water

MDPI

Article

Water allocation, return flows, and economic value in arid basins: Results from a coupled natural-human system model

Cameron Wobus [1]*, Eric Small [2], Jared Carbone [3], Ben Livneh [4], William Szafranski [5], Hannah Kamen [3], and Parthkumar Modi [4]

[1] CK Blueshift, LLC, Boulder CO USA 80303; cwobus@ckblueshift.com
[2] Department of Geological Sciences, University of Colorado Boulder CO 80309; eric.e.small@colorado.edu
[3] Department of Economics and Business, Colorado School of Mines, Golden CO USA 80401; jcarbone@mines.edu; hkamen@mines.edu
[4] Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder CO USA 80309; ben.livneh@colorado.edu; parthkumar.modi@colorado.edu
[5] Lynker Corporation, Boulder CO USA 80303; bszafranski@lynker.com

* Correspondence: cwobus@ckblueshift.com

Citation: Lastname, F.; Lastname, F.; Lastname, F. Title. *Water* **2022**, *14*, x. https://doi.org/10.3390/xxxxx

Academic Editor: Firstname Lastname

Received: date
Accepted: date
Published: date

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Abstract: The allocation of water in the arid western United States is governed by complex water laws that dictate who receives water, how much they receive, and when. Because these rules are generally based on the seniority of water rights, they are not necessarily focused on maximizing economic value across the entire economy. The maximization of value from water use economy-wide is a complex optimization problem that must explicitly consider each user's peak water demand, willingness to pay function, and the feedbacks among users in a coupled natural-human system model. In this study, we distill these complexities into a simple model of a two-user economy that allows us to explore the relationships among water availability, water use, and value in water-limited systems. We find that the total economic value generated from water-dependent users depends primarily on the total water available in the system. However, for a given volume of water available, the way that water is allocated between the two users also has a significant effect on economic value. The degree to which this allocation affects value depends primarily on the relative willingness to pay for water between the two users, and on the return flows generated from each sector's water use. While our simple two-user model is an abstraction of the complexities inherent in natural systems, our study provides important insights into the coupled natural-human system dynamics of water allocation and use in water-limited environments.

Keywords: keyword 1; keyword 2; keyword 3 (List three to ten pertinent keywords specific to the article yet reasonably common within the subject discipline.)

1. Introduction

Across the arid western United States, water is typically allocated by some version of a prior appropriations doctrine, wherein those with the most senior water rights – typically agricultural users –receive their full allocation of water prior to any other user being able to draw from the resource (e.g., [1,2]). This "rigid" allocation of water remains in place today, even though the vast majority of recent economic growth in the West has been driven by other sectors who may have a higher value for water (e.g., [3–5]). Importantly, in many cases the initial water allocation rules did not account for return flows - water that is not fully consumed by an upstream user and is, therefore, available for downstream use - since prior appropriations rules are typically based on the volume of water withdrawn rather than the volume of water consumed (e.g., [6–8]). The overall result is a mismatch between water policy, allocation, and value.

Identifying a better alternative, however, requires an improved understanding of the coupled natural-human system dynamics between water allocation and return flows in river basins. Specifically, individual decisions about where and how to use water affect the volume of water available at other points in the watershed, which create feedbacks that influence the total social value the water can generate (Figure 1). Identifying allocations that best serve society's needs therefore requires consideration of human decision-making, the physical constraints on water availability, and the feedbacks between them.

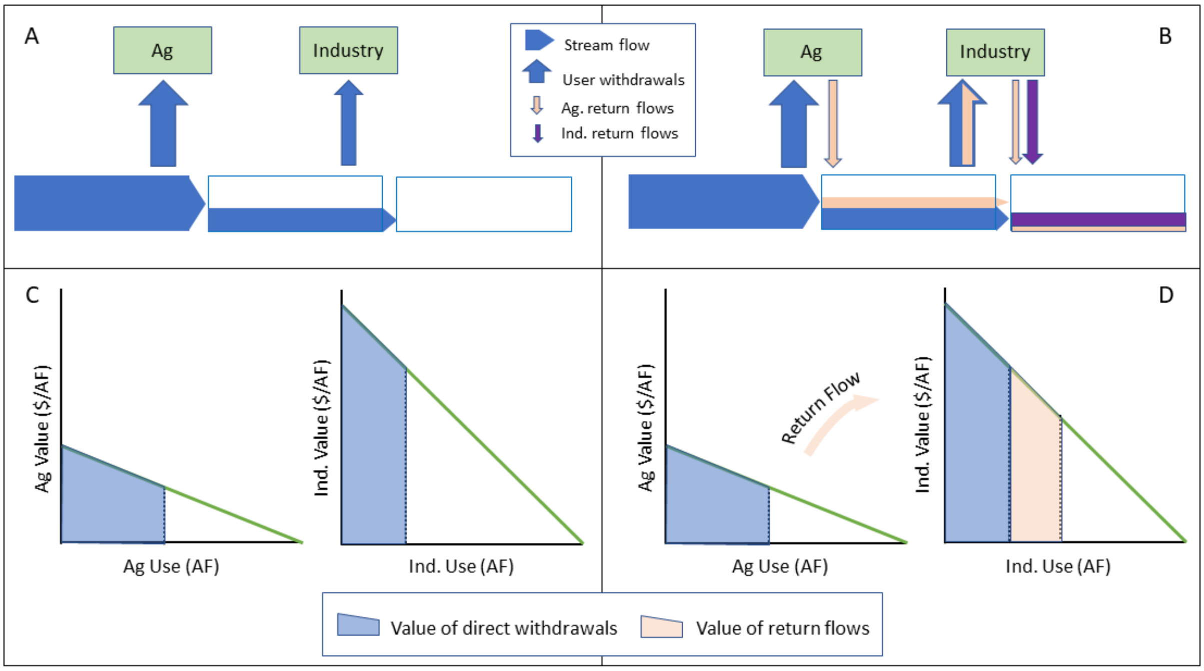

Figure 1. Schematic illustrating the relationships between water availability, water use, and economic output. A) In a system with no return flows, stream depletion is a simple sum of all users' water withdrawals. B) When return flows are considered, stream depletion depends on both water withdrawals and return flows, generating additional water that can be allocated for beneficial use. C-D) In our simple two-user system, total economic output is the sum of areas under the production curves for agriculture and industry. Note that more output is possible with return flows (D) relative to a system without return flows (D).

We developed a coupled natural-human system model that simulates streamflow, water allocation, return flows, and economic value in an idealized basin with two water users. The users differ in the total volume of water they require, their marginal value per unit of water, and the magnitude of their return flows. We use the model to test the hypothesis that natural-human system coupling is particularly strong, and opportunities for improving water allocation efficiency are increased, when return flows are significant and when water is scarce.

Our simple model shows that total economic value depends primarily on the total water available in the system. However, for a given volume of water available, the way that water is allocated between the two users can also have a significant effect. The degree to which this allocation matters depends on both the relative willingness to pay for water between the two users (a measure of economic value), as well as on the physical constraints on the system. These physical constraints include the relative position of each user within the basin, and the return flows generated from each sector's water use.

We contrast the general results of these model outputs with the economic outcomes that would be expected in real systems across the arid western United States (e.g., [9–11]). Our model thus provides a means to evaluate the gains in economic output that could be achieved by explicitly considering the value that each user places on water as a resource, as well as the return flows from each user. This latter component – consideration of return flows – has largely been ignored from existing physical-economic modeling analyses, with a few notable exceptions [12]. This represents an important knowledge gap, since additional water supply from return flows can significantly ameliorate water shortages, particularly during drought conditions.

2. Materials and Methods

Our simple system includes two water users, and water allocation is tracked between these users using a coupled economic-physical modeling framework. While we abstract away from many institutional details, the two water users in the system differ in ways that are meant to capture key features of agricultural and industrial users in western basins. Specifically, production in the agricultural sector requires more water overall, and more water per dollar of output, than in the industrial sector [5]. However, the value of access to additional water is also generally lower for the agriculture sector than it is for the industrial sector, at the typical allocation of water determined from prior appropriations [3,4,5].

In the economic component of our model, we impose linear willingness to pay (WTP) functions to represent each sector's marginal value per unit of water. A WTP function describes the maximum amount a user would be willing to pay to obtain an additional unit of water, as a function of that user's total allocation of water. In the context of an agricultural or industrial user, for example, this would correspond to the user's increase in profits due to the expanded output/sales the extra water would make possible. The maximum total economic value across users occurs at the allocation where all users have the same the WTP (Figure 1c-d). If one user has a higher WTP – for example the industrial user under prior appropriations – then total economic value can be increased by transferring a unit of water from the lower-value to the high-value user, holding total water availability constant.

The physical component of the model tracks consumptive use for each sector, and ensures that the overall water balance includes return flows from each user. If each use of water in the basin were 100% consumptive (i.e., if there were no return flows), identifying the optimal allocation based on the two users' WTP functions would be straightforward because the total water available in the system would be fixed (e.g., Figure 1a). However, because a change in water use upstream also affects the return flows available for downstream uses in the basin, identifying the optimal water allocation becomes significantly more complex (e.g., Figure 1b). Our contribution is to consider not only how total value from water use can be maximized, but also how these changes in return flows affect the total value of different water allocations.

We use the model to sequentially vary the total supply of water available, each user's relative WTP for water, and the return flows from each sector (Table 1). For each of these experiments, we assume that the maximum water demand from each sector is fixed. We set peak demand for the agricultural user at 500 acre feet (AF) and peak demand for the industrial user at 200 AF. We then loop through a series of allocations between users in which the upstream user takes anywhere from 0% to 100% of its total demand, subject to constraints from the total inflow. For example, if the total water available in the basin is only 300 AF, the maximum possible use by the agricultural sector is only 60% of its peak demand (300 AF/500 AF). For each of the possible water withdrawals and return flows from the upstream user, we assume that the downstream user will take as much water as remains up to its peak demand. Note that throughout these experiments we set actual values for agricultural and industrial uses, return flows, and other parameters for ease of interpretation. The absolute magnitude of peak demand values are of no significance because the system dynamics are driven by the *relative* values of each of these parameters.

Our experiments result in a series of plausible water allocations between upstream and downstream users, which we combine with the WTP functions for each sector to calculate the total economic value for each scenario. We then identify the single water allocation that maximizes economic value for each scenario of total water availability, allowing us to examine how total economic value is affected by the interplay between water shortages, return flows, and willingness to pay. Finally, we compare the maximum value attainable for each scenario to the value that would be achieved under a prior appropriations allocation, in which the upstream, senior user maximizes its own output without regard to optimizing total value economy-wide.

3. Results

Our analysis focused on three types of experiments: varying the total volume of water available in the system; varying the relative willingness to pay for water between the two sectors; and varying the return flows from each sector (Table 1).

Table 1. Summary of experiments designed to evaluate system response to total water, WTP ratios, and return flow fractions.

Experiment Type	Total Water (AF)	WTP Ratio	Ag Return Flow
Total Water (*Sect. 3.1*)	100	2:1	30%
	300	2:1	30%
	500	2:1	30%
WTP Ratio (*Sect. 3.2*)	300	1:1	30%
	300	2:1	30%
	300	4:1	30%
Return Flow (*Sect. 3.3*)	300	3:1	15%
	300	3:1	45%
	300	3:1	60%

3.1. Variation in total water available

Our first set of experiments focused on varying the total volume of water available in the system. In each of these experiments, the industrial sector has a willingness to pay for water that is double that of the agricultural sector, per unit of water. As expected, these experiments illustrate that economic value increases as the total volume of water increases. However, the relative allocation of water that maximizes value also varies as the total volume of water changes. This leads to a shift in water usage relative to a prior appropriations case in which the allocations are fixed.

Figure 2 illustrates this effect for three scenarios where agriculture is the upstream user, and where water is scarce relative to the total peak demand of the entire economy of 700 AF. In the scenario where water is most scarce (100 AF total), value is maximized when agriculture uses no water, and all of the water is allocated to the higher-valued industrial user downstream (Figure 2a). In a scenario with an intermediate level of scarcity (300 AF total), economic value is maximized when agriculture uses just over half of its peak demand (Figure 2b), leaving the remaining water and its return flows for the industrial user downstream. And finally, in a scenario with enough water to just meet agriculture's peak demand, value is maximized when agriculture uses 100% of its peak demand and the industrial user relies entirely on agricultural return flows (Figure 2c).

In each of these scenarios, water is scarce relative to the total demands of the two users. However, even though industry is willing to pay twice the amount per unit of water

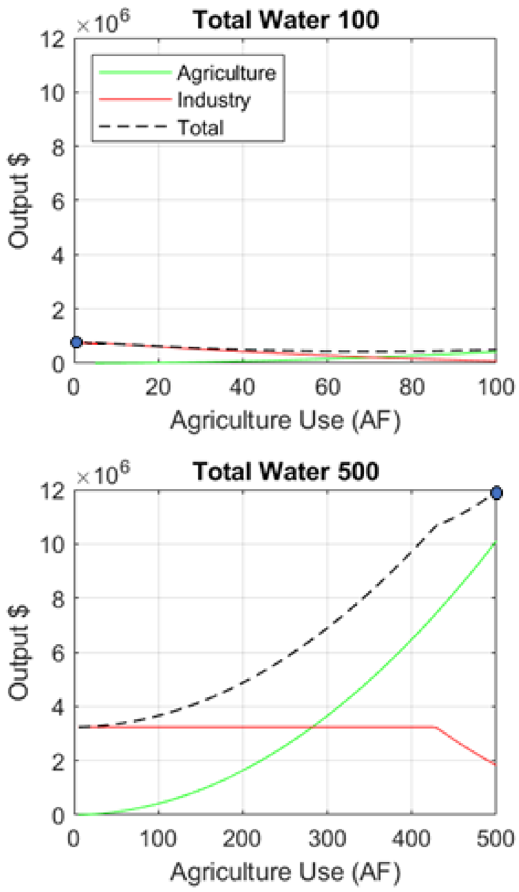

Figure 2. Comparison of water allocation between agriculture and industry and total economic output, for total water availability varying from (**a**) 100 AF to (**b**) 300 AF to (**c**) 500 AF. Maximum output (blue dots) is achieved for different relative allocations of water depending on the total water available. Note differences in x-axis between plots.

as agriculture, the maximum value is not always achieved when this sector simply takes all of the water it requires to maximize its own output. This underscores the importance of considering return flows, which can be seen in Figure 2b, where there is 300 AF of total water available. If the upstream agricultural user were to take only 150 AF of this water (red dot in Figure 2b), allowing industry to maximize its output by using the remaining 150 AF plus agricultural return flows, total economic value is actually lower than a scenario in which agriculture uses all 300 AF of the available water (60% of its peak demand; blue dot in Figure 2b). This is because the latter scenario still allows return flows to be used by the downstream industrial user, so that the total value for the industrial sector, while smaller than in the first allocation, does not go to zero. This is also true in the scenario where there is 500 AF of total water available (Figure 2c). In this case, even when agriculture withdraws all of the water from the system, its return flow (30% of 500 AF, or 150 AF) is almost enough to meet the industrial user's peak demand as well. Thus, even though the economic output per unit of water is half as large for agriculture as it is for industry, and there is not enough water to meet the full demand of both users, total economic value is still maximized when agriculture withdraws enough water to meet its full demand, given the assumed return flows from this sector.

3.2. Variation in relative value of water

Our second set of experiments focused on understanding the relationship between the value that each sector places on water and the optimal allocation of water between the two sectors. In these experiments, we varied the relative willingness to pay for water between the two users. To do this, we varied the slope of the demand curve for the (downstream) industrial user relative to the (upstream) agricultural user, and examined how the optimal allocation of water and total value changes for each of these scenarios. We characterized these differences as "willingness to pay ratios" of 1, 2, and 4, where the industrial user valued water the same, a factor of two higher, or a factor of four higher than the upstream user, per unit of water.

Figures 3a through 3c illustrate how the optimal allocation of water changes as the WTP ratio increases from 1 (Figure 3a) to 4 (Figure 3c), when the total water available is 300 AF (approximately 60% of the upstream agricultural user's total demand). As shown in Figure 3, when the WTP ratio is less than or equal to 2:1, value is maximized when the agricultural sector draws all of the available water and maximizes its output (blue dots in Figure 3a and 3b). In both of these scenarios, because agriculture is withdrawing its total maximum allocation, the downstream industrial user has access only to the return flow from the upstream agricultural user, which in these experiments is held fixed at 30% of agricultural withdrawals.

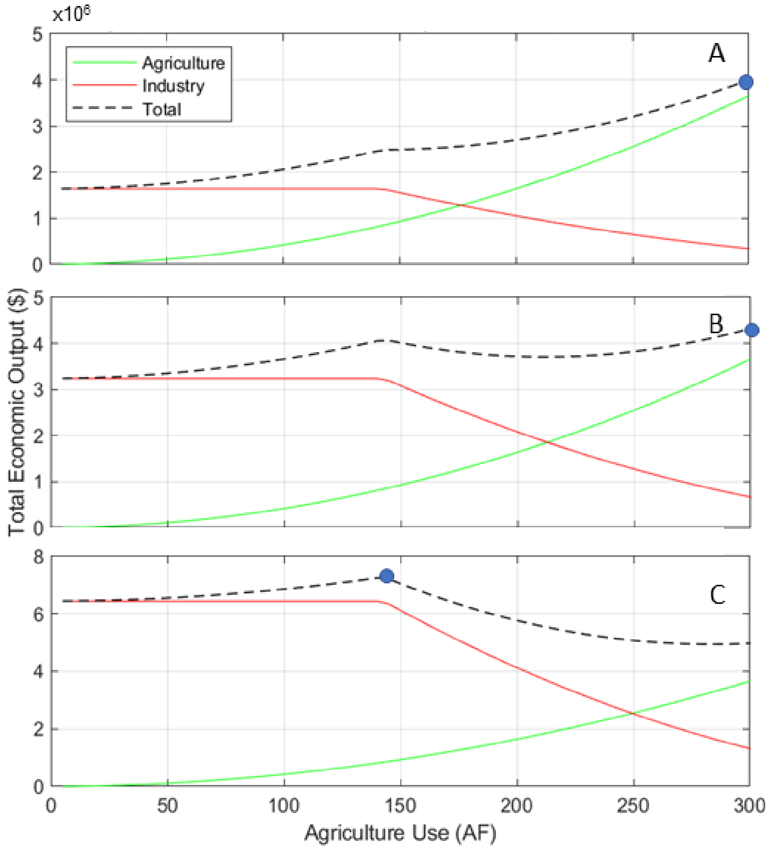

Figure 3. Comparison of optimal water allocation for 300 AF of total water, for WTP ratios of (**a**) 1:1, (**b**) 2:1, and (**c**) 4:1 between industrial and agricultural use. Maximum GRP (blue dots) is achieved for different allocations depending on relative WTP between the two sectors.

If the WTP ratio is increased to 4:1, economic value is maximized when the downstream industrial user is allowed to take the full 200 AF of water it requires to maximize the its own output (a sum of direct streamflow plus return flows from ~150 AF of agricultural use; blue dot in Figure 3c). In this scenario, the agricultural user's output is limited to what it can produce with only 100AF of water, or 30% of its total demand. However, because the value of water is substantially higher for the industrial user, total value in this scenario is approximately 50% higher than the total value in either of the previous scenarios. Thus, total output is determined not only by the total water available, but also by the differences in WTP for parties at different points within the basin.

3.3. Variation in return flows

In our final set of experiments, we examined the impact of varying the return flow from the agricultural user's withdrawals on the optimal allocation of water. As with the other parameters we explored, return flows exert the most leverage on economic outcomes when there is a water shortage. Thus, we focused these experiments on scenarios where the total water available (300 AF) is insufficient to meet the needs of both users.

Figures 4a through 4c illustrate how the optimal allocation of water changes as the return flows from the upstream use increase from 15% (Figure 4a) to 45% (Figure 4b) to 60% (Figure 4c). The lower return flow values of 15% and 45% approximately reflect the range of irrigation efficiencies for sprinkler and flood irrigation in agricultural systems in the Western United States, respectively (CWCB, 2017). In each of these experiments, the WTP ratio is set at 3:1, representing a 3x higher value per unit of water for the downstream industrial user than for the upstream agricultural user.

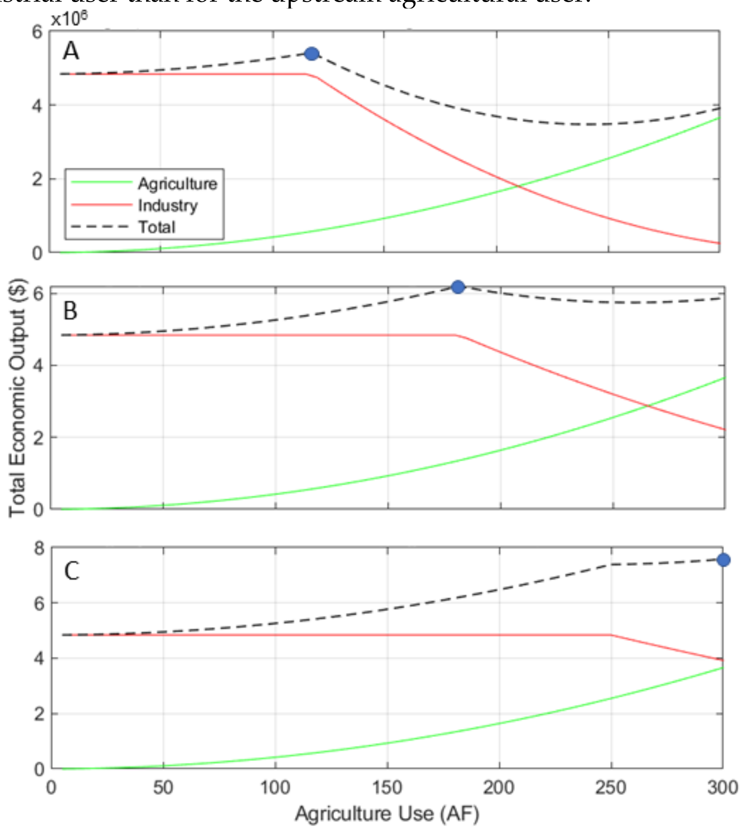

Figure 4. Comparison of optimal water allocation for 300 AF of total water, for upstream (agricultural) return flows of (**a**) 15%, (**b**) 45%, and (**c**) 60%. Maximum GRP (blue dots) increases, and optimal allocation shifts towards agricultural use, as return flow fraction increases.

The increase in return flow creates two effects, as shown in Figure 4. First, although the total volume of water available in all three of these experiments is fixed at 300 AF, the maximum economic value increases as the return flow fraction increases: the maximum attainable output with a 60% return flow is approximately 35% higher than it is when return flow is only 15%. This is simply a result of a higher total water availability for the downstream user, as return flows from the upstream user increase.

The second effect of increasing return flows is a shift in the optimal allocation of water between the upstream and downstream users. When agricultural return flows are lowest at 15%, total economic value is maximized when the agricultural sector uses only 25% of its total demand, or approximately 125 AF (Figure 4a), leaving the rest of the water for the higher-value downstream user. As agricultural return flows increase, however, the upstream agricultural sector can use a higher and higher fraction of its peak demand until at a 60% return flow it can use all of the water available (300 AF, or 60% of its peak demand) while still maximizing value for the whole economy. This scenario is possible because the lost revenue due to the water shortage for the industrial sector (200 AF – 0.6*300AF = 20 AF shortage) is more than compensated for by the increased production from the agricultural sector upstream.

3.4. Comparison to a prior appropriations scenario

For each of the evaluations above, we sought to find the allocation of water that maximized economic output, assuming that water could be freely re-allocated between users. In our final set of experiments, we compared two scenarios. The first is a "maximum value" scenario in which water can be freely traded to maximize overall economic output. The second is a "rigid" scenario in which the upstream user focuses on maximizing its own production. This latter scenario is similar to the way water is currently allocated across the Western United States: where a "senior" user makes decisions to optimize their own output, ignoring the needs of others. This system exists both because of the prior appropriations doctrine, and because mechanisms for water trade are currently limited (e.g., [4,11,13,14]).

Figure 5 shows the difference in total output between these "rigid" and "maximum-value" scenarios. In all cases, the user with the lower demand but higher value per unit of water ("industry") is downstream, and the user with the higher demand but lower value per unit of water ("agriculture") is upstream. The blue curves (rigid) represent the attainable total value for each scenario if the upstream user focuses on maximizing its own production, and the red curve represents the maximum attainable total economic value. The benefits of re-allocation of water away from the prior appropriations regime are highest when water is scarce, as shown by the grey shaded regions highlighting the difference between the two allocations.

Figures 5a and 5b compare model results where the WTP ratio is 3:1 (5a) vs 6:1 (5b). In both cases, the agricultural return flow is 30%. In each of these scenarios, the most rapid divergence between the "rigid" and "free trade" scenarios occurs between 0-200 AF of total water. Here, the added value from water re-allocation is a result of the upstream agricultural user releasing all of its water to the downstream industrial user, who places a higher value on each unit of water. Beyond 200 AF, the downstream industrial user's peak demand is fully satisfied, and agricultural production resumes. The difference between the rigid and trade optimized scenarios shrinks from this point up to a total water availability of ~400 AF (3:1 WTP ratio) or ~550 AF (6:1 WTP ratio), where the curves re-join. The location along the x-axis at which the rigid and optimized scenarios meet (400 AF vs 550 AF) reflects the difference in optimal allocation of water between the two sectors under these different WTP ratios (see Fig. 3).

Figs. 5b and 5c compare scenarios where the agricultural return flow is 30% (4b) vs 15% (4c) and the WTP ratio is 6:1 in both cases. As shown, the benefit of water re-allocation (grey shaded area) extends to a total water availability of ~650 AF when return flows are lower, vs ~550 AF when return flows are higher. This is because a total water volume of 550 AF is enough to satisfy both users' total demand (700 AF) when agricultural return flow is 30%, whereas the two users require a combined 650 AF of total water when return flows are lower.

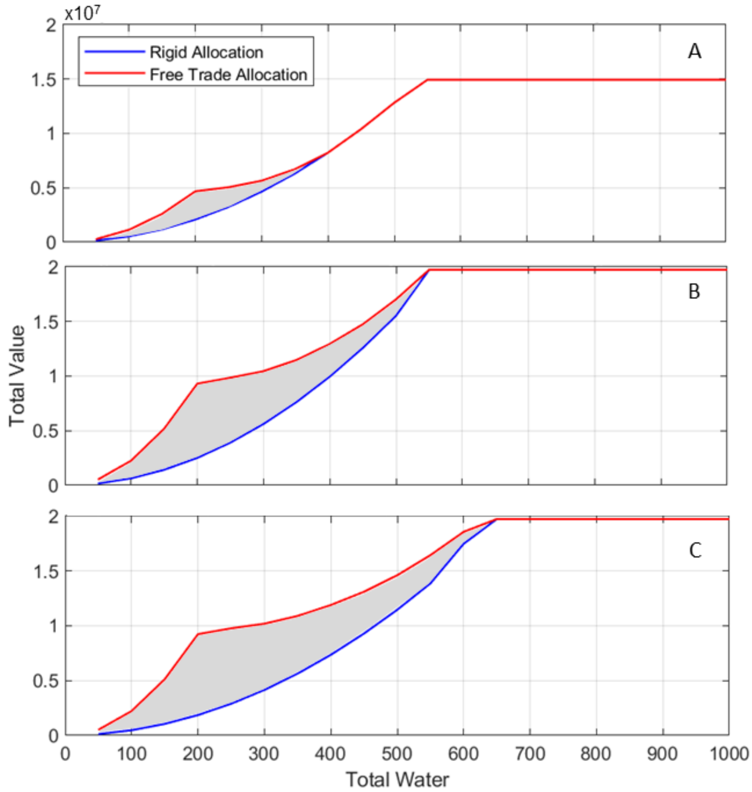

Figure 5. Comparison of attainable economic output under "maximum value" scenarios (red) vs a scenario in which the upstream user focuses only on maximizing its own output (blue). In all cases, the downstream user generates higher economic output per unit of water than upstream user. (**a**) WTP ratio of 3:1, agricultural return flow 30%. (**b**) WTP ratio of 6:1, agricultural return flow 30%. (**c**) WTP ratio of 6:1, agricultural return flow 15%.

In our initial model runs, we also modified the location of the two users in the system: placing the higher-valued industrial user upstream, rather than downstream from the lower-valued agricultural user. However, in these experiments where the higher-valued industrial user was upstream, economic value was almost always maximized when this user took its full allocation of water. The exception to this rule occurs when the WTP ratio is small and the return flow from the industrial user is also small. Figure 6 illustrates this effect for three scenarios where the industrial user is upstream. In the first two scenarios, the industrial user's WTP is twice that of the agricultural user and its return flow ranges from 10% (Figure 6a) to 40% (Figure 6b). In the third scenario, the industrial user's WTP is three times higher than the agricultural user and its return flow is 10% (Figure 6c).

In each of these cases, there is additional economic value to be added only over a very narrow range of total water availability, if the industrial user allows all of the water to be used by the agricultural user downstream. The peak increase in economic value from trade occurs at 500 AF of total water, where the complete transfer of water from industry allows the agricultural user to generate its maximum value. On either side of this peak, the range of total water availability over which trade increases economic value is sensitive to the return flow from industry and the WTP ratio. This is because the total economic value is universally higher with higher return flows or a higher WTP ratio, which limits the gains from trading downstream (compare the total value of "rigid" allocations between Figures 6a-6b). The same effect occurs when the WTP ratio is higher (compare Figures 6a-6c). For WTP ratios or industrial return flows much larger than the values shown in Figure 6, the advantages of water re-allocation disappear altogether.

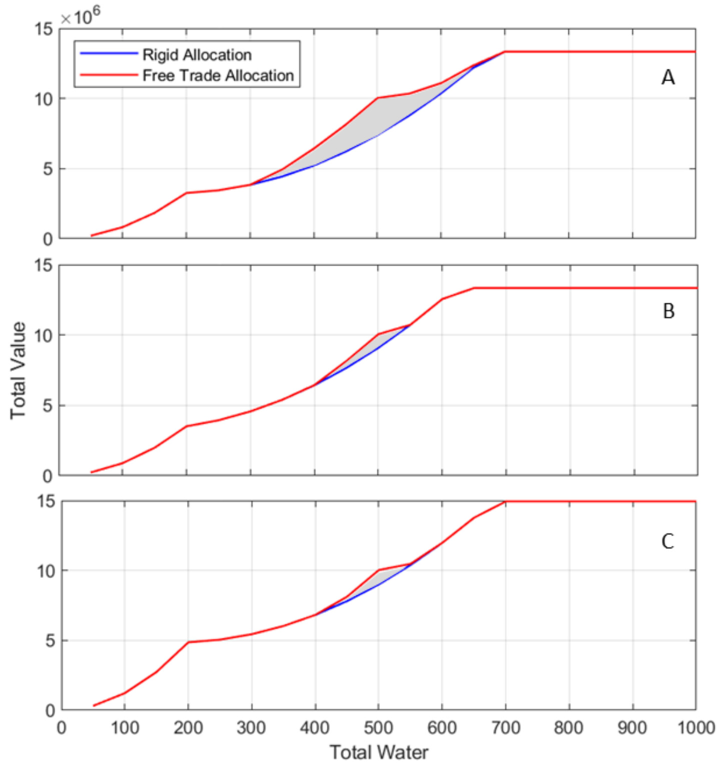

Figure 6. Comparison of attainable economic output under free trade scenarios (red) vs a scenario in which the upstream user focuses only on maximizing its own output (blue) when the higher valued industrial user is upstream. (a) WTP ratio of 2:1, industrial return flow 10%. (b) WTP ratio of 2:1, industrial return flow 40%. (c) WTP ratio of 3:1, industrial return flow 10%.

4. Discussion

Our simple model demonstrates two key points related to water allocation and use in water-scarce environments: First, we show that return flows cannot be ignored in analysis of economic value from these systems, because the optimal allocation of water depends on how much of the water is returned and can be used downstream. Second, we show that when water is scarce relative to total demand, the total economic value from water-intensive industries can be increased when water is re-allocated relative to a "rigid" prior appropriations system. While this result is consistent with prior research on the topic (e.g., [13,15,16]), our model also illustrates several new points about the dynamics of this coupled natural-human system.

When water is re-allocated between users relative to a "rigid" allocation, we find that the change in total economic value is sensitive to at least three conditions: the scarcity of water relative to the total demand across all sectors (see Figures 2 and 5); the difference in willingness to pay for water between sectors (Figure 3); and the return flows from the upstream user (Figure 4). Our model also shows that the maximum economic value for the entire economy is not always achieved when a lower-valued, upstream user sacrifices all of its output in favor of a higher-valued, downstream user. This is because a fraction of the upstream user's withdrawals remain available to the downstream user as return flows, allowing some of the water in the system to be extracted twice. Depending on the return flow fraction from the upstream user and the relative willingness to pay for water between the two users, the downstream user may be able to maximize its value in a water-scarce scenario even if the upstream user takes a fraction of the water for its own use (see Figures 3-4).

Our economic analysis is idealized, in that we used a partial equilibrium analysis rather than a more complete, computable general equilibrium (CGE) analysis to simulate the value placed on water. Because of this, our current framework implicitly assumes that no other prices in the economy (like wages of workers in each sector) are impacted by the allocation changes described here. We further assume that there are no other market failures (tax distortions, non-market goods, etc.) that would be impacted by changes in water allocation. These additional complexities are best explored in a CGE framework, which is a focus of ongoing research.

Our physical model is clearly an abstraction of real water systems, which are characterized by multiple users with a range of demands, values and seniority. While our modeling framework is a simplification of the many processes, interactions, and feedbacks among multiple users in real systems, it is also easily interpreted, allowing us to explore the key factors that control the dynamics of this coupled human-natural system. Future work will be focused on gradually adding complexity to the model, so that we can begin to explore time-varying water demand and supply among multiple user groups in a more realistic system.

Author Contributions: Conceptualization: C.W., E.S., J.C., B.L., B.S., H.K., and P.M.; methodology: C.W. and E.S.; formal analysis: C.W.; writing – original draft preparation: C.W.; writing – review and editing: C.W., E.S., J.C., B.L., B.S.,, H.K., and P.M.; supervision, B.L.; project administration, B.L.; funding acquisition, B.L., E.S., J.C., and C.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by US National Science Foundation Grant #2009922, awarded to B. Livneh

Data Availability Statement: Model code and materials used in the preparation of this manuscript will be made available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. MacDonnell, L.J. Prior Appropriation: A Reassessment. *SSRN Journal* **2015**, doi:10.2139/ssrn.2691098.
2. Zellmer, S.B.; Amos, A.L. *Water Law in a Nutshell*; 2021; ISBN 978-1-64020-414-0.
3. Brewer, J.; Glennon, R.; Ker, A.; Libecap, G.D. Water Markets in the West: Prices, Trading, and Contractual Forms 2007.
4. Howe, C.W.; Goemans, C. Water Transfers and Their Impacts: Lessons from Three Colorado Water Markets1. *JAWRA Journal of the American Water Resources Association* **2003**, *39*, 1055–1065, doi:10.1111/j.1752-1688.2003.tb03692.x.
5. GRIFFIN, R.C.; BOADU, F.O. Water Marketing in Texas: Opportunities for Reform. *Natural Resources Journal* **1992**, *32*, 265–288.
6. Johnson, R.N.; Gisser, M.; Werner, M. The Definition of a Surface Water Right and Transferability. *The Journal of Law and Economics* **1981**, *24*, 273–288, doi:10.1086/466984.
7. Gould, G.A. Water Rights Transfers and Third-Party Effects. *Land & Water L. Rev.* **1988**, *23*, 1.
8. Huffaker, R.; Whittlesey, N.; Hamilton, J.R. The Role of Prior Appropriation in Allocating Water Resources into the 21st Century. *International Journal of Water Resources Development* **2000**, *16*, 265–273, doi:10.1080/07900620050003161.
9. Burness, H.S.; Quirk, J.P. Appropriative Water Rights and the Efficient Allocation of Resources. *The American Economic Review* **1979**, *69*, 25–37.
10. Libecap, G.D. The Assignment of Property Rights on the Western Frontier: Lessons for Contemporary Environmental and Resource Policy. *The Journal of Economic History* **2007**, *67*, 257–291, doi:10.1017/S0022050707000101.
11. Leonard, B.; Costello, C.; Libecap, G.D. Expanding Water Markets in the Western United States: Barriers and Lessons from Other Natural Resource Markets. *Review of Environmental Economics and Policy* **2019**, *13*, 43–61, doi:10.1093/reep/rey014.
12. Weckström, M.M.; Örmä, V.A.; Salminen, J.M. An Order of Magnitude: How a Detailed, Real-Data-Based Return Flow Analysis Identified Large Discrepancies in Modeled Water Consumption Volumes for Finland. *Ecological Indicators* **2020**, *110*, 105835, doi:10.1016/j.ecolind.2019.105835.
13. Chong, H.; Sunding, D. Water Markets and Trading. *Annual review of environment and resources* **2006**, *31*, 239–264.
14. Howitt, R.; Hansen, K. The Evolving Western Water Markets. *Choices* **2005**, *20*, 59–63.
15. Ghosh, S.; Cobourn, K.M.; Elbakidze, L. Water Banking, Conjunctive Administration, and Drought: The Interaction of Water Markets and Prior Appropriation in Southeastern Idaho. *Water Resources Research* **2014**, *50*, 6927–6949, doi:10.1002/2014WR015572.
16. Hagerty, N. Liquid Constrained in California: Estimating the Potential Gains from Water Markets. 80.