greater than 1 and an expansion if it is less than 1. Table 4 reports the normalized predicted shares for the OLS and bootstrap regressions, again using specification 2.

**Table 4.** Actual Share, Predicted Share, and Normalized Predicted Share<sup>a</sup>

Compact	State	Actual Share	Predicted Share		Normalized Predicted Share	
			OLS	Bootstrap	OLS	Bootstrap
Arkansas	Colorado	0.60	0.54	0.58	0.58	0.59
	Kansas	0.40	0.39	0.40	0.42	0.41
Bear	Idaho	0.23	0.50	0.50	0.44	0.47
	Utah	0.24	0.34	0.32	0.31	0.30
	Wyoming	0.52	0.29	0.26	0.25	0.23
Belle Fourche	South Dakota	0.90	0.89	0.84	0.85	0.85
	Wyoming	0.10	0.15	0.14	0.15	0.15
Big Blue	Kansas	0.07	0.12	0.11	0.14	0.11
	Nebraska	0.93	0.78	0.85	0.86	0.89
Caddo Lake	Louisiana	0.50	0.53	0.49	0.55	0.50
	Texas	0.50	0.43	0.49	0.45	0.50
Cheyenne	South Dakota	0.80	0.74	0.75	0.76	0.75
	Wyoming	0.20	0.24	0.25	0.24	0.25
Colorado	Lower Basin	0.50	0.55	0.54	0.53	0.50
	Upper Basin	0.50	0.50	0.54	0.47	0.50
Upper Colorado	Arizona	<0.01	0.11	0.19	0.10	0.18
	Colorado	0.51	0.39	0.32	0.37	0.30
	New Mexico	0.11	0.15	0.18	0.14	0.16
	Utah	0.23	0.29	0.29	0.28	0.27
	Wyoming	0.14	0.11	0.09	0.11	0.09
Costilla Creek	Colorado	0.35	0.30	0.39	0.30	0.37
	New Mexico	0.65	0.67	0.65	0.70	0.63
La Plata	Colorado	0.50	0.63	0.59	0.54	0.54
	New Mexico	0.50	0.53	0.50	0.46	0.46
Republican	Colorado	0.11	0.14	0.11	0.15	0.12
	Kansas	0.40	0.23	0.22	0.25	0.23
	Nebraska	0.49	0.57	0.60	0.60	0.65
Sabine	Louisiana	0.50	0.35	0.35	0.36	0.34
	Texas	0.50	0.63	0.69	0.64	0.66
Snake	Idaho	0.96	0.99	1.00	0.94	1.00
	Wyoming	0.04	0.06	0.00	0.06	0.00
Yellowstone	Montana	0.68	0.49	0.54	0.57	0.54
	Wyoming	0.32	0.36	0.45	0.43	0.46

<sup>a</sup>The variable for actual share is AllocationShare. The predicted share entries are derived from specification 2 and are not constrained to equal 1 within a compact. The normalized predicted share entries are computed by equiproportionately rescaling the predicted shares for a given compact while constraining them to sum to 1. Both actual shares and predicted shares are rounded off to hundredths.

[70] The normalized predicted shares reflect the reality of allocating the total water endowment. In some cases, but not in all cases, the normalized predicted shares are closer to the actual shares than the predicted shares are (Table 4). Using these normalized shares for specification 2, the MAE is 0.073 for the OLS prediction and 0.078 for the bootstrap prediction. These are slightly lower and therefore slightly better as a measure of forecast accuracy than the comparable measures of MAE with the nonnormalized prediction errors.

#### 4.4. Study Limitations

[71] In interpreting the results, it is important to note several limitations of this study. Because of limited data, a few compacts were not covered in the database, and variables were not included for all possible allocation criteria. Furthermore, because of the small data set and, thus, the low number of degrees of freedom in estimating regressions, the regressions did not include interaction variables, despite the fact that such interrelationships may be considered in actual negotiations. Finally, numerous proxy variables are possible for several of the criteria evaluated, and numerous alternative methods are available for quantifying each of them. Given these limitations, this study presents an initial framework for empirical analysis of the application of water

allocation criteria, one that can be built upon in future research.

## 5. Summary and Conclusions

[72] Jurists and legal scholars are loathe to characterize formulas for equitable water allocation, and thus one might be surprised to find a quantitative pattern emerge from interstate river compacts. Yet OLS regressions indicate that several variables play a statistically significant role in determining compact allocations, despite a small database for the analysis. These variables include three of the legal criteria for equitable allocation involving land base (LandShare), population base (PopulationShare), and prior water use (PriorWaterShare). They also include two political factors involving riparian position on the watercourse (RiparianPosition) and key Congressional appointments (CommitteeChair).

[73] Bootstrapping presents an alternative method to OLS for evaluating the presence or absence of systematic weighting in compact allocations. This method may produce more reliable (less biased) results than OLS, given the lack of independence between different observations and the small number of observations in the data set. In our study, two variables, PopulationShare and PriorWaterShare, are particularly robust, appearing significant in both specifica-

tions in both OLS and bootstrap models. The result with *PriorWaterShare* is not surprising, as historical use was specified explicitly in some of the compacts as an allocative criterion. *Muys* [1971] notes that several compacts explicitly specify existing uses as an allocative criterion, and about half indicate that allocations include federal uses, which can be significant. Still, the statistical significance of the *PriorWaterShare* coefficient could not be assumed a priori, especially given that the U.S. Supreme Court explicitly rejected a strict doctrine of prior appropriation in favor of equitable apportionment based on a range of criteria [*Sherk*, 2000]. The variables *LandShare*, *RiparianPosition*, and *CommitteeChair*, although they were significant using OLS, are not significant in the bootstrap regressions. These results are consistent with U.S. Supreme Court rulings, which have rejected *LandShare* and *RiparianPosition* as criteria for equitable apportionment [*Sherk*, 2008]. A chair position on an important Congressional committee, of course, has never been a recommended criterion. We should note that while the estimated coefficients on these three variables are not statistically significant in the bootstrap regressions, their sign and relative magnitude remained similar to those in the OLS regressions.

[74] Do the regression estimates provide numerical formulas for the allocation of transboundary water resources? A few perspectives are relevant here.

[75] The role of the U.S. Supreme Court creates a unique institutional setting for negotiated settlement in the case of river compacts. The Court is equipped with the equitable apportionment doctrine for interstate water allocation and, although not required to, may accept the role of final arbiter if states cannot form a compact. Through this lens, water compacts should approximate a fair solution; otherwise, a state could be expected to cast its lot with the Court or appeal to Congress for apportionment.

[76] The regression estimates without political variables (specification 1) represent a positive analysis of relative impact of equitable apportionment criteria on compact allocations. The explanatory variables are limited to those proposed in various legal venues as relevant factors for developing equitable allocation. Results from either the OLS or bootstrap regressions, as reported in Table 3, could provide a reference point for future compact negotiations or, in the international realm, treaty negotiations. Study results may be helpful in highlighting certain criteria that seem to have received particular emphasis or, alternatively, that may have been neglected in previous negotiations.

[77] An immediate application of this idea would involve assessment of two river basins in the southeastern United States, the Apalachicola-Chattahoochee-Flint river basin (a transboundary river in Georgia, Alabama, and Florida) and the Alabama-Coosa-Tallapoosa river basin (a transboundary river in Georgia and Alabama). Compacts for both basins were completed in 1997, yet they did not specify formulas for water allocation among the states. The compacts subsequently were terminated when the states failed to agree upon allocation formulas [*DuMars and Seeley*, 2004; *Sherk*, 2005]. The compacts included provisions for protecting the water quality, ecology, and biodiversity of the river systems. Implementation of these provisions would require particular attention in the context of a numerical formula for our research, as the compacts that we studied, having been

signed between 1922 and 1979, do not include water earmarked for in-stream environmental flows.

[78] The regression estimates with political variables (specification 2) represent a positive perspective for explaining compact water allocations that includes factors other than those provided by legal theory or jurisprudence (e.g., the influence of Congressional committee chair, *CommitteeChair*). The OLS estimates provide a relatively good fit to the data, with an  $R^2$  of 0.84. In the same vein, both the OLS and bootstrap estimates provide a basis for making reasonably accurate predictions of individual state shares of the compacts. Interesting research questions, which are limited by the small sample size, include whether such patterns are consistent over time and whether and how they might change with the recent inclusion of new allocation criteria for ecological water needs and environmental impact.

[79] With this context of goodness of fit serving as a backdrop, we can also use the predicted shares to identify “outlier” compacts, i.e., compacts with actual shares that vary substantially from predicted shares (Table 4). The Sabine River Compact and Yellowstone River Compact are outliers among the two-state compacts. Among the three-state compacts (the Bear River Compact and Republican River Compact), actual and predicted shares vary substantially for two states in each compact. Arizona and Colorado within the five-state Upper Colorado River Compact similarly have actual and predicted shares that vary substantially. These outliers both confirm that the compact allocation process is not simply formulaic and raise a question about the nature of the specific negotiation processes underlying these compacts. This question could be the basis for future research using case study methods.

[80] The main venue for further statistical analysis is international transboundary water agreements. Given the parallel between the criteria laid out in U.S. law and international law, are the current results transferable to international agreements, and if not, how do they differ? Given the propensity of parties to engage in issue linkage and side payments as a means for reaching agreements in water negotiations [e.g., *Carraro et al.*, 2005; *Dinar*, 2009], do parties receiving less than the share predicted by the regression results receive other forms of compensation to entice them to sign agreements? The answers to such questions are left to future research.

## Appendix A: Description of Data and Variables

### A1. Dependent Variable

[81]  $\text{AllocationShare}_{sc}$  is the share of river water allocated by an interstate compact  $c$  to a state  $s$ , in fractional terms. The units range from 0.01 to 0.99 and sum to 1 within a compact. The allocation percentage is given directly in the compact in some cases. In other cases, the percentage was calculated on the basis of allocations of water quantities contained in the compact. States that were signatories to a compact but that did not receive water are not included in the data set. Although over 20 compacts provide quantitative allocations, several were not included in the data set because of difficulty in accurately determining quantitative allocations to the states.

## A2. Variables Describing a Compact

[82] Compact is the name of a river compact. Compactno is an identifying number for each compact. State is the state name.

## A3. Independent Variables

[83] Each variable and how it was calculated is described below. A list of the data sources is given in section A4. The raw data for many of the explanatory variables are county-level data, for example, county-level data on income or population. The data are typically aggregated on a “basin-wide” basis within the state, not on an “entire state” basis. That is, the data are summed over counties in the river’s watershed in the state, not over all counties in the state. Counties were included in the database if any part of the county was within the basin of the river or water body covered by the compact. County boundaries used in GIS were 1980 county boundaries. In a small number of cases, county boundaries changed between the period of compact ratification and 1980. In such cases, various measures were undertaken in order to best approximate the county boundaries at the time of ratification. Last, for the variables that were constructed as shares, the share ranged from 0.01 to 0.99. The numerator was a value for a particular state, and the denominator was a summed value over all states in the compact, such that the shares for each such variable sum to 1 within a compact.

[84] LandShare<sub>sc</sub> is a state’s share of the aggregate area in the compact’s river basin (data source 1).

[85] RelativePrecip<sub>sc</sub> is a measure of relative precipitation per area (data sources 1 and 2.). The numerator is mean annual precipitation (in inches) within each state basin area, divided by per state basin area (in square meters). The denominator is mean precipitation divided by area computed on a basin level over all states in the compact. The variable is constructed so as to remove the influence of land area in the measurement of precipitation. The variable is greater than 1 (or less than 1) if the basin within the state has a higher (or lower) precipitation per unit area than the entire compact basin. Average precipitation for a per state basin area was calculated by multiplying average precipitation data for each hydrologic unit (as defined by the USGS hydrological boundaries data layer; see data source 1) in a basin by the relative area of the hydrologic unit and then taking the average for each state.

[86] NonCompactPrecipShare<sub>sc</sub> is the share of rainfall volume in each state falling outside of the relevant river basin (data sources 1 and 2). Volume per state was calculated by multiplying mean annual rainfall per hydrological unit by each unit’s area for all hydrological units outside of the compact basin in each state. Share was calculated by dividing each state’s volume by the volume total for all states in the compact.

[87] MeanTemperature<sub>sc</sub> is the mean temperature for counties within the river basin during the irrigation season, April–September (data sources 1 and 3). The temperature data are categorical data, with nine ordinal categories representing different temperature ranges. Means for each county were calculated and then multiplied by county area, then summed over the total number of basin counties for each state, and then divided by total basin area in order to derive a basin-wide mean temperature. Mean temperature

data are available for the period 1971–2000. Although most compacts were signed prior to this period, relative changes in temperature were unlikely to have changed substantially in the interim period.

[88] PopulationShare<sub>sc</sub> is the share of population in counties within the basin (data sources 1 and 4). The numerator is the population of counties within the compact basin, summed over counties, to give population of the state basin. The denominator is state basin population summed over states in the compact. Population data are from the decennial census closest to the year in which the compact was signed.

[89] PopulationGrowth<sub>sc</sub> is the growth rate of population in counties within the basin for the 20 year period covering the decennial census in the decade before and after the census closest to compact signing (data sources 1 and 4). The sum of basin county population from the decennial census occurring 10 years after the census used to calculate the PopulationShare variable was divided by the figure for the census 20 years prior on a per state basis.

[90] RelativeIncome<sub>sc</sub> is a relative measure of per capita income in counties within the river basin (data sources 1 and 5). The numerator is per capita income in the state, computed on a basin basis. The denominator is per capita income over all states in the compact, computed on a basin basis. The variable is constructed so as to remove the influence of population in the measurement of income. The variable is greater than 1 (or less than 1) if the basin within the state has higher (or lower) per capita income than the entire compact basin. Historical county-level income data are available only for the years 1959, 1969, and 1979. The year closest to compact ratification was used. For compacts ratified prior to 1959, 1959 income was used.

[91] PriorWaterShare<sub>sc</sub> is a measure of historical irrigation water use for agriculture in counties prior to compact signing (data sources 1 and 6.). Prior water use was calculated by multiplying total irrigated area (in acres) by mean water application rate (in acre-feet per acre) for each county. The numerator is water use of counties within the compact basin, summed over counties to give water use of the state basin. The denominator is state basin water use summed over states in the compact. For Caddo Lake Compact, because of missing data, total irrigated area was multiplied by average statewide water application rates.

[92] RiparianPosition<sub>sc</sub> is a binary variable equal to 1 if the state was the most upstream state in the compact and 0 otherwise.

[93] StatePopulation<sub>sc</sub> is the share of total state population of basin states within a compact (data source 4). Data are from the decennial census in the year closest to the year in which the compact was ratified.

[94] CommitteeChair<sub>sc</sub> is a binary variable indicating whether a state had a representative who chaired a Congressional committee with jurisdiction over interstate river compacts in the Congressional session during or prior to compact signing (data source 7).

## A4. Data Sources and Notes

[95] Note that all GIS data (area, state, county, and watershed boundaries; precipitation; and temperature) were analyzed using ArcGIS 9 software. Map areas used Albers Equal Area Conic (USGS version) data projection.

[96] The data sources mentioned in section A3 are (1) areas and boundaries, (2) precipitation, (3) temperature, (4) population, (5) income, (6) irrigation water use, and (7) Congressional committee chair. Specific details are as follows.

[97] 1. Area data layer sources are from U.S. Geological Survey hydrologic units (watersheds), state boundaries, and county boundaries (1980) map layers, all accessed from <http://nationalatlas.gov/on> 5 May 2004.

[98] 2. Precipitation (rainfall) data are from the U.S. Geological Survey, U.S. Department of the Interior. The source is USGS average annual precipitation, 1961–1990 map layer, accessed at <http://nationalatlas.gov/on> 18 August 2009.

[99] 3. Temperature data are from NOAA's NCDC, U.S. Department of Commerce. Temperature map layers were accessed at [http://cdo.ncdc.noaa.gov/cgi-bin/climaps/climaps.pl?directive=order\\_details&subnrnm=&region=Lower%2048%20States&filename=temp0313](http://cdo.ncdc.noaa.gov/cgi-bin/climaps/climaps.pl?directive=order_details&subnrnm=&region=Lower%2048%20States&filename=temp0313) on 18 August 2009.

[100] 4. Population data are from the U.S. Census Bureau, U.S. Department of Commerce, <http://www.census.gov/population/www/censusdata/cencounts/index.html>, accessed on 5 May 2004.

[101] 5. Income data are from two sources. Historical county-level income data are from <http://www.census.gov/hhes/www/income/data/historical/county/index.html>. State income data are from the Bureau of Economic Analysis, U.S. Department of Commerce, <http://www.bea.gov/regional/spi/default.cfm?selTable=summary>, accessed on 26 September 2005.

[102] 6. County-level data on average irrigation application rates and irrigated area are from reports of the U.S. Census of Agriculture [U.S. Census Bureau, various years] from the year closest to the year of compact ratification for which data are available.

[103] 7. Data on relevant committee chairs in the U.S. House of Representatives and U.S. Senate are from *U.S. House of Representatives* [2002] and *U.S. Senate* [1989].

[104] **Acknowledgments.** The authors thank Naomi Feldman for assistance with the statistical analysis and Shaw Lacy for assistance with GIS. Helpful comments were provided by Gary Libecap, other participants at the International Water Resource Economics Consortium meeting in Berkeley, California, in 2009, and three anonymous reviewers.

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