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Integrated Policy Solutions for Water Scarcity in Agricultural Communities of the American Southwest

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Abstract: The conventional approach of policy interventions in water management that focus on the portions of the system that directly relate to water often lead to unintended consequences that potentially exacerbate water scarcity issues and present challenges to the future viability of many rural agricultural communities. This paper deploys a system dynamics model to illustrate how expanding the policy space of hydrology models to include socioeconomic feedbacks could address these challenges. In this regard, policies that can potentially mitigate general water scarcity in a region of the American Southwest in southern New Mexico are examined. We selected and tested policies with the potential to diminish water scarcity without compromising the system's economic performance. These policies included supporting choices that reduce or limit the expansion of water-intensive crops, promoting workforce participation, encouraging investment in capital, and regulating land use change processes. The simulation results, after the proposed boundary expansion, unveiled intervention options not commonly exercised by water decision-makers, bolstering the argument that integrated approaches to water research that include socioeconomic feedbacks are crucial for the study of agricultural community resilience.

Keywords: water scarcity; socioeconomic policy; agriculture; system dynamics; simulation

1. Introduction

Managing scarce water resources in dryland—arid and semiarid—regions remains challenging. Although development economists do not usually consider water in the production function of their models, except for narrow crop pattern analyses [1–3], it has become an increasingly important factor in economic development processes, especially where agriculture is significant [4]. Similarly, typical hydrology models ignore feedback effects of socioeconomic factors such as income or population [5,6]. There are only a few interdisciplinary studies that take both sides of the equation into account (e.g., Picardi and Saeed [7], Saysel et al. [8], Simonovic and Rajasekaram [9], Gunda et al. [10]). This paper bridges this gap through a previously developed system dynamics model [5] that considers important feedback loops within and between the two interconnected systems: water and society. This boundary expansion offers a policy space that we explored to reveal the effects of innovative water solutions that are usually untapped by traditional disciplinary analyses. Exploration of the policy space builds a foundation to foster "resilience thinking" in collaboration with stakeholders [11]. The analysis of the implications of innovative alternatives is an important institutional role for supporting social learning, which is essential to adaptively manage social–ecological complexities [12].

In this study, we build on an original system dynamics model [5] to address a water resources management problem in the county of Doña Ana in southern New Mexico, US. The problem of the study site is the scarcity of water resources, which is a common contemporary issue. The underlying causes of extreme water scarcity are characterized

by the multiple dynamics of drought. Much study has emerged in recent years on this socio-environmental challenge. A recognition has emerged that drought is generated from across the socio-environmental system, leading to five distinct definitions of drought: meteorological, agricultural, hydrological, socioeconomic, and ecological [13]. Our contention is that it is critical to look at the integrated system spanning these effects. The community of researchers that have been central to studying vulnerabilities to drought have concluded that a critical goal is to build the social and institutional capacity to anticipate water scarcity issues and mitigate the effects of drought through planning and policy interventions [14,15]. The capacity for innovation has been found to be critical for the resilience, adaptability, and transformability of socio-ecological systems [11]. We have been working with a large cross-section of stakeholders, and to address our goal to facilitate building social and institutional capacity, we tested the expansion of the analysis boundary beyond traditional approaches. Exploring innovative potential dynamics is a critical step in laying the groundwork for our future stakeholder collaboration, which will further develop the model from the perspective of stakeholder decisions.

The common policy interventions in water management consider the supply side, while the demand side is usually ignored. The supply-side policies that typically focus upon the portions of the socio-hydrologic system that directly relate to water, such as water efficiency, result in narrow applications that often lead to unintended consequences [16]. Some of the direct consequences are hydrologic; for example, flood irrigation from surface water provides important benefits of recharge to groundwater aquifers, and conversion in these systems to drip irrigation has resulted in plummeting groundwater levels in many instances. When pumping groundwater, such efficient systems offer important benefits, but errors in the water quantity allowance or distribution have resulted in higher water use overall since a much higher volume of water is actually consumed by the crops, which we call a higher consumptive use, and thus a much lower volume is returned to the surface or groundwater system [16].

Indirect consequences can challenge the viability of rural agriculture. In southern New Mexico, as with other places with large agricultural water use, water scarcity impacts the value of water, which has frequently increased above the agricultural output value of the land. There are strong incentives for farmers to sell their water rights, fallow their fields, and leave agriculture [17]. While many argue that the densification of agriculture and the transfer of water to higher monetary value activities may provide some societal benefits, it is also critical to consider values that agricultural communities hold that are adversely affected, as well as the multi-functional benefits of agriculture [18]. The departure of Americans from a livelihood of farming along with the concentration of the farming industry has been identified as one of the most significant transitions of the past century [19]. By 2000, the number of farms had fallen by 63%, and less than two percent of Americans remained working as farmers [20]. Trends of policies to support farmers' well-being have declined, with over 93% of farming families adapting by earning off-farm income [20]. The preservation of agricultural land has been recognized internationally as an important priority to address predicted critical needs such as feeding a growing world population, providing food security for local regions and disadvantaged communities, and fostering multiple potential ecosystem services such as increasing the health of the surrounding ecological systems [21]. Policies of ecosystem service payments demonstrate the value of the multi-functional benefits, where downstream communities pay upstream farmers, for example, to adopt sustainable practices [22]. The multiple values of agricultural land and sustainable practices beyond crop output lead us to our overarching goal of examining the long-term sustainability of the overall social–hydrologic systems. Additionally, water scarcity is one of the largest challenges to resilience for the agricultural community [23]. Here, we test policies that ease some pressure on water resources but at the same time improve the general economic welfare of the society and do not invoke competition between sectors.

The study site, as is common for many agriculture-based communities in dryland regions, has been struggling to keep a balance between actual and sustainable use and thus is facing chronic water scarcity [24–27]. The historical estimate and one potential future scenario of a measure of water scarcity for our study site, generated by the system dynamics model presented in this paper, is shown in Figure 1. The presented measure, which shows an example of the persisting nature of water scarcity, is a normalized 10 year moving average of the discrepancy between actual use and sustainable supply that would ensure that total outflow from the system stays equal to or lower than the total inflow, meaning that neither surface water deliveries to downstream users nor groundwater balance would be compromised. The discrepancy is then divided by the total withdrawals to reflect the magnitude of the shortage relative to the system's demand. The 10 year moving average is used to reflect the long-term cumulative causation effects of the system.
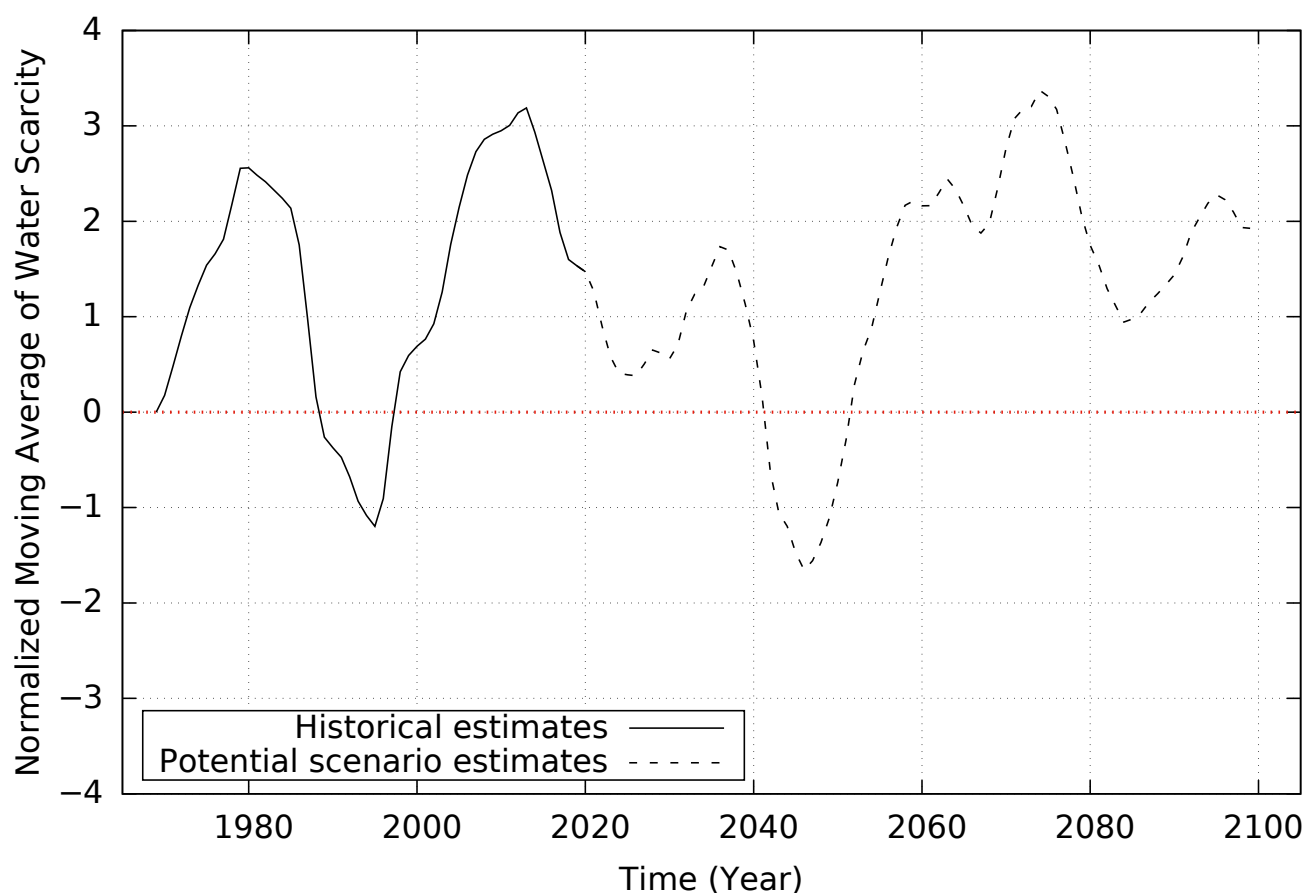

Figure 1. Potential magnitude of a preliminary estimate of water scarcity in the Hatch and Mesilla Valleys.

Water scarcity is characterized in the model as a discrepancy between total actual water withdrawals and total "sustainable" water supply. Sustainable water supply is defined here as the amount of water available for supply that does not compromise surface water delivery to downstream users or affect the balance of groundwater flows. This quantity ensures that total outflow from the water stocks stays equal to or higher than total inflow to the stocks for an extended period of time. The current water scarcity trend (Figure 1) lays above the zero line for most of the time periods. This does not only damage the viability of agriculture in the region, but may also cause a number of ecological, environmental, and economic issues in the long term.

To decrease the trend of water scarcity, several policies could theoretically be implemented. A policy that has been proposed across the Southwest and in this region is a change in cropping patterns toward less water-demanding crops that could reduce water demand pressure and subsequently could ease water scarcity issues. In 2005, the state of New Mexico implemented a surface water allotment restriction for water-intensive, high-value crops (e.g., pecan) that has, in effect, slowed down the expansion of such crops in the state [28]. We modify the original Lower Rio Grande (LRG) model to contain the feedback structure needed to test this policy in retrospect. We analyze the results of this test and discuss the implications. We also discuss the practical difficulties in the implementation of further restrictions of this kind and argue that some socioeconomic interventions that are usually outside of the traditional water policy sphere could ease the implementation burden and are likely necessary to support the overall management system. We then tested the expanded boundary in our analysis to enable future stakeholder collaboration. In particular, we focus on workforce participation, non-agriculture investment, land use changes, and income distribution schemes. Simulation results indicate that a socioeconomic policy package can mitigate water scarcity issues, depending on the case at hand.

To report our findings, this paper is organized as follows. Section 2 describes the methods we have used in this paper, including the original LRG model that we applied here as well as our modifications that are informed by a real-world policy and the feedback structure underlying it. Section 3 explains policies that we have identified as potential solutions to the problem and presents their impacts. This section also discusses the uncertainty experiments under alternative climate scenarios and the interpretations of the results. Section 4 then concludes the paper.

2. Methods

A reliable policy analysis model must include key decisions and relationships that are endogenous to its structure and affect the issue that the policy aims to address [29]. That is, the model should reflect the changes in decisions and functions as the system's dynamics evolve. Models that do not include the key feedbacks fail to reliably predict the dynamic behavior of social-ecological systems over the long term [5]. As such, the model we use here is based on a Lower Rio Grande (LRG) system dynamics model that includes important feedback interactions of the system. This model is extensively documented in Langarudi et al. [5]. Updated documentation of the model also accompanies this paper in the Supplementary Materials. The LRG model is calibrated for southern New Mexico's Doña Ana County, which nearly completely contains the Hatch and Mesilla Valleys, using historical data that are also reported in the Supplementary Materials. The primary purpose of the model is to explore the impact of alternative policies or scenarios on the long-term dynamics of water and society. In support of that goal, as advocated by Gallagher et al. [30], this work develops system dynamics tools that lay the groundwork for future collaborative modeling with our stakeholders.

As illustrated in Figure 2, the LRG model operates as an offshoot that utilizes the outputs of the New Mexico Dynamic Statewide Water Budget (NMDSWB), a hydrology simulation model developed by the New Mexico Water Resources Research Institute (NMWRRI). Running on a monthly basis from 1975 to 2099, NMDSWB utilizes extensive data inputs and deploys a water balance approach to characterize historical behavior and predict future trends of New Mexico's water resources. To learn more about the data sources and technical details of this model, please refer to Peterson et al. [31].

Although NMDSWB and LRG models are separate structurally, the NMDSWB model's outputs are used to drive the LRG system dynamics model's exogenous inputs and calibrate and validate its outputs. The LRG model is minimalistic in its design and reliance on exogenous drivers, which enables a more focused and dynamic analysis of the study question. The exogenous variables are limited to surface water inflow, precipitation, irrigation precipitation, temperature, and workforce participation rate.
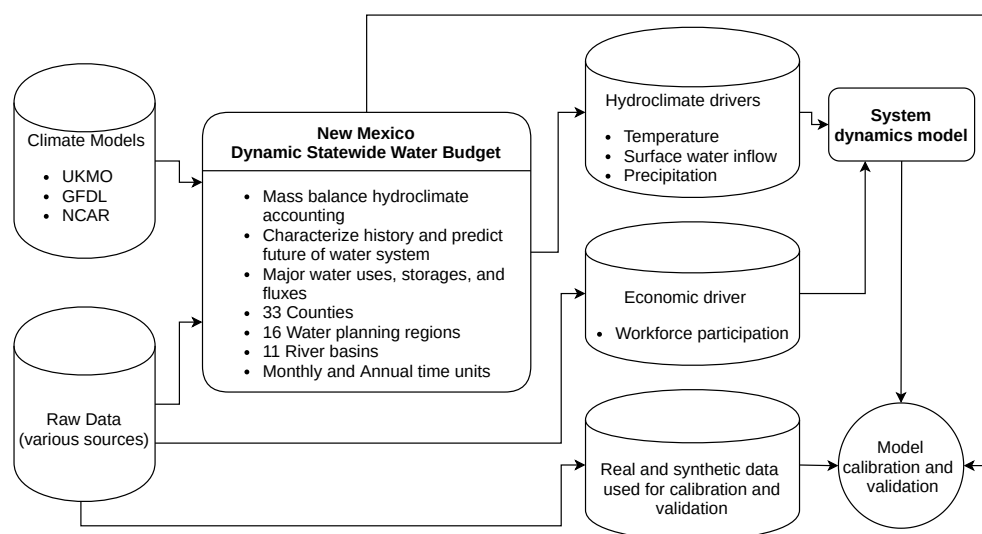
Figure 2. Schematic connection between the LRG system dynamics model and New Mexico Dynamics Statewide Water Budget (NMDSWB) [31].

A simplified overview of the LRG model architecture is shown in Figure 3. The model consists of modules categorized into four groups: water and climate, agriculture, economy, and population. There are complex feedback networks that regulate the interactions within and between the water and society systems. Feedbacks of particular note include the groundwater–surface water interactions as well as the interrelationship between water, population, capital, and agriculture and non-agriculture employment and production. The logic and evidence behind these relationships are documented in the Supplementary Materials.
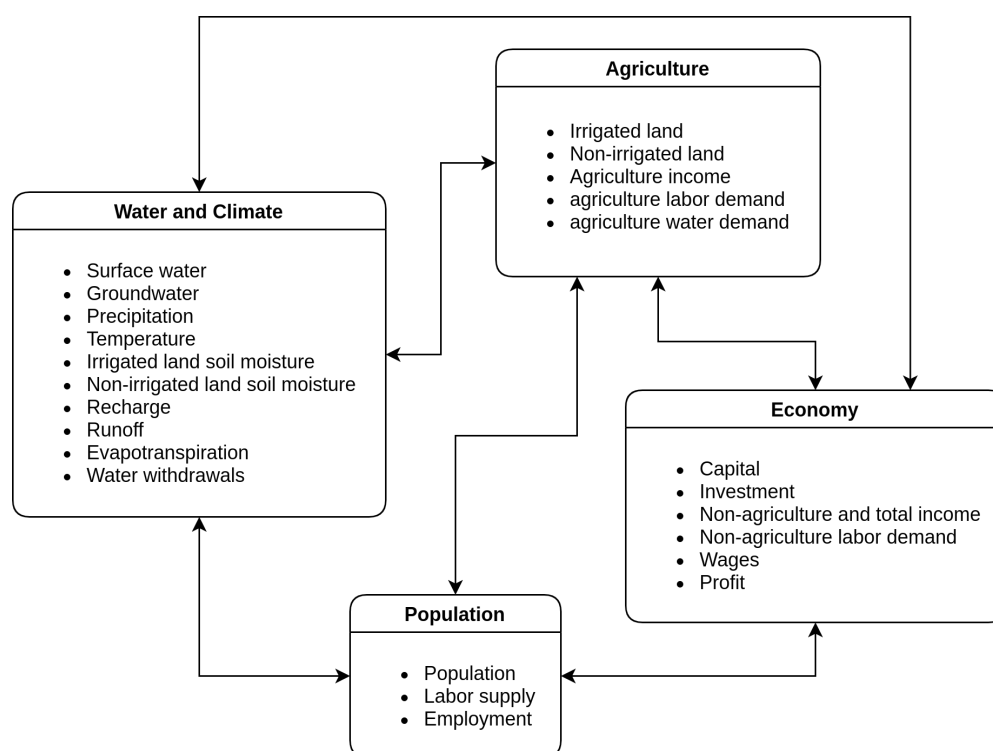

Figure 3. High-level structure of the system dynamics model.

The model successfully passes the conventional system dynamics confidence building tests using the practical guide provided by Langarudi and Radzicki [32]. Details of the verification and validation processes are explained in the Supplementary Materials. The model structure is built upon the fundamental physical and behavioral rules that exist in many dryland social–hydrology systems. Thus, the model can serve as a generic structure for systems that have similar boundaries.

The original LRG model was developed for the exploration of water–society interactions and was not targeted toward policy testing. As such, it needed some further modifications before we could use it to incorporate and test some specific policies, and we revalidated these modifications using the historical data. A water policy that is argued to be effective in addressing water scarcity is to place a limit on the volume of water associated with a water right, which in effect limits the expansion of water-intensive (e.g., orchard) crops. Around 2005, this policy was indirectly applied to some extent in our study area by limiting the ability to increase the quantity of surface water allocation desired by farmers of water-intensive crops, thus practically reducing the incentives for the unlimited growth of such crops [28]. The expansion of pecan trees did indeed slow down in the area after 2005, as depicted in Figure 4, which presents the historical trend of land allocated to pecan trees in the region both in absolute (panel a) and relative (panel b) numbers. The trend is S-shaped growth with the initial exponential increasing until 2005, when the growth decelerates and eventually halts.
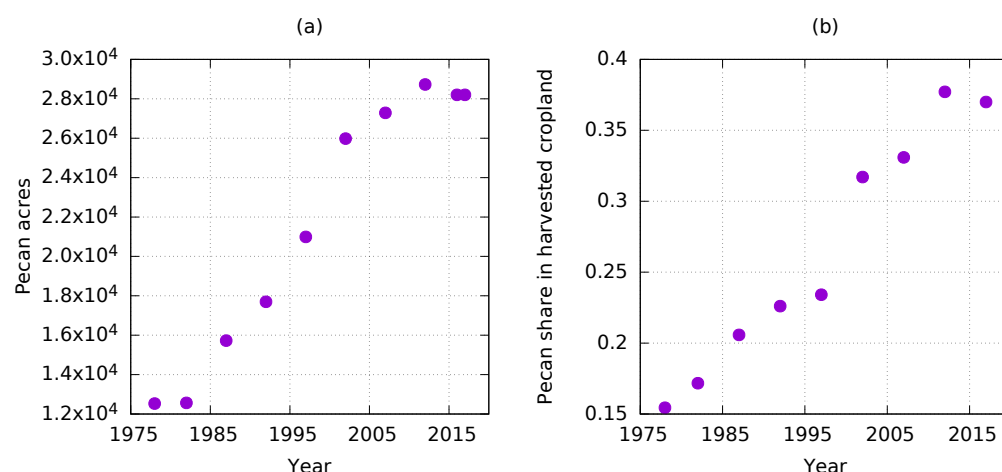

Figure 4. Change of cropping pattern in the study region represented by the land allocated to pecan (**a**) and its share in total harvested cropland (**b**) [33].

Agricultural income also exhibits S-shaped growth (panel a in Figure 5). The original LRG model keeps the cropping pattern constant and assumes that the income growth is driven by technological growth, which itself is an increasing function of capital (any non-human means of production and services such as infrastructure, machinery, equipment, technology, etc). This simplification might be adequate for the exploratory purpose of the original model; however, the cropping pattern trend shown in Figure 4 is probably the main driver of the S-shaped growth of farm income, particularly because pecans are more profitable than other local crops. The scatter plot in Figure 5 (panel b) reveals the significance of this relationship. Moreover, in contrast to the original assumption, this new formulation is more useful as it enables us to test the impact of a political limit on the expansion of water-intensive crops.
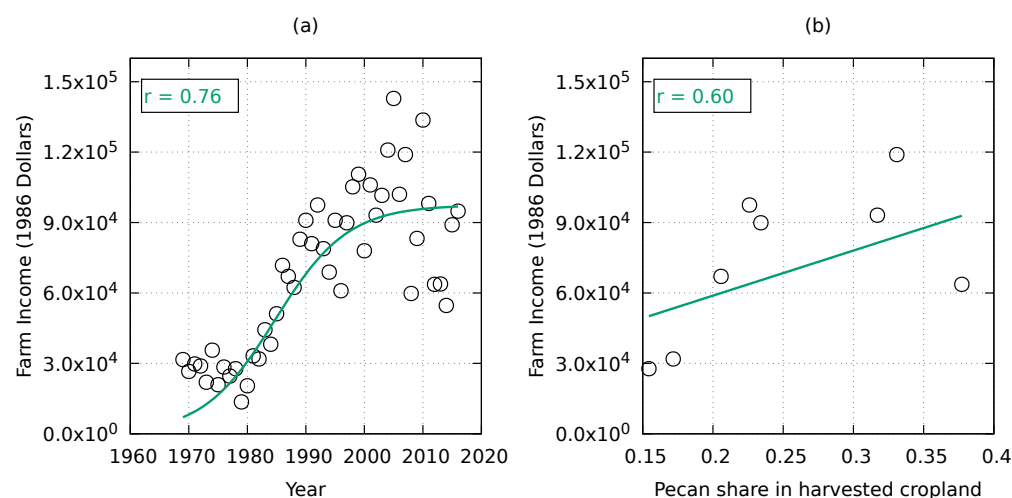
Figure 5. Historical trend of farm income in the study region (**a**) [34] and its relationship with the share of pecan in total harvested cropland (**b**).

To simulate the dynamics of crop patterns at an aggregate level, we introduce two new assumptions. First, the market incentivizes high-value crops, such as orchard crops, despite their large water requirements. Second, water availability per unit of land serves as another incentive for investment in water-intensive crops. Water-intensive crops usually generate more income and, in the long term, make the agriculture sector more attractive. Consequently, more land will be irrigated, or the declining trend of irrigated land will become less steep, if water availability is high. To capture these mechanisms, the following changes are made to the original LRG model:

1. The normal water requirement (an average level of water that is required for an acre of irrigated land), which was constant in the original model, is now a function of the perceived water supply per acre. This modified function increases with a decreasing rate (i.e., $f' > 0$ and $f'' < 0$). That is, the water requirement (share of water-intensive crops in total land) increases as water availability increases. However, the marginal addition to water requirements derived from additional units of water availability declines as the water requirement increases. The diminishing marginal requirement reflects the physical limitation of the system in expanding water-intensive crops. A smoothed (perceived) value of water supply is used instead of its instant counterpart in order to capture the fact that the information farmers obtain in advance for planning is approximate, and they cannot react to the actual changes in the water supply per acre instantaneously. Cropping patterns are set in advance due to the requirement of considerable planning and implementation efforts, and changes will lag behind actual water distributions;

2. The water supply per acre is introduced as a ratio of agricultural water use and total irrigated land. Note that water used for irrigation is affected heavily by the surface water inflow to the system, which is an exogenous driver and depends on the volumes of upstream snowpacks. Therefore, water supply per acre, which depends on irrigation use, is also influenced by the variations of the surface water inflow;

3. The effect of crop pattern on income is added as a nonlinear function of the normal water requirement with $f' > 0$ and $f'' > 0$. Model calibration reveals that f'' is relatively large, indicating that additions to the normal water requirement increasingly add to the income. Note that any addition to the normal water requirement means an accelerated increase in the share of water-intensive crops in the total land, explaining the increasing slope of the effect function. This effect then will enter the agriculture production function as a multiplier.

As depicted in Figure 6, the structural changes mentioned above add at least two major negative feedback loops to the original model.
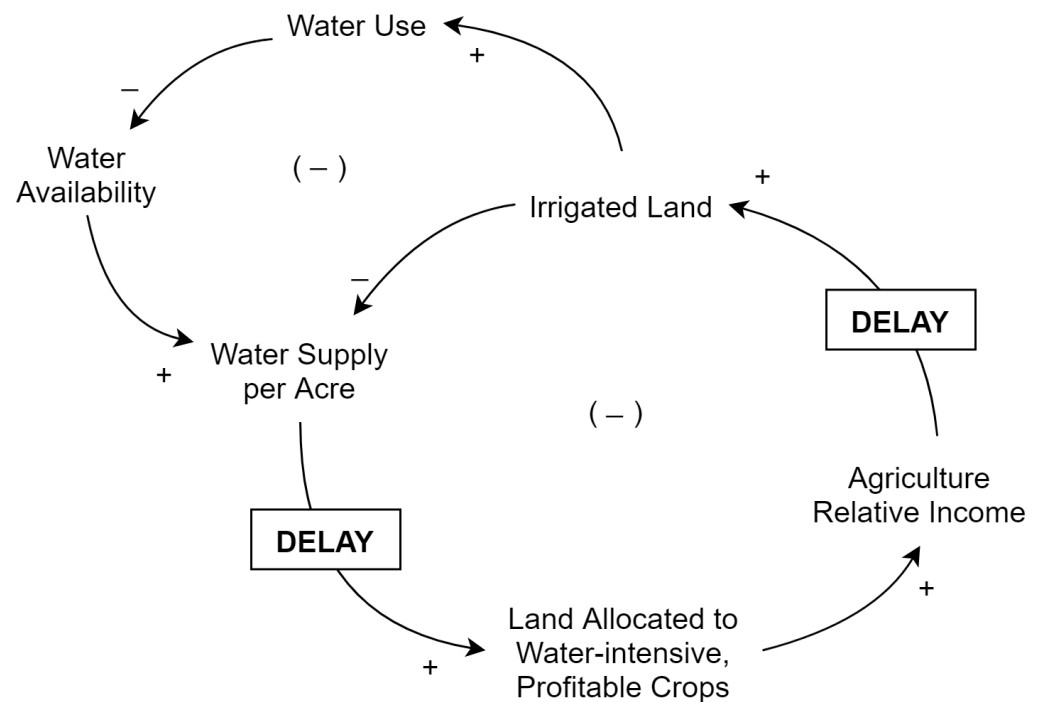

Figure 6. Additional feedbacks created by the new assumptions.

3. Results and Discussion

With the modified LRG model, we could then test the impact of the implementation of the 2005 policy, which limited the volume of water associated with a water right and in effect slowed down the expansion of water-intensive crops. We compared the results to a situation that did not assume such an imposed limitation.

As such, in Equation (1), the average crop water requirement (y) is a function of available water per acre (x) and features a natural limit (α) and an artificial or imposed cap (λ). Naturally, the average water requirement will not exceed a certain level depending on the crop portfolio of a region. In the model, this limit is assumed to be around eight acre-feet per year (AFY), a cap which includes the distribution from the reservoir before conveyance losses and groundwater allocations, which vary from 1.5–2.5 AFY. Note that this value is not the actual requirement but a hypothetical cap. Currently in the region, per acre of land, 3 feet of water is supplied from surface water, 1.5 from groundwater and an additional 1 foot is provided for some pecan fields, leading to 5.5 feet per acre per year. However, depending on the condition of water, these values could change in the long-term to match the realities of the system. Additionally, it should be noted that approximately half of the released water will be lost through conveyance. Therefore, the water requirement here is calculated to be about twice as large as the actual consumption required by the average crop.

$$y_t = \min\left(\lambda, \frac{\alpha}{1 + e^{-\beta x_t}}\right) \tag{1}$$

The actual requirement moves increasingly close to λ as x increases. When x is very small, the requirement drops to a value close to 4 feet per acre per year. The imposed or artificial limit then could be anywhere between four and α. The base model assumes $\lambda = \alpha$,

so no artificial limit is imposed. In our policy test, we assume $\lambda = 6.5$ which is closer to the average of the reality of our case study.

The modified model is calibrated so it fits the original LRG model for the historical period. Figure 7 presents a comparison between the behavior of the base and the limitation scenarios applied on the modified model for the key variables; i.e., cumulative water shortage, income per capita, irrigated land, and equality.
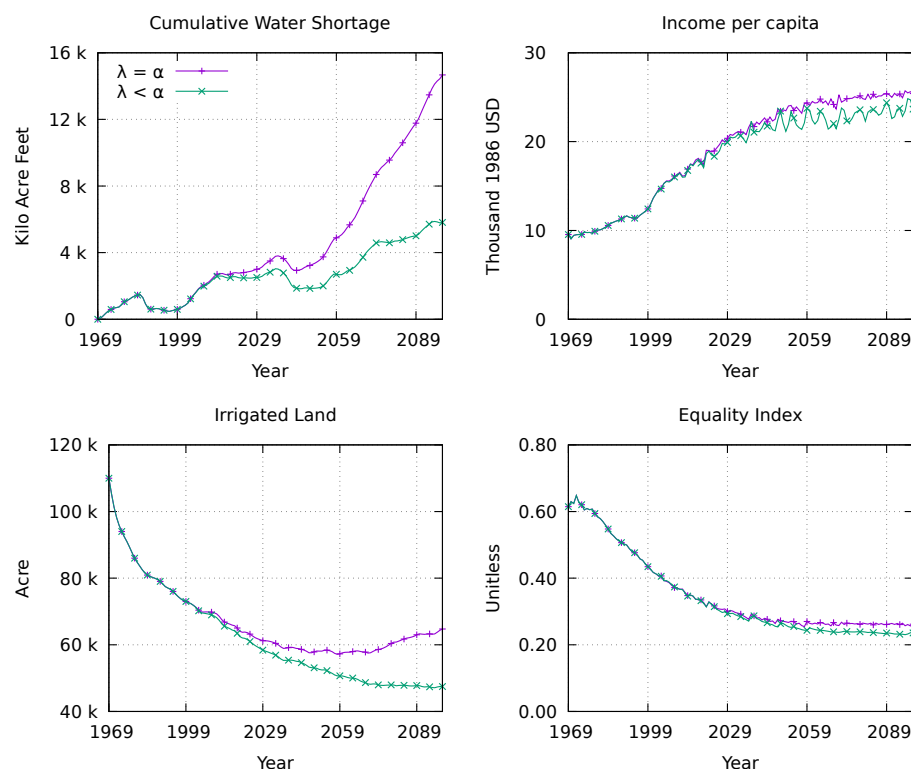

Figure 7. Simulation output for key variables of the modified model under two scenarios: (1) $\lambda = \alpha$, i.e., there is no cap imposed on water requirement, and (2) $\lambda < \alpha$, i.e., a cap is imposed on water requirement, so the expansion of water-intensive crops is prohibited after a certain level.

To ensure that the policy results are accurately valued, we use cumulative water shortage instead of the normalized water scarcity index presented in Figure 1. The normalized index is a useful measure for a problem statement because it captures the magnitude of the problem relative to the size of the system. It divides the amount of water shortage by total withdrawals (demand), making the index comparable with situations in other water-scarce areas. This practice (dividing the shortage by demand), however, makes the shortage index an inappropriate policy measure because it underestimates the value of the demand-side water management exercises versus supply-side exercises. To illustrate, let us assume that, in a system, the water supply is 80 units and water demand is 100 units; then, the scarcity index will be 20%. In reaction to the water shortage, the management implements a policy that successfully reduces water demand to 90 units. In this case, the numerator of the scarcity index (demand–supply) declines, but simultaneously, the denominator (demand) also drops; that is, the reduction in the index does not fully compensate for the magnitude of the decline in demand. The water scarcity index will be about 11.11% in this example. Now, assume that the management increases water supply, instead of reducing the demand. Further, assume that the magnitude of the increase in supply is equal to the amount of demand reduction in the previous demand-side policy example; that is, supply increases from 80 to 90 units while demand remains at 100 units. This time, the index declines to 10%. This appears to be a more successful policy than the demand-side policy.

However, the difference between the two is simply an artifact of the particular formulation of the index.

Not imposing a cap on the water requirement is shown to change the system's dynamics (Figure 7). In this case ($\lambda = \alpha$), the declining trend of the irrigated land turns around after about three decades into the future, which accelerates the surge of water shortage. Income per capita rises due to greater levels of agriculture. Wages also rise as the unemployment rate declines, thus leading to higher levels of equality.

One counterintuitive outcome is that, under the new setting, the surface water outflow that the region is supposed to deliver to downstream users improves. Accumulated surface water outflow increases by about 2%. Tracking the simulation outputs for causes and effects in the model reveals that this outcome is due to the greater return flow generated by the greater irrigation that is supplied from the groundwater. Increases in groundwater pumping for irrigation lead to increases in surface water return, as irrigation drainage recharges surface water through horizontal flow and runoff.

Another interesting outcome is that even the strict control of cropping patterns ($\lambda < 6.5$) cannot reverse the increasing trend of water shortage. To search for alternative levers that could help to achieve this goal, we experimented with the model by running extensive, exploratory sensitivity simulations on the model. These simulation experiments helped us to find solutions outside of the usual water resources management and policy domain.

The exploratory simulation experiments to search for additional high leverage policies were guided by a dynamic hypothesis, as illustrated in Figure 8. This hypothesis consists of two groups of positive feedback loops that basically form a success-to-the-successful system archetype—a simple causal structure that explains a wide variety of dynamic problems Wolstenholme [35], Clancy [36]. The two positive feedback loops on the northeast part of the diagram that represent agricultural growth compete with the three southwest loops that represent non-agricultural growth. The policies presented in this section strengthen the non-agricultural growth. The non-agriculture systems are usually more productive than agriculture systems; that is, total gain in the non-agriculture loops is greater than total gain in the agriculture loops. Thus, the policy disturbance hypothetically leads to reduced levels of agriculture and shifts the economic resources toward the non-agriculture sector. We expect that, through this shift, the system will eventually reach a new balance where water demand is lower; thus, the water shortage is reduced. However, this reduction requires a loss of irrigated land from the total water budget, even if it does not necessarily decrease agricultural income. Thus, we examine these existing dynamics and alternative policies that provide support for the viability of agricultural communities with the additional consideration of the dynamics of land under production in agriculture.

The following subsections describe the resulting interventions that we derived through sensitivity simulations and are followed by the test outcomes. The objectives of these policies were twofold: (1) they do not impose the tension that water policies usually create between powerful political entities that are stakeholders of the water resources, and (2) they not only ease some pressure on water resources but at the same time improve the general economic welfare of the wider society.
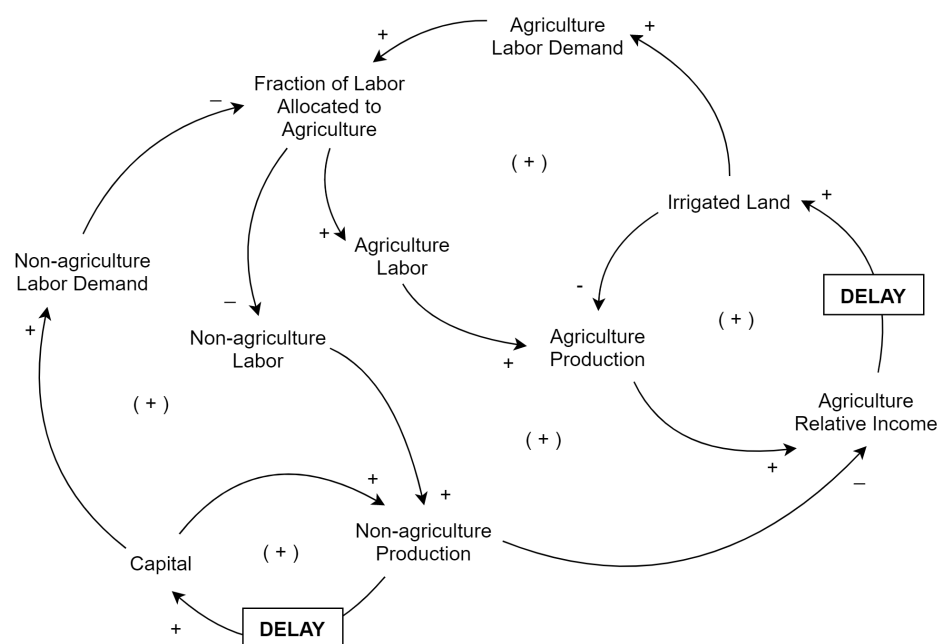
Figure 8. A dynamic hypothesis that explains the potential channels through which the selected policies may restrict water shortage.

3.1. Policy A: Promote Workforce Participation

Change in workforce participation was shown to have potential as an intervention to boost economic performance. Although this policy is expected to improve both agriculture and non-agriculture sectors, the non-agricultural sector will probably benefit more due to the dynamics explained earlier (Figure 8). As a result, in this scenario, we expect a decline in irrigated land over time, which will result in a reduction of total water use in the long-run.

The greater workforce participation could be achieved by encouraging more productive individuals to join the workforce. Several practical approaches could promote participation. For example, paid parental leave and government-funded childcare could help women to remain in the labor force. Furthermore, laws and regulations could change in favor of less-represented individuals to participate in a broader set of industries with more flexible work arrangements. An investment could also be made to attract young professionals to the region.

Workforce participation in the model is an exogenous time series, driven by historical data. For the future periods, it remains constant at the last data point available, which is 44.35%. This last value can be changed to reflect the policy implementation. Here, we assume that it is possible to increase this value to about 50%.

3.2. Policy B: Encourage Capital Investment

Perhaps the most classical economic development policy is to encourage investment in capital in order to improve the productivity of the workforce, which was shown to have a significant effect on the system's dynamics. Similar to Policy A, this intervention will strengthen the non-agriculture positive feedback loops in the model and conceivably lead to lower water use in the long-run (see Section 3.1). Here, we assume that it is possible to increase the fraction of yearly profit that is invested from 8% (base case value) to 10%. In reality, this investment boost might be too ambitious. However, the scope of this research is not to find a solution for investment; the focus was to examine the impact of such intervention on the social–hydrology system.

3.3. Policy C: Regulate Land Use Changes

We found that results were highly sensitive to regulations that incentivize a change of land use in or out of agriculture. There are two main categories of land use assumed in the model: agriculture and non-agriculture. While the trend has been towards the reduction of agricultural land, our model allows for the regulation of land use changes in both directions: reductions and increases. This is important because of the fluidity of land use; for example, new innovative regulatory proposals propose water-banking strategies that avoid permanently fallowing land through rotating its use. The model structure for this is simple. Agricultural use refers only to irrigated land because almost all agriculture in the region is irrigated. Therefore, when farmers fallow a piece of land even temporarily, that piece will be considered as part of the non-agriculture use. This does not cause any verification issue in the model as the non-agricultural land does not enter the production functions. The only use of this land in the model is to calculate water-related variables such as runoff, recharge from non-irrigated land, etc. Land use adjustment is assumed to be a very long-term process (10 years on average). This time delay could be changed in order to test the impact of facilitated land use adjustment processes. We expect that a faster adjustment, when accompanied with policies A and B, may lead to a closer-to-optimum behavior in terms of water use as it accelerates the feedbacks shown in Figure 8. To perform the experiment, we reduced the average delay to 5 years.

3.4. Policy D: Increase Wage Rate

We expect policies A to C to exacerbate the declining trend of equality in the base run. A natural response to this unintended consequence is to implement a form of income redistribution, which is also shown to have a significant impact on this system. The simplest way to apply such a policy in the model is to increase the wage rate. As shown above, the equality declines over time in the base simulations, and that is due to the relative dynamics of wages and total income. Equality is defined in the model as the share of wages paid to the labor in terms of the total income of the society. If the share of wages in income increases, equality increases proportionately and vice versa. Thus, in general, our model indicates that total income grows faster than total wages. The gap will then be the profit of capital. Although this is obviously a simplified representation of equality, it does not impact the results of the model because equality is merely a performance output and does not affect any other model variables.

In order to improve equality, we can increase the average wage rate in the model. This could be achieved by increasing the minimum wage rate. To implement this policy in the model, we raised the average (normal) wage rate by 10%. We do not expect this change to influence the water system significantly. Instead, this may help to alleviate some of the negative social consequences of growth-oriented policies. Additionally, it responds to the decline of farm policies to impact the well-being of farm households, where fewer than 25% of farms receive income support [20]. For farmers, a rise in their wage rate would likely require a rise in food prices to reflect a more viable food system.

3.5. Policy Simulations

The simulation results presented here revealed that the selected policies could exert control over the chronic water scarcity issue. Figure 9 demonstrates comparative graphs that represent the cumulative impact of policies. As could be expected, promoting work-force participation (Policy A) and boosting capital investment (Policy B) increased income per capita. These policies stimulated the non-agricultural sector, thus absorbing some of the production factors from agriculture, including land and labor. As a result, irrigated land declined, which in turn eased some of the pressure from water demand. Consequently, cumulative water shortage dropped. Equality also dropped after the policies, primarily because increasing capital investments contributes mainly to the capital gains while wages do not increase proportionately. As such, the wage–income ratio declines.

Accelerating land use changes (Policy C) in addition to policies A and B led to a much lower cumulative water shortage. This achievement was due to the lower irrigated land levels in the mid-term, although the equilibrium level of irrigated land was very close to the previous scenario. This result indicates that the reduction of agricultural land is ultimately not necessarily a long-term strategy for water-use reduction. However, it does produce gains in the mid-term; the decline in irrigated land is sufficient to save considerable volumes of water, as reflected by the "cumulative" water shortage graph in Figure 9.

To compensate for the negative social consequences of policies (reduced equality), Policy D (increased wage rates) is added to our policy package. Fortunately, this addition does not offset previous policy achievements while it recovers a major part of the equality index that was lost due to Policies A + B + C. The negative impact of higher wage rates on income per capita is negligible.
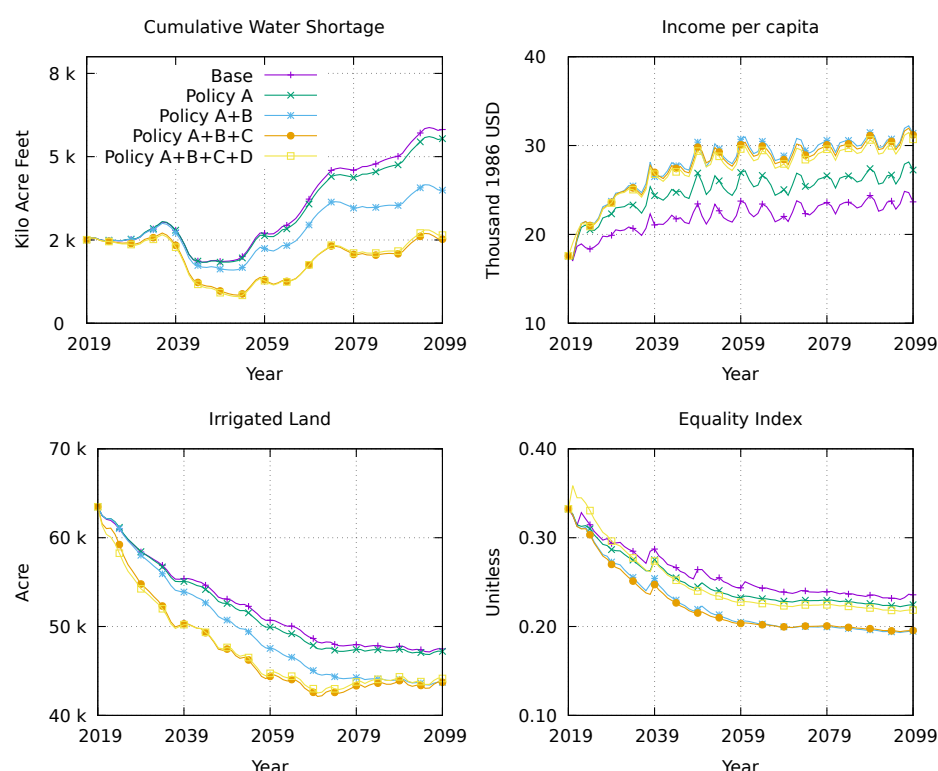

Figure 9. Impact of the selected socioeconomic policies on the social–hydrology system. Note that, to preserve additional agricultural land or offset other undesirable consequences, these policies can also be easily employed in combination with additional water policies, such as more significant water-efficient cropping choices and water-efficient management.

Surprisingly, although the policies led to lower levels of irrigated land, which could instigate unintended consequences, the simulation results indicated that farm incomes remain intact. As Table 1 shows, the average farm income during the future period (2020–2099) is reduced only marginally in some scenarios (less than 6%). Considering the steeper decline in irrigated land, the farm income per acre (an indicator of productivity and efficiency) in fact increased, as shown by the measures on the second row of Table 1. Such improved productivity and efficiency lend themselves to the reduced reliability of groundwater and increased use of surface water for irrigation. A greater fraction of surface water use for irrigation occurred because of the reduced pressure on water demand. Generally speaking, for irrigation purposes, surface water has higher quality than groundwater and results in greater agricultural yields. Therefore, the decline in irrigated land is compensated by the eventual increase in yield, thus preserving total farm incomes. This result also suggests that, with a policy that intends to reverse the declining trend

and instead preserve agricultural land, policies A, B, and D can significantly increase the viability of agriculture. These findings lay a foundation for policies that incentivize the multi-functional benefits of agriculture. For example, the addition to the total income of the society that was achieved through the tested policies could be taxed and used to compensate for any potential loss in the agriculture sector.

Table 1. Change in average farm income compared to the base simulation in response to different policies.

Policy	A	A + B	A + B + C	A + B + C + D
Average farm income	6.38%	−0.24%	−5.72%	−3.08%
Average farm income per acre	7.16%	4.72%	3.49%	5.93%

Here, we examined only socioeconomic policies to improve the behavior of the water system. It can be easily shown that additional water policies, such as investment in crop varietal research, market development to support more significant water-efficient cropping choices, and incentivizing water-efficient management such as cover crops, could be implemented to improve the behavior even further.

3.6. Policy Outcomes under Uncertainty

To account for climate uncertainty in the simulation of future time periods, the model requires external inputs for its exogenous variables; i.e., surface water inflow, temperature, and precipitation. These inputs are provided by the NMDSWB model. To estimate these inputs, NMDSWB uses climate models generated by Global Circulation Model runs over three (low, high, and moderate) greenhouse gas emission scenarios, downscaled for New Mexico. These models are the National Center for Atmospheric Research (NCAR) model, representing a low-emissions scenario; the Geophysical Fluid Dynamics Laboratory (GFDL) model, representing a high-emissions scenario; and the United Kingdom Met Office (UKMO) model, representing a moderate-emissions scenario [31]. In the previous simulation runs, the UKMO scenario was used as it provides a middle ground between the two extreme emissions scenarios. The dynamic behavior of the main exogenous drivers of the LRG model generated by NMDSWB for the three hydro-climate scenarios are shown in Figure 10.

To take the climate uncertainties into account, we tested the policies on the model again with each scenario. The test results indicate that, under the NCAR scenario, water availability increases and scarcity is controlled naturally; thus, no policy intervention is required. Under the GFDL scenario, however, the water scarcity is so severe that the tested policies are unable to reverse the unsustainable trend of cumulative water shortage (see Figure 11). At the end of 2099, the water shortage is still rising, although in the policy case, the total shortage is lower than the base scenario. The economic performance, similar to the UKMO case, is boosted, which is not surprising.
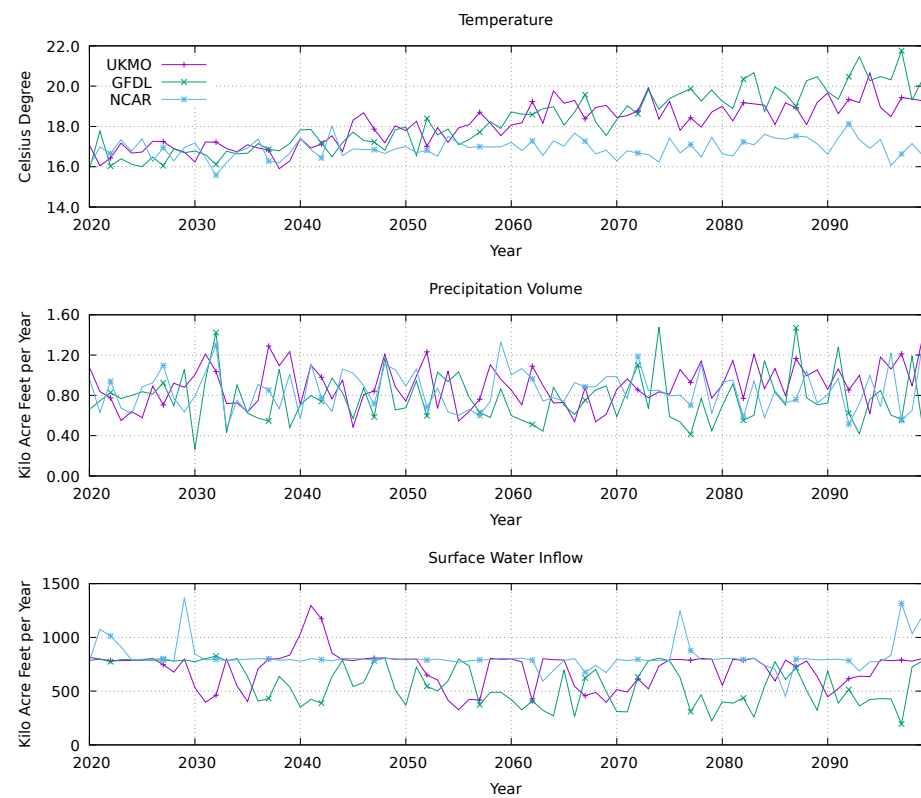
Figure 10. Alternative future scenarios for the model's externally driven (exogenous) variables.
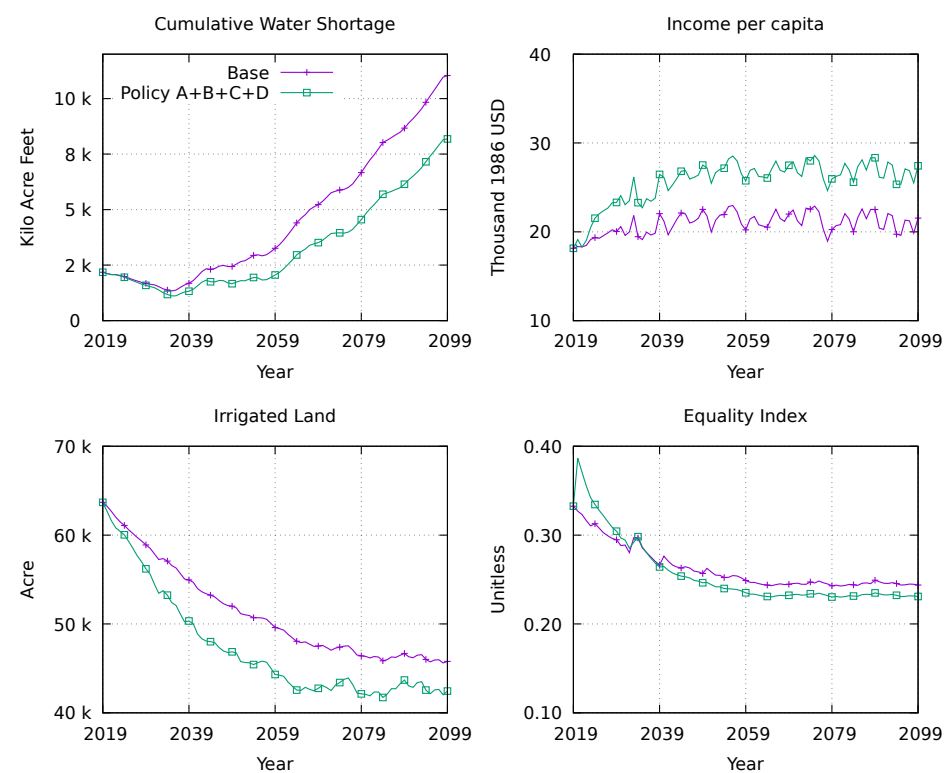

Figure 11. Impact of the policies under the GFDL climate scenario.

4. Conclusions

This study applies a system dynamics model to tackle a common issue in water resources management: worsening water scarcity. Contemporary water management is usually focused on water supply and considers demand as an exogenous component that needs to be met. This perspective often results in narrow applications and inevitably to unintended consequences; Say's law is in effect here. Supply-side interventions mitigate the water shortage problem in the short term, but they create greater demand in the long term, which in turn counters the initial positive gains [37]. Socioeconomic variables such as economic and population growth drive water demand. Therefore, we hypothesized that socioeconomic policies could influence water dynamics and leverage the system to control the water shortage issues.

Our model represents a social–hydrology system calibrated for a southern region in New Mexico; i.e., Doña Ana County. The model relies mainly on its endogenous feedback structure rather than exogenous drivers, which allows for more accurate policy analysis behavior because it accounts for dynamic reactions of decision-makers to policy changes. The endogenous structure includes important socioeconomic variables such as population and economic growth. Simulation runs of the model show that the inclusion of socioeconomic feedback in a water model can extensively expand the policy space and thus help us to find alternative or supplementary solutions for water issues.

Introducing a new feedback structure that leads to the accelerated deterioration of water scarcity into the model revealed the importance of control over cropping patterns and strategies. Reducing and limiting the expansion of water-intensive crops results in the deceleration of the growth of water shortages. Thus, the default and increasingly widespread solution to reducing water competition and scarcity has been to allow the reduction of agricultural land and the sale or trade of water rights to other uses. However, this is not a solution that considers the support of agricultural viability. Controlling cropping strategies raises the potential for the financial gains of the farmers to be impacted. Pecans are currently recognized as a highly valuable crop and the most viable investment for farmers in the studied region. Farmers require technical and market support to develop alternative cropping strategies. Simulation results also show that simply limiting the expansion of water-intensive crops is helpful but insufficient to restrain water scarcity. In the long term, an integrated approach of water conservation measures is required, such as cover crops, as well as a more extensive change in cropping patterns to less-water-intensive crops that are adapted to local conditions, economic incentives driven by strong markets, and proven farming technologies.

To improve the system's performance beyond what we achieved with the enhanced cropping patterns, a selection of socioeconomic policies was applied. The particular boundary selection of our model allowed this experiment. The policies tested on the model were (A) promoted workforce participation, (B) increased capital investment, (C) faster land use adjustment, and (D) increased wage rates. These policies led to considerable improvements in the results. They sustained the water system and at the same time indicated means to offset potential negative impacts to the socioeconomic system. In particular, they reduced total irrigation demand by reducing irrigated land without affecting farm income, which caused the farm income per acre to rise. This occurred because, due to the lower pressure on water demand, the total water supplied for irrigation comprised a greater share of surface water and a lower share of groundwater. This led to a relatively higher agricultural yield, thus maintaining farm income. The results also suggest the possibilities of alternate paths to agricultural land preservation, which would likely require additional water policies, such as more significant water-efficient cropping choices and water-efficient management.

The policy analyses presented in this paper have been tested for robustness in our modeling experimentation, which is not reported here in its entirety. The results show that uncertainty in the exogenous hydro-climate drivers does not change the implications of the policies we tested but significantly affects their necessity and effectiveness. Nonetheless, further validation tests and stakeholder thinking are required before applying the recom-

mendations in the real world. We will also need to examine each policy under a broader range of circumstances to make sure that they will not create unintended consequences that we have not predicted yet. Furthermore, the presented model has been applied only to one region so far. The value of the model will be enhanced by future research applications in other dryland regions of the world. Variations in the initial settings of social–ecological systems, including their legal, governance, and ecosystem components, can generate different dynamic behavior [38]. Although the model can be easily applied to any social–hydrology systems in arid and semi-arid regions, application to different regions would require additional rigorous testing to be performed on the model to make sure that it remains sound and robust under reasonable variations in parameters, assumptions, and initial settings.

As with all other abstract models, the presented LRG model is merely a simplified representation of the real-world and cannot be used for all kinds of water policy evaluation. The current model considers high-level water–economy–population interactions and lacks details regarding some components such as irrigation technologies. Currently, we are working with our local stakeholders to incorporate their mental models and decision-making processes in the model to improve the accuracy of the model assumptions in specific areas deemed valuable by our clients. Accordingly, the model assumptions will evolve, and additional innovative interventions will arise. The goal is to create better models by incorporating a more robust and accurate representation of decision-making processes by testing alternative formulations of information and utility perception [39], as perceptions have been proven to be crucial in water resources management [40]. This water and society study presents innovative approaches that are critical for building social and institutional capacity. The analysis of socioeconomic feedbacks integrated into water research is crucial for achieving resilience in the agricultural community.

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