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Analysis

Does Socioeconomic Feedback Matter for Water Models?

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ABSTRACT

While integrated systems approaches have been recognized as critical for management of the ecology, water resources management models typically ignore a defining feature — feedback mechanisms between socioeconomic and hydrologic variables. They treat essential variables such as population, economic growth, and sometimes even irrigated land, as exogenous drivers. In this paper, a minimalistic "closed-loop" social hydrology model is developed for a southern region in New Mexico and compared to an "open-loop" (partially exogenously driven) model. Results reveal that the integration of the social feedback links into a hydrology system may change the implications of water-related policy analysis. The introduced closed-loop model can serve as a generic structure for any social hydrology system.

1. Introduction

The importance of cumulative circular causations (in simple terms, feedback loops) within and between hydrologic and socioeconomic systems is hardly debatable. Hydrologists have long recognized watersheds as managed dynamic systems, and have exposed the importance of functional bio-physical and social management drivers. An important example of this understanding yielded the Integrated Water Resource Management (IWRM) approach, which can trace its origins back to the establishment of the Tennessee Valley Authority in the United States in 1933 (Stålnacke and Gooch, 2010). Yet, there is agreement that the underlying conceptual frameworks of integrated systems approaches require development, and as well, an emerging recognition of the need to assess the feedbacks within these systems (Medema and Jeffrey, 2005; Stålnacke and Gooch, 2010; Pollard and du Toit, 2011). It is argued that feedback loops are crucial factors in dynamics of complex issues in water resources management (Ortiz et al., 2007; Fernald et al., 2007, 2010, 2012, 2015; Turner et al., 2016; Page et al., 2019; Gunda et al., 2018). There are sophisticated hydrology models that include hydrologic feedback links, as reviewed by Winz et al. (2009) and Mirchi et al. (2012). Some even include interactions of the hydrology with other sectors such as energy or food (a recent study by Khalkhali et al. (2018) is an example). Yet, simulation models that take most of the crucial feedback links into account, in this case socioeconomic feedbacks, are rare (Bahaddin et al., 2018).

This paper responds to this theoretical gap by developing a system dynamics[1] model that takes into account key feedback loops in a social-hydrology system to enable us to look at longer term trends (e.g. over ten years), as well as shorter term trends. The objective is to evaluate policy sensitivity of the model to its socioeconomic feedback structure. To that end, we assess the model for implications of example policies under alternative climate scenarios. The assessment then is repeated with some alteration in the model structure that excludes the linkages from the hydrology system to three primary socioeconomic variables: population, total income, and irrigated land. This alternative model is called "critically-open-loop" ("open-loop" for short) as it features broken social-hydrology feedback loops. The results of the "closed-loop" (the original) model are compared with those of the "open-loop" model. The assessments cannot reject the hypothesis that the socioeconomic feedback loops significantly influence potential policy recommendations of a dynamic water model.

The paper is organized as follows. Section 2 elaborates on the background of this research. Section 3 explains the model structure in an aggregate fashion. Section 4 describes the confidence building tests that the model has passed. Scenarios and policy implications of the closed-loop versus open-loop models are analyzed in Section 5. These results are discussed further in Section 6. Section 7 then concludes the paper.

2. Background

With a few exceptions (Saysel et al., 2002; Simonovic and Rajasekaram, 2004), the majority of the social-hydrology models leave some essential socioeconomic variables out of the boundary or treat them as exogenous scenario inputs which are not affected by the model behavior. Population and economic growth rates are two of such variables. Xiao-Jun et al. (2011) come close to a fully closed-loop model. Nonetheless, the model lacks the feedback from the hydrology system

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[1] System dynamics is a computer simulation method developed in the 1950s (Forrester, 1961) and since then has been applied to many different areas such as healthcare (Homer and Hirsch, 2006), political economy (Langarudi and Radzicki, 2018), and resource management (Simonovic, 2002).

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to population. In a recent effort, Duran-Encalada et al. (2017) develop a model to analyze the changes in the water quantity and quality in the US-Mexican transborder region due to global climate change. Their model includes population but understandably fails to endogenize the economic growth rate. Another model that addresses implications of the green economy transition in the Western Cape Province of South Africa (Musango et al., 2015), has both economic growth and population as endogenous variables inside the model boundary. However, GDP (as an aggregate measure of economic activities) does not affect the water demand and is not affected by water stress directly. The only determinants of water demand are population and agriculture production. Land change is tracked in the model, but it does not affect any other variable in the model. Finally, Pienaar et al. (2017) consider GDP, irrigated land, and population as endogenous variables, but water availability does not influence the population growth directly.

In this paper, we argue that it is critical to endogenize population, economic growth, and irrigated land within the boundary of any aggregate water model. Agriculture and industrial growth depend directly on water (Simonovic, 2000). Kuil et al. (2019) also show that water availability influences the dynamics of population. Considering these variables as exogenous drivers, or not integrating them appropriately with the hydrology variables, could be acceptable but only for a short-term (less than ten years) analysis. To accurately predict longer-term hydrologic trends, these variables must be incorporated internally. In a socioeconomic system, population and economy not only impact but also react to the water availability in the long-run (Bai et al., 2017).

The model presented here, works as an overlay to another model, the NM Water Resources Research Institute's Dynamic Statewide Water Budget (NMDSWB) (NMWRRI, 2018). Using a mass balance approach, the NMDSWB model characterizes historical behavior and generates future scenarios of New Mexico's water resources dynamics. The model uses stocks to define how much water of a given type is present at a given location over a specified period and uses flows to quantify the movement of water between the stocks or areas of interest. It features four levels of mass balance accounting units (MBAU): counties, water planning regions, river basins, and statewide. The time unit of the model is monthly, and the simulation horizon extends from 1975 to 2099 with historical data covering until 2011. Water storage is tracked in four separate stocks: the land surface, surface water, human storage and distribution, and groundwater. There are 16 fluxes representing water movement between stocks within or in and out of a given MBAU. These include precipitation, surface water in and out, surface water and groundwater diversions and returns, and combined consumption (5 fluxes), surface water evaporation, groundwater evapotranspiration, runoff, surface water-groundwater interaction, land surface ET, recharge, and groundwater inflow and outflow.

While separate regarding feedback structure, the overlay model uses the NMDSWB model's outputs to drive the few exogenous variables and define and calibrate the system relationships and behavior. The model consists of seven modules: water, water use, agriculture production, non-agriculture production, population, labor, and wage. Stocks of groundwater and surface water interact with each other and with the rest of the model to generate the dynamic behavior of the social-hydrologic system. In particular, population and economic growth (both in agriculture and non-agriculture sector) not only determine water use, thus affecting the hydrology system, but also react to the dynamics of the water. In other words, strong feedback connections exist within and between the hydrology and socioeconomic modules of the model to govern its dynamic behavior. The model achieves minimal reliance on exogenous drivers, making it a novel tool for policy and scenario analysis. There are only 5 exogenous variables (surface water inflow, precipitation, irrigation precipitation, temperature, and workforce participation rate) in the model that drive 9 equations out of a total 97 (reliance factor = 9.3%)[2].

The model is calibrated for southern New Mexico's Doña Ana County, also known as the lower Rio Grande (LRG) water planning region of the NM Office of the State Engineer (OSE). Simulation time ranges from 1969[3] to 2099[4]. The model has been subject to the usual system dynamics confidence building tests. The test results suggest that the model cannot be rejected as an abstract characterization of the real system, at least for this particular region. The model can arguably serve as a generic structure for future social-hydrology modeling efforts as its fundamental structure consists of universal physical and behavioral rules.

Table 1
Boundary of the model.

Endogenous	Exogenous	Excluded
Surface water (SW)	SW inflow	Power generation
Groundwater (GW)	Precipitation	Navigation
GW recharge	Temperature	
Irrigated land	Labor participation	
Non-irrigated land		
Capital		
Technology		
Population		
Employment		
Wages		
Income		
Farm production		
Ag water demand		
Non-ag water demand		

3. Model Structure

The boundary of a model should be defined based on the goals that it is supposed to achieve. For any variable to be added to the model, we should ask whether or not it contributes to the model's goals. Boundary of the original model that is used and presented by the current analysis is summarized in Table 1 which lists important variables included as either endogenous or exogenous versus those excluded.

The primary goal of the model is to predict the dynamic behavior of key water use under different circumstances. Therefore, water use categories must be included as endogenous variables, i.e., they must be calculated within the model boundary. Significant drivers of water use include population, production, agriculture, navigation, and power generation (Simonovic, 2009, p. 19). Thus, these components should be inside the boundary as endogenous variables as well. The reason is that given enough reaction time, all these components respond to changes in a natural system. Note that navigation and power generation are excluded from the current model due to the absence of such sectors in our case study region. These important socioeconomic variables should normally be included in an endogenous social-hydrology analysis.

Additionally, there are some exogenous variables within the model boundary, meaning that their dynamics does not depend on the state of other model variables. They stand alone and are predefined as independent scenarios. Hydroclimate exogenous variables that cannot be predicted endogenously by this finer scale, regional model are surface water inflow, temperature, precipitation, and irrigation precipitation. The only socioeconomic variable that remains exogenous is workforce participation for simplicity. With a more complicated and extensive model structure, this variable could become endogenous. In fact, more feedback mechanisms could be added to our analysis. However, the

[2] The model has 205 variables excluding those used for policy/scenario design. Among these variables, 97 are endogenous variables, 9 are exogenous variables (data inputs), and the rest (99) are constant parameters.

[3] Majority of time series (especially the economic data) used by the model are available only from 1969.

[4] Exogenous scenarios that the model uses for the future time periods run until 2099.

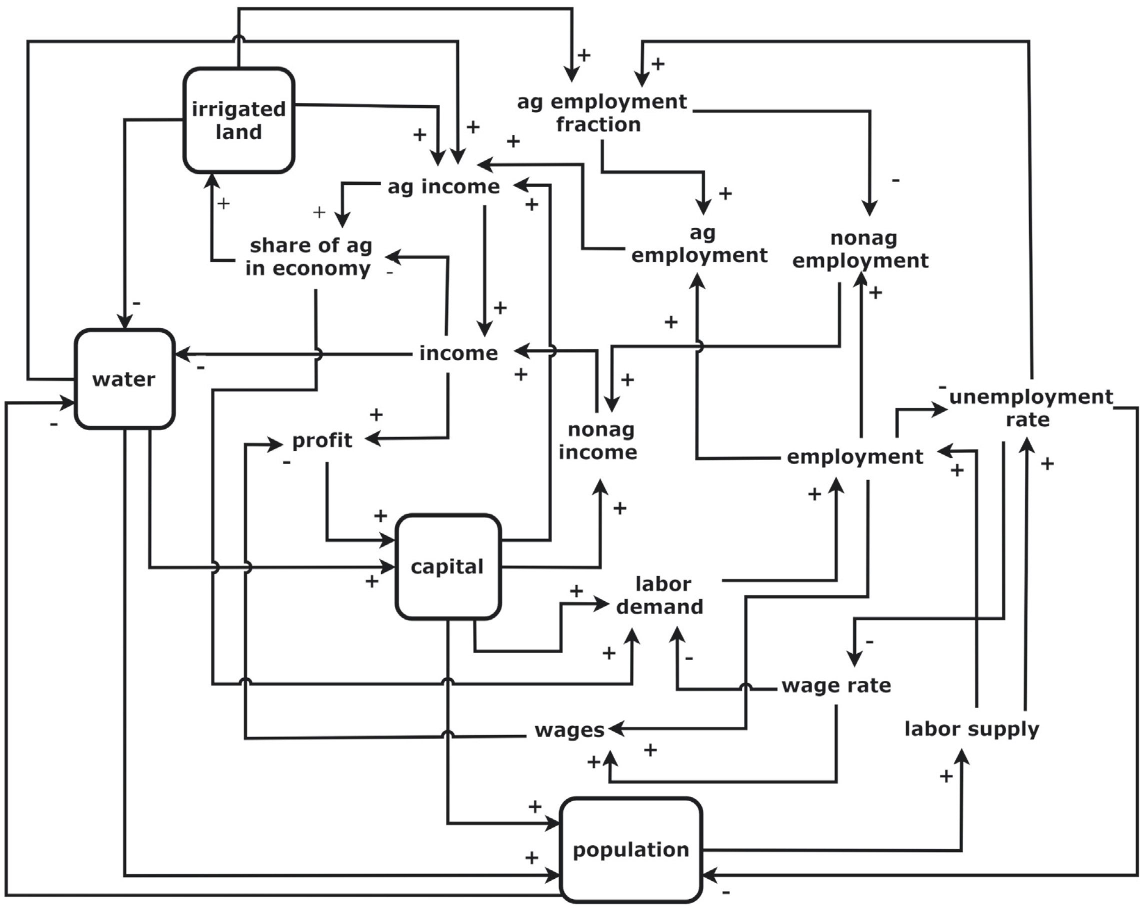

Fig. 1. Causal structure of the model.

goal here is not to create the most realistic or comprehensive model. In contrast, we try to achieve a minimal socioeconomic feedback structure that might generate policy sensitivity. Selection of variables also depends on the level of aggregation of the model. A disaggregated model might include more variables inside each socioeconomic sector. For example, population could disaggregate into age cohorts. Similarly, agriculture could branch out into farming and ranching. Details of the model boundary and other modeling choices, and rational, facts, and evidence behind them are explained extensively in the supplementary materials that accompany this paper. Here, we only focus on the aggregate feedback structure of the model.

A simplified overview of the causal structure of the model is shown in Fig. 1. Income, irrigated land, and population determine the demand for water. Water demand and availability of water indicate the amount of water that is used.

Total income is a sum of agriculture and non-agriculture income. Non-agriculture income is a Cobb-Douglas function of production factors: labor (non-agriculture employment) and capital[5]. Capital develops through investment provided through profits. Profit is total income minus wages.

Wages are a multiplication of wage rate by total employment. Wage rate is a decreasing function of the unemployment rate. As unemployment rate increases, wage rate declines, and vice versa. Shape of the function is asymmetric with smaller sensitivity to the higher unemployment rates so taking into account stickiness of the wages.

Employment is determined mainly by labor demand. However, it cannot exceed labor supply. While population infuses labor supply, labor demand is driven chiefly by capital development. Wage rate and agricultural activities (represented by the share of agriculture in total income) also influence the labor demand. Wage rate has a negative impact on labor demand. As wage rates increase, employers tend to demand less for labor. The effect of agriculture on total labor demand is based on the theory of "agricultural-demand-led-industrialization" developed by Adelman (1984) and Vogel (1994). Expansion of agriculture can lead to "backward and forward linkages" (Hirschman, 1958; Rothschild and Sen, 2013) through activities such as investment in irrigation, roads, bridges, storage facilities, canals, research and development in seeds, cultivation techniques, animal breeding, and conservation and sustainability methods. This expansion will increase the demand for workforce in these sectors.

The employed labor is distributed between agriculture and non-agriculture sectors through the agriculture employment fraction. This fraction dictates the share of agriculture employment in total employment. The rest of employment is then allocated to the non-agriculture sector. Many residents in the lower Rio Grande region work both in agriculture and non-agriculture sector at the same time. Therefore, the agriculture employment fraction could be considered as a fraction of total human resources spent in agriculture in contrast to the amount that is spent in the non-agriculture sector. It is assumed that unemployment rate and irrigated land are the two factors that affect the agriculture employment fraction[6]. As the unemployment rate increases,

[5] Here, capital refers to all non-human means of production such as infrastructure, machinery, equipment, and technology. Actual data for capital is not available at the county level. Hence, wherever the capital is used in the model, it is divided by its hypothetical initial level so that it becomes normalized. Therefore, only relative changes of capital are taken into account and thus the uncertainty regarding its absolute values is avoided.

[6] This assumption is justified through an econometric analysis which is

individuals will have more available time. Thus, they can spend more time in the agriculture sector. Also, as more land is allocated to agriculture and being irrigated, more labor will be needed to work in agriculture.

Total land in the model could be allocated between irrigated and non-irrigated (municipal, industrial, etc.) lands (the latter is not shown in Fig. 1). Land allocation scheme is dependent on the attractiveness of agriculture and non-agricultural activities which is proxied by the share of each sector in total income. As the share of agriculture in total income increases, more land is allocated to farming and irrigated land increases. Expansion of irrigated lands leads to greater use of water for irrigation.

Irrigated land, agriculture employment, and technology (proxied by capital development) are production factors that determine agriculture income. There are also hydrologic variables that influence agriculture income. The arrow that connects "water" to "ag income" in Fig. 1 represents all these influences in an abstract fashion. These variables include precipitation, water availability, and share of groundwater in total irrigation water. The latter factor reflects the fact that significant use of groundwater could negatively affect agricultural yield, because salinity increases with groundwater declines.

Finally, a logistic function is used to simulate population. This function incorporates two arguments: a growth rate and a carrying capacity. The growth rate is a decreasing function of the unemployment rate. Econometric analysis conducted by the authors reveal the significance of this relationship. Carrying capacity of the region can increase as infrastructure (represented by capital) expands. The carrying capacity may also be affected by the availability of water resources. Greater water availability allows the region to accommodate more population. However, more population would mean greater non-agriculture water consumption.

4. Confidence Building Tests

To trust outputs of a model, it should be subjected to confidence building tests. The more tests a model passes, the more its results can be trusted. The current model successfully passes many common system dynamics confidence building tests including boundary adequacy, integration error, unit consistency, extreme condition, parameter assessment, structure assessment, anomalous behavior, and behavior reproduction[7].

Most of the tests are performed as a part of our recursive model development process[8]. For example, all the equations are tested to make sure that they are necessary for potent and impotent dynamics of the model, thus justifying adequacy of its boundary[9]. The integration time interval is adjusted to minimize the integration error. Unit consistency is checked automatically by the software[10]. The model equations are put under extreme conditions to see if they remain robust throughout the simulations. Structure and parameters of the model are justified based on physics of the system, theory, and the literature (see the supporting material for full details on modeling choices, structural design, data sources, and parameter selection). Some behavioral anomalies were detected during the model development. Causes of the anomalies were identified and fixed in the current version. Behavior reproduction tests are also reported in the supporting material.

Other confidence building tests are performed only partially or not at all. These include sensitivity analysis, family member tests, and system improvement. Sensitivity tests are performed but not in a systematic fashion. A comprehensive sensitivity analysis remains an essential next step. Family member tests are other tasks to be completed in the future. In this regard, the model will be calibrated for other water planning regions in New Mexico to see if it can characterize the dynamic behavior of those family member systems. Finally, it is impossible to test the model for system improvement which is, indeed, one of the most complicated tests for any model. In reality, not every recommendation of a model will be fully applied in practice. Even if the recommended interventions are implemented with a high level of fidelity, many other changes will coincide with them during the implementation process. These external factors might distort the outcome of the intended implementation, thus obscuring the actual impact of the model on the real system. Therefore, it is challenging to accurately evaluate the true effect of a model on the behavior of the real-world system. Only after extensive applications of a model, one can judge its practical benefits and usefulness.

5. Closed-loop vs. Open-loop

It has been argued here that water models should consider socioeconomic feedback links. Models with socioeconomic feedback links are called here "closed-loop" models, as is the common terminology for models that incorporate feedbacks. Other models which do not include critical socioeconomic feedback links, subsequently, are referred to as "critically-open-loop," or "open-loop" for short. Note that open-loop models here could still include feedback loops. In fact, there are water models in the literature that are feedback-rich in their hydrologic structure, as discussed in Section 2. The only factor distinguishing closed-loop models from open-loop models in this paper is the "socioeconomic" feedback due to the hypothesized effect that the missing feedbacks would change the policy outcomes. A water demand model may incorporate hydrologic feedback links, but, it is still an open-loop model in the sense that it does not take the socioeconomic variables as endogenous components into account. An example of a closed-loop model is shown in Fig. 1. Fig. 2, in contrast, demonstrates a potential open-loop counterpart of the same model. In this diagram, the dashed arrows represent broken links from the closed-loop model. For example, the population in the open-loop model is an exogenous driver, whereas, in the closed-loop model, it is determined endogenously based on capital, unemployment rate, and water availability.

How important is it to consider the socioeconomic feedback in a water model? This question is important because such a consideration is not costless. Additional causal relationships impose more complexity to the model, thus increasing the cost of the modeling. One should, therefore, justify the additional cost inflicted by such complexity.

Usefulness of water models usually relies on the ability to inform policies. Therefore, to examine the significance of the difference between a closed-loop model versus an open-loop model, one should focus on the policy implications of the two model types. If a closed-loop model implies that a specific policy leads to a particular set of outcomes, the open-loop counterpart of the same model should also suggest the same policy outcomes to conclude that the difference between the closed-loop and open-loop models is negligible. For example, assume that a policy to analyze is a stricter control over surface water allotment. We call this policy, Policy A. Now, assume that the closed-loop model shows that Policy A leads to a "greater" groundwater storage (compared to a base scenario) at the end of the simulation. If the open-loop model also implies that Policy A results in a "greater" groundwater storage at the end of the simulation, we conclude that

(footnote continued)
reported in the model documentation (see the supporting material).

[7] For detailed explanation on the confidence building tests see Sterman (2000, ch. 21). Langarudi and Radzicki (2013) provide a practical guide on the use of these tests.

[8] The current model has gone through 19 major revisions, each of which has had several minor revisions.

[9] The central question of the current paper – whether or not a variable should be endogenous or exogenous – is, in fact, a boundary adequacy question. Hence, the boundary adequacy and its policy implications are discussed further in Section 5.

[10] The model is replicated in three different softwares for practical reasons. These include Vensim DSS (Ventana, 2017), Powersim Studio (Powersim, 2017), and Stella Architect (ISEE, 2018).

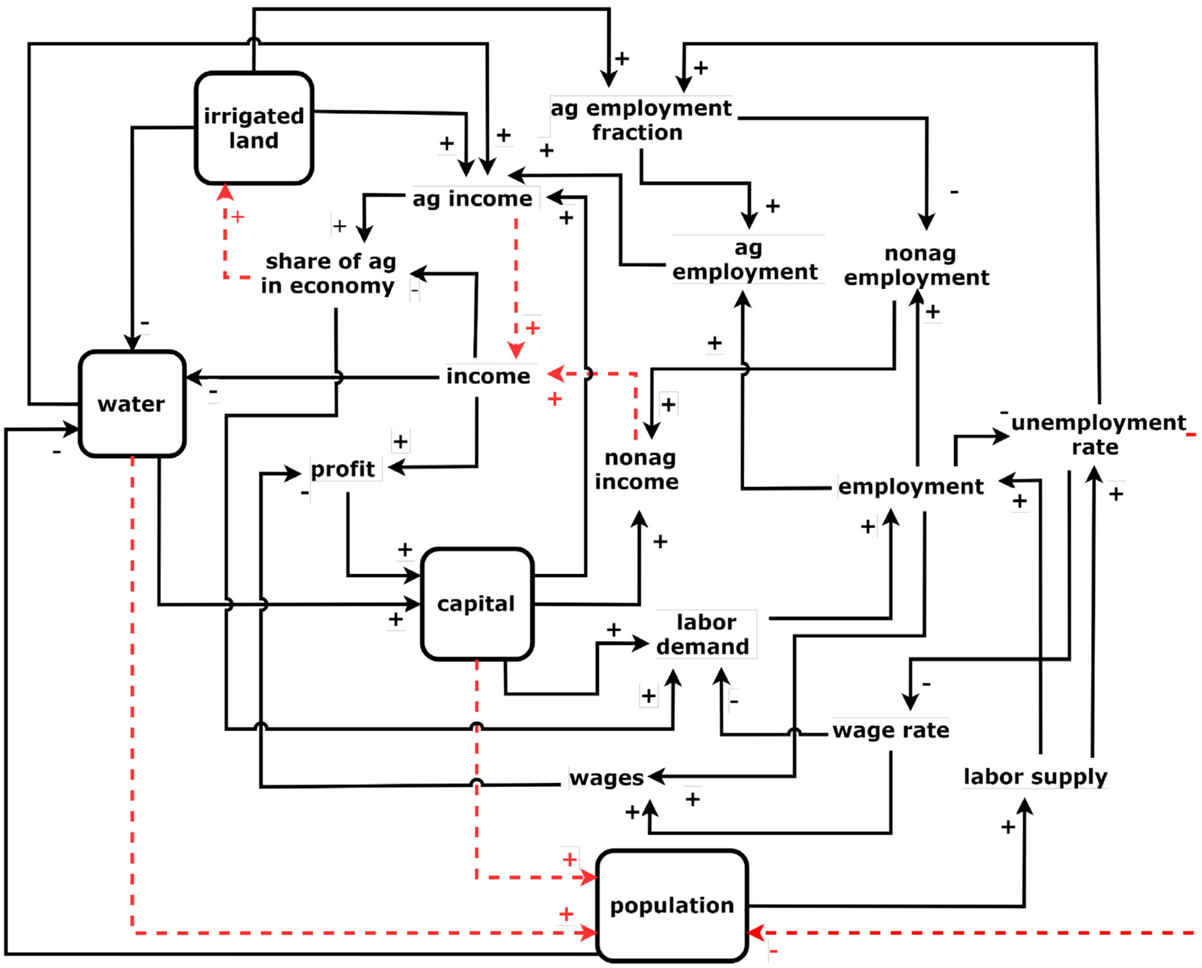

Fig. 2. An example of an open-loop version of the model.

policy implication of the closed-loop model is "similar" to the open-loop model's. If, in contrast, the open-loop model showed a "lower" groundwater storage because of Policy A, we could say that the two models are "conflicting" concerning the policy implications. This section explains an experimental design to address such comparisons.

5.1. Exogenous Drivers

To run the model for future time periods, exogenous variables (workforce participation rate, precipitation rates, and surface water inflow) require external input. Historically (since 1990), workforce participation has been changing from 40% to 45%. Although, since 2005 the variation range has been limited to 44–45% with an average of 44%. Hence, for the future scenario projections, this variable is held constant at 44%.

Input for hydrology and climate variables is supplied from the NMDSWB model. The NMDSWB model generates the inputs using several climate models, namely UKMO (United Kingdom Met Office), GFDL (Geophysical Fluid Dynamics Laboratory), MPIM (Max Planck Institute für Meteorologie), and NCAR (National Center for Atmospheric Research). These climate models are derived from Global Circulation Model runs that span three different greenhouse gas emissions scenarios (NMWRRI, 2018). NCAR is a low-emissions scenario, UKMO is a moderate-emissions scenario, and MPIM and GFDL are high-emissions scenarios that have been dynamically downscaled in New Mexico for use by researchers involved in the Statewide Water Assessment (NMWRRI, 2018). Here, the UKMO case is used as the base case because it provides a moderate emissions scenario. The NCAR and GFDL cases are used to represent low and high emissions scenarios, respectively[11]. Fig. 3 shows the future dynamic behavior of the four inputs for each of the scenarios.

For the open-loop model, three additional exogenous drivers exist that require external inputs. These are population, total income, and irrigated land. One way to provide the input for these variables is to run the closed-loop model and export the required outputs. However, running the model with different climate scenarios will lead to different outputs for the variables. To take uncertainties into account, we run the closed-loop model with each scenario and save the result with a different name.

5.2. Policies and Performance Measures

To test the model, we need some policies to be defined and applied to both the closed-loop and open-loop versions and then compare the outputs. Many different policies could be examined depending on the needs of a social hydrology system. However, the goal of this paper is not to provide policy recommendations for a real-world case. The goal is to show the difference between a closed-loop and an open-loop water model. Therefore, two simple policy interventions are introduced.

The first policy targets a surface water allotment scheme. In the

[11] The NMDSWB's outputs of the MPIM case are relatively similar to the GFDL case. Therefore, only one of them is decided to be used in this paper. From the current paper's perspective, there has been no reason to prefer the GFDL case over the MPIM case, though. The selection has been made merely on an ad-hoc basis.

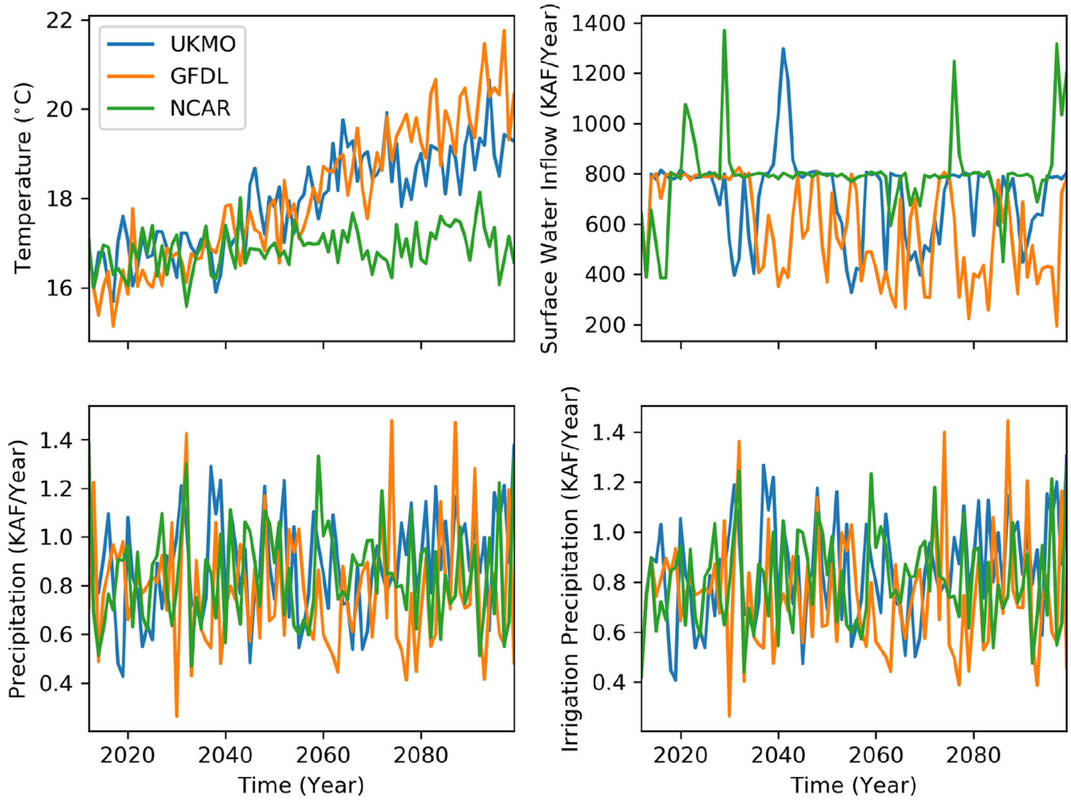

Fig. 3. Future scenarios for exogenous drivers of the model.

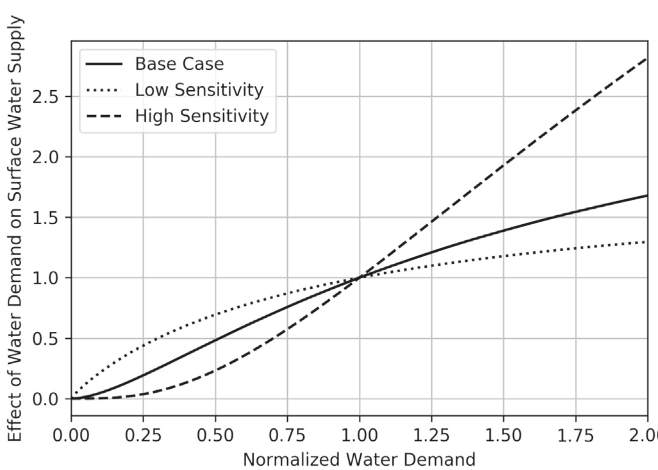

Fig. 4. Surface water supply policy schemes.

model, it is assumed that surface water allotment is a function of water demand. As demand increases, the supply of surface water increases but not proportionately. The sensitivity of surface water supply to water demand could be changed to reflect different supply strategies. High sensitivity indicates an aggressive supply strategy whereas low sensitivity, a passive supply strategy. The aggressive supply strategy is when a unit change in water demand leads to more than a unit of change in water supply. The passive supply strategy is when a unit change in water demand leads to less than a unit of change in water supply. These policies are illustrated in Fig. 4.

The second policy targets policymakers' impression of groundwater availability. The availability then not only impacts groundwater supply but also changes the society's perception of total water availability thus affecting future economic investments and population growth (Page et al., 2019). In the model, groundwater availability is governed by a coverage time which is assumed to be 300 years. That is, policymakers' mental model is set to sustain groundwater withdrawals for at least 300 years into the future. The shorter this coverage time is, the shorter-sighted the policymakers' strategy would be. Two alternative modes of strategic thinking, besides the base case, are considered. Low groundwater availability perception is reflected by doubling the coverage time to 600 years. High groundwater availability perception, in contrast, is reflected by the coverage time being set at 150 years.

To have a meaningful comparison between the simulation results, we need to select some performance measures that reasonably reflect the model's overall behavior. To decide which performance measures to select, one needs to consider various factors such as goals and preferences of the policymakers (or the society, in general), and the possibility and practicality of improvement in the selected measures. However, in most cases, water models focus on net change in groundwater storage as it is the savings account of a hydrologic system. Hydrologists usually try to balance all the withdrawals from the groundwater storage with its total recharge in a similar manner that a local government tries to balance its expenses with its revenues so that the total budget remains steady in the long-run. Therefore, net change in groundwater storage is used here as the primary performance measure. Nevertheless, a surface water withdrawal measure should also be used to make sure that both sources of water supply are considered in our analysis. Therefore, cumulative surface water withdrawals for agriculture is selected as the secondary performance measure[12].

[12] Surface water withdrawals for non-agriculture use is not included here because this measure has been insignificant for the current study region. Further, this measure is considered as cumulative so that its final value at the year 2099 (final simulation time) could be comparable under different simulation cases.

5.3. Model Comparison

A naming protocol is developed for the simulation runs here to explain the analyzing process efficiently. The name of each run consists of 4 letters, e.g., UGBL where the first letter represents the climate scenario from which the exogenous hydrologic drivers are produced. In UGBL, U stands for the UKMO climate scenario. Other options are G (GFDL scenario) and N (NCAR scenario). The second letter in the runs' name indicates whether the simulation is generated by the closed-loop or by the open-loop model. If the letter is C, the simulation run is generated from the closed-loop model. Otherwise, the result is from the open-loop model. The open-loop model uses a climate scenario to run the hydrologic variables. The exogenous socioeconomic scenarios, however, could be driven by the same or different climate scenarios so that uncertainty in future trajectories of the variables is accounted for. Again, U, G, and N are used to represent UKMO, GFDL, and NCAR scenarios respectively for these cases. The third letter in the name represents the status of surface water supply policy while the fourth (last) letter represents the state of the groundwater availability perception. Each policy/scenario then takes three statuses: L (low), B (base), and H (high). In the example, the third letter is L, meaning that the sensitivity of surface water supply policy is low. The second letter is B, meaning that groundwater availability perception remains unchanged (equal to its base case setting).

To compare the policy outcomes of the four models (a closed-loop and three open-loop cases) a formal procedure is developed as shown in Fig. 5. This procedure could be summarized as the following steps[13].

1. Preparation (not shown in Fig. 5)
   (a) Run the closed-loop model with a hydroclimate scenario that is not used before.
   (b) Save the results of the socioeconomic drivers for the open-loop model in a spreadsheet.
   (c) End the preparation step if all hydroclimate scenarios are used; otherwise go to step 1-1.
2. Run the closed-loop model with a hydroclimate scenario that has not been used before and save the end time value of the performance measures.
3. Run the open-loop model using a socioeconomic driver that has not been used before and the exact same hydroclimate scenario selected in step 2 and save the end time value of the performance measures.
4. Select a policy combination that has not been tested before and apply it to the closed-loop model and save the results.
5. Apply the exact same policy combination from step 4 to the open-loop model and save the results.
6. For each performance measure of the closed-loop model, compare the policy result from step 4 with the base run from step 2 and record the discrepancy between them.
7. For each performance measure of the open-loop model, compare the policy result from step 5 with the base run from step 3 and record the discrepancy between then.
8. Compare the discrepancies from steps 6 and 7; if both show changes in the same direction, mark and record the experiment as a "similar" policy implication; otherwise, record it as a "conflicting" implication.
9. Repeat from step 4 until all the policy combinations are tested; then proceed to the next step.
10. Repeat from step 3 until all the socioeconomic scenarios are used; then proceed to the next step.
11. Repeat from step 2 until all the hydroclimate scenarios are used; then stop.

Table 2 demonstrates an example of the results for the primary performance measure (cumulative change in groundwater storage) for the case of UKMO scenario. Rows of the table represent the policy combinations (last two letters of the name of simulation runs as explained before). Columns of the table represent relative discrepancy between the outcome of the policies and the base run for each model. Each cell shows the changes in the performance measure relative to a counterpart that is achieved from the base case. More precisely, assume y is the final value of our performance measure with no policy applied (thus, BB) and y' is the same measure but after applying a policy combination. Then, the cells in Table 2 could be given by ρ as shown in Eq. (1) where i (1 to 9) and j (1 and 2) represent number of rows (policy combinations) and the models (closed- or open-loop) respectively.

$$\rho_{ij} = \frac{y'_{ij} - y_j}{|y_j|} \tag{1}$$

Note that in Table 2, for each row (combination of policies), the result of some open-loop scenarios notably disagrees with the result of the same policy combination in the closed-loop column. Assuming that increasing cumulative change in groundwater storage is a plausible policy outcome, different models suggest different impact for any specific policy combination. For example, the HH policy (combination of aggressive surface water supply and liberal perception of groundwater availability) increases the groundwater storage by 80% if the open-loop model is used. The same policy combination increases the groundwater storage by 77% if the closed-loop model is used. The open-loop model overestimates (or the closed-loop model underestimates) the impact of the policy. As another example, the HL policy (combination of aggressive surface water supply and conservative perception of groundwater availability) increases the groundwater storage by 81% if the open-loop model is used. The same policy combination increases the groundwater storage by 83% if the closed-loop model is used. In this case, the open-loop model underestimates (or the closed-loop model overestimates) the impact of the policy.

The disagreement between the closed-loop and open-loop model is not limited to the absolute numerical gap. Some results even differ in terms of policy implications. For instance, the closed-loop model implies that the BH policy (liberal perception of groundwater availability) "increases" the groundwater storage by 2.29%[14] whereas the open-loop model implies that the same policy "decreases" the groundwater storage by 2.03%. The closed-loop model also shows that the policy BL (conservative perception of groundwater availability) has a negative impact on groundwater storage. This policy leads to a 2.11% decline in groundwater storage, if the closed-loop model is used. The open-loop

[13] The flow process presented here has some redundancy in computation, thus not efficient from a programming perspective. As a result, the actual algorithm we used for the analysis evolved to a more complex, but more efficient process, although the logic remained the same. We assume that our readers are more interested in the logic of our analysis rather than the nuances of the programming techniques. Hence, we present only the logical flow here.

[14] Obviously, this is a counterintuitive result. Detailed analysis of why and how the conservative attitudes toward availability of groundwater can lead to further depletion of groundwater is beyond the scope of this article. As a concise explanation, nonetheless, it can be shown that in the short-run, a conservatory approach to the use of groundwater leads to similar results as indicated by the open-loop models. That is, depletion of groundwater storage slows down but mainly through conservation in the non-agricultural uses because in this particular region (lower Rio Grande), surface water resources are used exclusively for agriculture while groundwater is the sole supply of non-agriculture sector. The initial success in water conservation efforts decelerates the socioeconomic development leading to lower rates of economic and population growth. On the other hand, agriculture flourishes as an alternative to non-agriculture sector that is not affected by this particular policy. Consequently, irrigated land expands which eventually causes the depletion rate of groundwater resources to accelerate in the long-run.

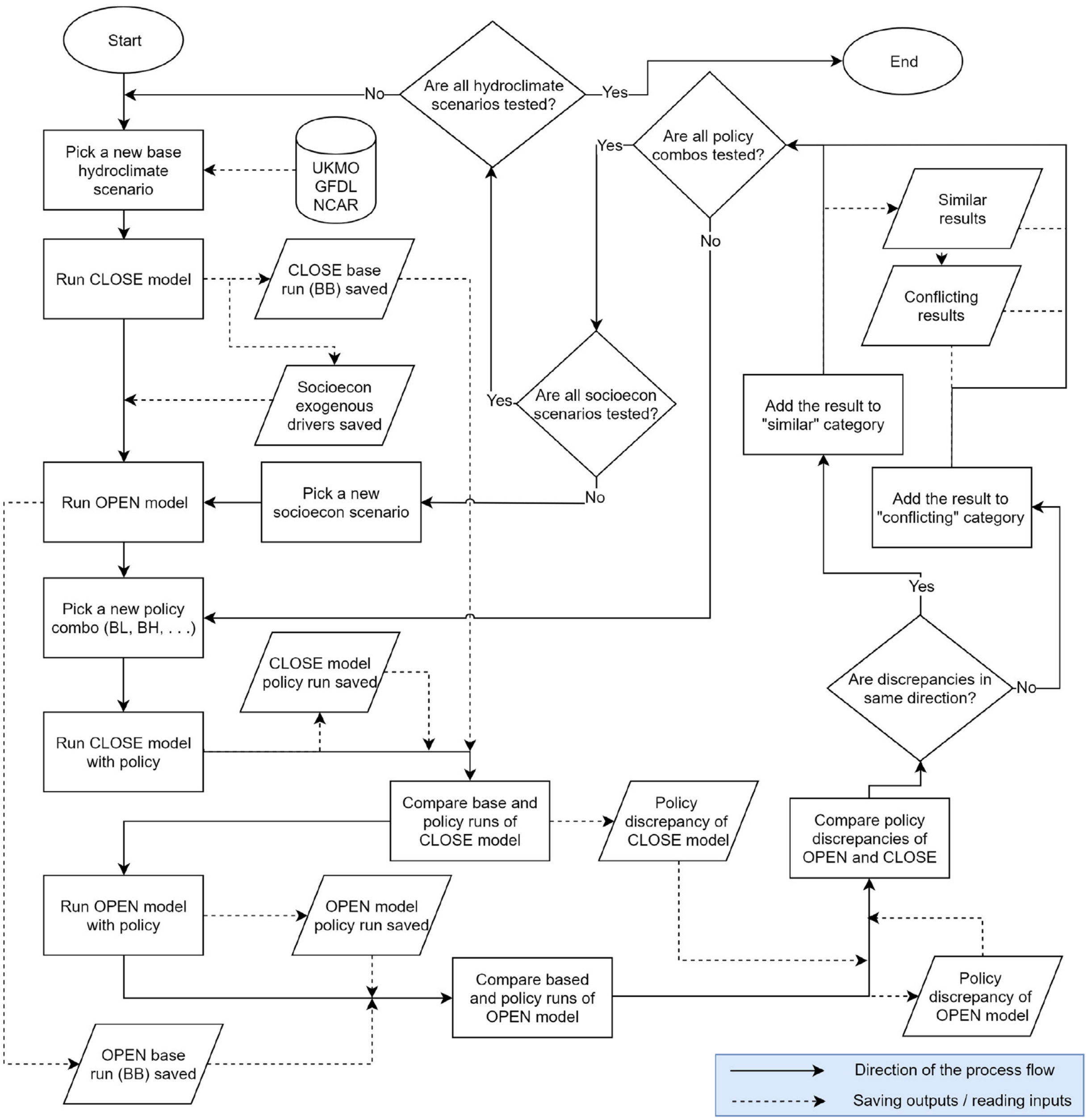

Fig. 5. Model comparing procedure.

Table 2
Relative discrepancy between policy and base runs for cumulative change in groundwater storage (case of UKMO).

Policy	Closed-loop	Open-loop
BB	0	0
BH	0.0229	−0.0203
BL	−0.0211	0.0142
LB	−0.3837	−0.3980
LH	−0.3399	−0.4281
LL	−0.4219	−0.3769
HB	0.8068	0.8101
HH	0.7715	0.8018
HL	0.8302	0.8157

model, in contrast, reveals the opposite outcome. The groundwater storage increases by 1.41% due to the policy. The open-loop model rejects the BH policy, but the close-loop model does not. The closed-loop model rejects the BL policy, but the open-loop model does not.

Two example policies from Table 2 are illustrated graphically in Fig. 6. The solid (red) line represents the base case against which the policies are compared. The left and right graphs show the BL and LB policies, respectively. The dotted lines represent policy result of the open-loop model while the dashed lines represent the output of the closed-loop model. Notice that for the BL policy (the left-side graph), cumulative change in groundwater simulated by the closed-loop model lays lower than the base run, while the result of the open-loop model lays higher than the base case. These results indicate "conflicting" (opposing) policy implications. For the LB policy (the right-side graph), both policy runs lay above the base run. These cases, although different regarding the numerical magnitude of the results, represent "similar" policy implications.

Table 2 presents only one of the 18 result tables (2 measures for each three base hydroclimate cases and for each three socioeconomic cases) consisting of 144 comparisons in total. The question now is that how many of these comparisons suggest conflicting policy implications. A Python script was developed to systematically compare the results as

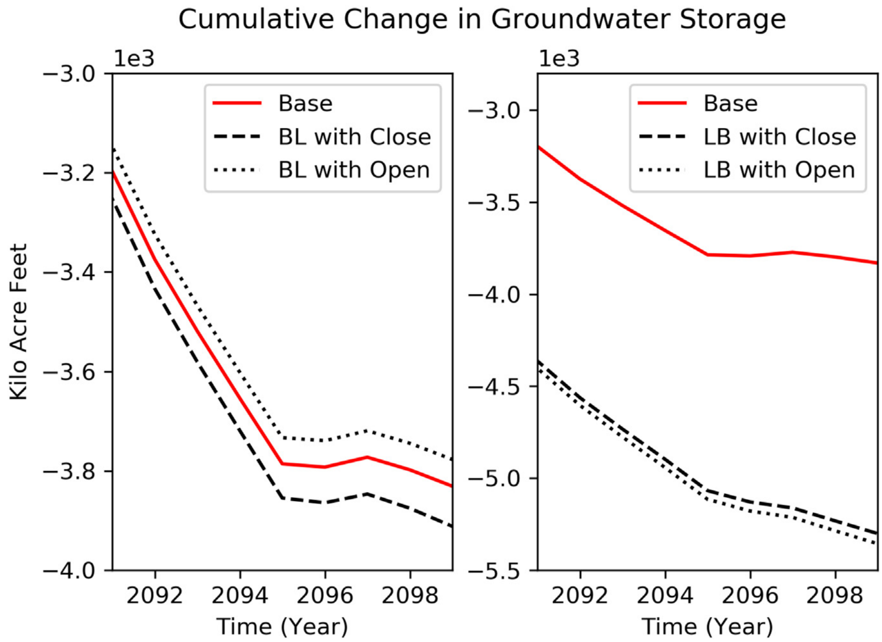

Fig. 6. Two examples of comparison of policy tests (left: "conflicting" policy implications, right: "similar" policy implications).

Table 3
Number of compared simulation runs that suggest conflicting policy implications.

Performance measure	Conflicting outcomes
Cumulative Change in Groundwater Storage	12 (16.67%)
Cumulative Agriculture SW Withdrawals	18 (25.00%)
Total	30 (20.83%)

Table 4
Test of significance for the gap between conflicting policy outcomes.

Performance measure	N	Min	Mean	Max	sd	*t*
Cumulative Agriculture SW Withdrawals	18	0.53%	0.67%	0.79%	0.09%	32.809
Cumulative Change in Groundwater Storage	12	2.78%	3.42%	4.68%	0.72%	16.576

presented in Fig. 5 [12]. The outcome (summarized in Table 3) reveals that for both performance measures, a significant number of comparisons suggest conflicting policy implications. In 30 out of 144 total comparisons (i.e. 20.83% of runs), the closed-loop model rejected a policy that was recommended by the open-loop model and vice versa. Table 4 shows that numerical discrepancy between the conflicting policy outcomes is significant too.

6. Discussion

Linking ecology, economics, and society is essential for the efficient management of natural resources (Plummer and Armitage, 2007). Simulation results presented in this paper confirm this idea by revealing that the modeling choice to include or exclude socioeconomic variables such as population, income and irrigated land as endogenous variables is critical. A wrong modeling choice regarding these variables could lead to incorrect policy outcomes and recommendations. In a closed-loop model, the socioeconomic variables react to changes in the state of the hydrologic system. They do not stay steady as predefined exogenous scenarios in open-loop models suggest. For example, when a tight water supply policy for agriculture is applied, water stocks change in the long-term. This change translates into a different perception of water availability down the road. Water availability perception then affects economic investment, agriculture, and population dynamics. Economic changes propagate through agriculture and population in the same way that changes in agriculture feed back into the economy and population and that the changes in the population feed back into the economy and agriculture. All these changes then lead to further changes in water use dynamics, thus affecting the socioeconomic system even further, for example, this could lead to over-extraction of natural resources. Such cumulative circular causation could prove significant if the simulation horizon is long enough. The lack of socioeconomic feedback in hydrologic projections may have contributed to the current state of frequent occurrences of over-extraction. The exact cause, however, is extremely difficult to pinpoint to a single analysis. As expounded in Section 4, the process of policy adoption almost always involves greater complexity than model analyses because in real-world situations, policies are usually implemented through multiple political channels or influences. Furthermore, it takes a long time for policy effects to fully unfold while other societal variables are also concurrently changing.

Although numerical outputs of a closed-loop model always differ from an open-loop model's, their policy recommendations may not. Our experimentation shows that two conditions are decisive for the models to oppose each other in terms of policy implications. The first condition is the time horizon of the analysis. In Fig. 6 (the left-side graph), we saw that the policy BL had conflicting outcomes when applied to the two models. That diagram shows only the latest time periods of the simulation. Fig. 7 expands the dynamics of that experiment. The two models produce "similar" policy recommendation if we stop the simulation at 2029. More interestingly, the closed-loop model shows greater policy outcome than the open-loop in that period. Within this period, the BL policy is supported by both models. However, as the simulation continues, the policy recommendation of the closed-loop model changes (to a reject) while the open-loop model still recommends the policy. This switch in the direction of policy outcome is observed for most of the conflicting results. The switch usually happens after 20–30 years through simulation. The socioeconomic feedbacks start to work much earlier than this time frame. However, it takes time for the effects to become powerful enough to counter the initial responses created by the policy.

The second condition that decides the conflict between the closed- and open-loop models is the power of the implemented policy. As

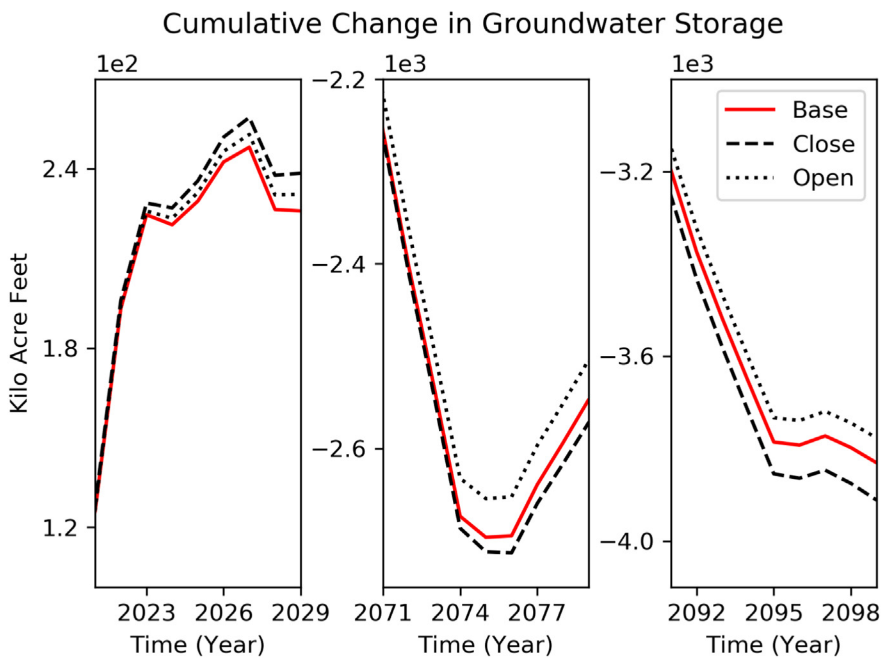

Fig. 7. Dynamics of an example policy test (BL) on open- and closed-loop models.

mentioned earlier, socioeconomic feedbacks take time to counter the initial effects of a policy. If that initial effect is large enough, then the feedbacks offset them partially but cannot turn them around. In these situations, the models still disagree numerically, but they produce the same recommendation. This behavior is seen in Fig. 6 (right-side graph) where the closed-loop model offsets some of the negative impacts of the LB policy produced by the open-model. The discrepancy between the results and the base run is so wide, though, that the compensation is not enough to change the fate of the policy.

7. Conclusion

The model introduced in this paper is calibrated and validated for the case of a southern region in New Mexico, US. The model provides a minimalistic structure as an essential starting point for any social-hydrology modeling effort. The structure can be extended to include more details depending on the purpose of the study.

Our analysis shows that for some variables, boundary selection in a water analysis could be critical. For water models, it is vital to include and test the impact of socioeconomic variables (in particular, population, economic performance, and irrigated land) as endogenous components. A model could lead to misleading (if not wrong) policy recommendations if it lacks the necessary socioeconomic feedback links. Simulation results reveal that up to 25% of the times, a closed-loop model could reject (recommend) a policy that was recommended (rejected) by an open-loop model.

The experiments conducted in this paper are carefully designed in order to minimize the structural differences (other than the socioeconomic feedback) between the two models. Even the base simulation runs for the open-loop model are produced by the corresponding runs of the closed-loop model so there is absolutely no difference between the base runs of the two models for each hydroclimate setting. This ensures that the conflicting results of the two models are exclusively due to the socioeconomic feedback loops that are switched off in the open-loop model.

Nevertheless, the study has its limitations. Although the model is fully assessed regarding structure, parameters, boundary adequacy, etc., it still needs to pass further confidence building tests. In the next step, the model will be applied to a southeast region in New Mexico to address these issues. Furthermore, economic uncertainties could impact hydrologic dynamics (Langarudi and Silva, 2017). Even the way human perceptions are formulated in a model might affect its results (Langarudi and Bar-On, 2018). To deal with the uncertainties, a more comprehensive sensitivity analysis is in order. The simulation tests presented in this paper then will be reexamined in different model settings to assure the robustness of the results.

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Appendix A. Model Equations and Documentation

Equations and documentation of the model presented in this article can be found online at https://doi.org/10.1016/j.ecolecon.2019.01.009.

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