Quantifying the value of stakeholder elicited information in models of coupled human-water systems

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Key Points:

- We develop socio-hydrologic models (SHMs) to capture human-water interactions in the operation of Nagarjuna Sagar reservoir in Southern India
- We assess the sensitivity of SHM structures to varying levels of stakeholder elicited information
- Stakeholder elicited SHM structures improve reproduction of reservoir storage

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Abstract
Causal loop diagrams (CLDs) based on expert and/or stakeholder inputs inform the quantitative structure of socio-hydrological models (SHMs). However, a systematic exploration of the sensitivity of CLDs and SHMs to different levels of stakeholder inputs is lacking. For a large multi-purpose reservoir in southern India, we explore this sensitivity by developing three CLDs that integrate reservoir water balance, groundwater pumping, and consumer water use patterns. CLD1 is a conventional water balance-based reservoir model, while CLD2 additionally incorporates the reservoir operator's judgment and groundwater pumping. CLD3 further incorporates the adaptive behavior of water users by adjusting demands in response to long-term (5-year) droughts. The correlation between observed and simulated monthly reservoir storage (2000-2013) for SHM1, SHM2, and SHM3 is 0.57, 0.85, and 0.87, respectively. SHM3 also outperforms SHM1 and SHM2 in simulating the relative use of surface and groundwater for irrigation purposes in the command area of the reservoir. Simulated demand deficits, command area groundwater levels, and minimum environmental flow satisfaction downstream of the reservoir for 1968-2013 using the three models exhibit substantial differences. SHM1 and SHM2 simulate deteriorating groundwater levels under the multi-year drought of 2001-2003 while SHM3 does not due to the consideration of adaptive farmer behavior. Thus, our understanding of water and food security during a multi-year drought can be significantly affected by the level of stakeholder inputs incorporated in the models. We highlight the importance of testing different SHMs structures to better understand human-water interactions under extreme conditions.

1 Introduction

Human interference in the natural hydrological cycle has increased in the Anthropocene. This has led to methodological developments to understand and model the dynamics of coupled human-water systems (Du et al., 2020; X. Li et al., 2018; Noël & Cai, 2017; Merz et al., 2020; Sivapalan et al., 2012; Cai et al., 2015). Several studies focus on feedback and interactions among water resource systems and human behavior in relation to floods, droughts, water supply, and groundwater exploitation. Exploring complex human-water interactions requires understanding of human behavior, changes in biophysical and socio-economic systems, and evolving water resources management strategies, all of which are central to addressing the interlinked Sustainable Development Goals (Di Baldassarre et al., 2019). Socio-Hydrological Models (SHMs) quantitatively couple social and hydrologic processes, and can help to explore the complex decision context of several water resource systems (Di Baldassarre et al., 2021; Herrera-Franco et al., 2021; Troy et al., 2015; Yu et al., 2020; Khadim et al., 2023). They allow the modeler to explore the dynamic co-evolution of coupled human-water systems by abstracting salient features of both systems (Sivapalan et al., 2012). They have been applied to enable decision-making at farm scale, understand system dynamics, and identify trade-offs between environmental and economic measures (Foster et al., 2014; Inam et al., 2017; Van Emmerik et al., 2014; Pande & Savenije, 2016; O'Keeffe et al., 2018; Wescoat Jr et al., 2018; Ghoreishi et al., 2021).

Development of a causal loop diagram (CLD) is a critical step during the qualitative phase of studying system dynamics for human-water interactions (Gohari et al., 2013; Ram & Irfan, 2021). CLD integrates multiple elements of the water resources system including human, ecological and hydrological aspects. Often CLDs are conceived using existing data and the modeler's knowledge of the system (Gohari et al., 2013; R. Li et al., 2018; Ram & Irfan, 2021; Daniel et al., 2021). However, a few studies have highlighted the value of multi-stakeholder input for developing CLDs that capture a range of feedbacks and interactions. Examples include analyses of conflicts in policy-making for groundwater protection (Giordano et al., 2017), an economic view of the urban water system (Mbavarira & Grimm, 2021), examining water-food-energy nexus systems (Purwanto et al., 2019), hydropower projects (Voegeli & Finger, 2021), and water quality management (Halbe et al., 2018). For example Giordano et al. (2017) identified interactions between individual perceptions of farmers, regional water managers, and an irrigation consortium. They showed how decisions from regional water managers impact farmers' behavior and the probable mechanisms through which water pricing drives groundwater exploitation from illegal pumping activities.

While CLDs provide a useful conceptual representation of a system, a CLD-only approach without model-based simulation may be insufficient for risk assessment and decision making (Blair et al., 2021). SHM development from CLDs that are informed by stakeholders is now accepted practice, but with evolving methodologies. Approaches include eliciting data for each CLD element (Blair et al., 2021), using group exercises with stakeholders to understand the complexity of Water-Energy-Food systems (Purwanto et al., 2021), and collecting primary data on water consumption and irrigation scheduling using semi-structured interviews (O'Keeffe et al., 2018). However, SHMs are not always validated using observations for key state variables (Troy et al., 2015; Wine, 2020; Ross & Chang, 2021). In some cases, models are validated using limited period information, or from other sources like newspaper articles (Chen et al., 2016; Elshafei et al., 2015; D. Li et al., 2019; Wei et al., 2017). Sometimes the model is developed and not validated due to unmeasured/intangible variables in the model or lack of observational data (Sung et al., 2018; Müller & Levy, 2019; Kandasamy et al., 2014). An adequate representation and simulation of the dynamics of the socio-hydrologic system is necessary to derive insights on the feedback between human and water systems (Elshafei et al., 2014; Di Baldassarre et al., 2015). Therefore, although validating complex SHMs is daunting, there is a recognized need to find appropriate methodologies (Kwak et al., 2021), such as use of proxy variables (Roobavannan et al., 2017).

As SHMs represent diverse hydrologic and socio-economic, and human-water interactions, model development and validation are by definition study area specific. Here, an important question arises - how much stakeholder information is needed to arrive at a decision relevant representation? The answer is perhaps partly related to protocols for validating SHMs. Here, we explore a methodological approach to SHM development that uses a multi-model framework that systematically increases the incorporation of stakeholder information across model structures. These structures are then evaluated using observations of key state variables to arrive at their relative representativeness of the system. We apply this framework to understand the dynamics of a large multi-purpose reservoir in southern India for the historical time periods. The main contributions of our study are:

1. We explore how stakeholder information can be included in a systematic manner using multiple CLDs and the implications of the resultant SHM structures on the state of the socio-hydrological system being studied.
2. For a large-scale multi-purpose reservoir in India, we evaluate the ability of available data in helping identify a representative SHM.
3. We analyse downstream environmental flows, water shortages, and groundwater level in the command area of the reservoir using all SHMs to highlight the degree to which our interpretation of the human-water interactions may differ across model structures.

2 Study Area and Data Sources

The Nagarjuna Sagar (NS) reservoir is one largest and most important irrigation projects in the Krishna basin, a major river basin in Southern India. NS has a storage capacity of 5,733 Mm^3, which is around 20% of the average annual inflow at the reservoir site for 1968-2016. It sustains a large community of farmers with an irrigable area of ~9,000 km^2. Historical data shows substantial upstream developments that have impacted volumetric inflows into the reservoir (Table 1). Compared to available water and storage, water demands on the NS reservoir are quite high with total annual demand of 8,535 Mm^3. The reservoir water is used for irrigation, domestic and industrial water supply. Since 2004, NS supplies ∼123 Mm^3 of water annually to Hyderabad, a pharmaceutical and software hub with more than 7 million inhabitants, and is expected to increase supply to 370 Mm^3 by 2030 (Molle et al., 2010; Van Rooijen et al., 2005). Marginal and small farmers account for 60% of the area operated by holdings in the NS command area (Figure S1 in Supporting Information S1). Upstream changes may have contributed to the severe drought period of 2002-2004; the longest contiguous drought within the 1969-2010 period (Venot et al., 2007), and may further increase the potential for future droughts (Biggs et al., 2007; Gaur et al., 2008). The NS reservoir is committed to supplying 2,264 Mm^3 to the Krishna Delta (irrigated area of 5,400 km^2) (Molle et al., 2010). Hence, the NS reservoir faces severe challenges in meeting increasing multi-sectoral demands. This situation has precipitated into a proposal of a major inter-basin water transfer project, within the larger National River Linking Project, that aims to increase water availability to the NS reservoir by transferring around 16,400 Mm^3 of water from the Godavari River basin (NWDA, 2021). A majority of these transfers are prescribed during monsoon and post-monsoon seasons.

3 Methodological Framework

Broadly the methods follow the steps detailed in Figure 2. We begin with the conceptualization of the NS reservoir system without any stakeholder information. The initial model stucture along with various sub-modules is described in section 3.1. Next, semi-structured interviews are performed to gather stakeholder information. The procedure followed for conducting the interviews is detailed in Section 3.2. The information from these interviews is used to develop alternative CLDs. Finally, SHMs based on the three CLDs are validated against observations of key state variables and water security metrics are used to understand the conditions on the project's command area (Section 3.3).

3.1 Preliminary Conceptualization of the NS reservoir: CLD1

Causal loop diagrams (CLDs) help conceptualize the system by defining and connecting key elements, thus enabling a comprehensive understanding of interactions (Sterman, 2000; Simonovic, 2009). To develop the pre-interview CLD (CLD1), the analyst conceptualizes the natural hydrologic processes and associated human interferences without any stakeholder interaction. In the context of the NS reservoir, this includes identifying rainfall-runoff module, reservoir water balance and operating policy, and water use patterns in the project's command area (Figure 3). This CLD is developed without any stakeholder inputs but relies on historical data, the analyst's understanding of the system, and the assumption that the reservoir will be operated following a rational scheme that releases water for demand satisfaction followed by release of any excess water exceeding reservoir's live storage capacity.

The CLD includes reservoir module, and command area module. The reservoir module includes the human elements of reservoir operation that is prescribed using standard release rules (Section 3.1.2). Inflow from the river is the input to the reservoir module, which is assumed to be determined by natural rainfall runoff processes. Ideally, one would start with a rainfall-runoff model, but we have inflow data and so do not include it here. We assume that reservoir operators will release water as per the estimated demands. The command area module tracks demand deficits based on aggregate domestic, industrial, and agricultural water demands.

Table 1. Different historical characteristics of the NS reservoir.

Characteristic	Variable	Value	Data source
Hydro-climatology	Mean annual precipitation, temperature (catchment area)	760 mm (1901-2015), 26ºC (1951-2015)	Srivastava et al. (2009); Pai et al. (2014)
	Potential evapotranspiration	1767 mm (1951-2015)	Srivastava et al. (2009); Hargreaves and Samani (1985)
	Average annual inflow	43323 Mm^3 (1967-1981), 26608 Mm^3 (1982-2015)	Irrigation and CAD department, Telangana
	Major drought in historical time period	2001-2004	Precipitation based
Reservoir related	Maximum storage capacity	5733 Mm^3	Irrigation and CAD department
	Storage data [monthly, 2000-2020]	Average monthly storage 3375 Mm^3	WRIS (www.india-wris.nrsc.gov.in)
Command area related: Land use, Socio-economic conditions	Land use in command area for Year 2005	Cropland: 80% Forest: 12% Water bodies/ wetlands: 5% Others: 3%	Roy et al. (2016)
	Construction of large dams (Name, year)	Srisailam (1981), Narayanapura (1982), Jurala (1996)	Lehner et al. (2011)
	Groundwater	Area average of 47 well data (Figure 1)	WRIS (www.india-wris.nrsc.gov.in)
	Population in command area (2011 Census)	∼216030	2011 census
	Irrigation demands	7000 Mm^3	Veena et al. (2021)
	Domestic water supply demands	550 Mm^3	Veena et al. (2021)
	Industrial demands (assumed equal to domestic)	550 Mm^3	Veena et al. (2021)
	Economic condition in Krishna basin (purchasing power parity)	+98% from 1990 to 2005	Nordhaus and Chen (2016)
	Irrigated area	11822 km^2	Veena et al. (2021)

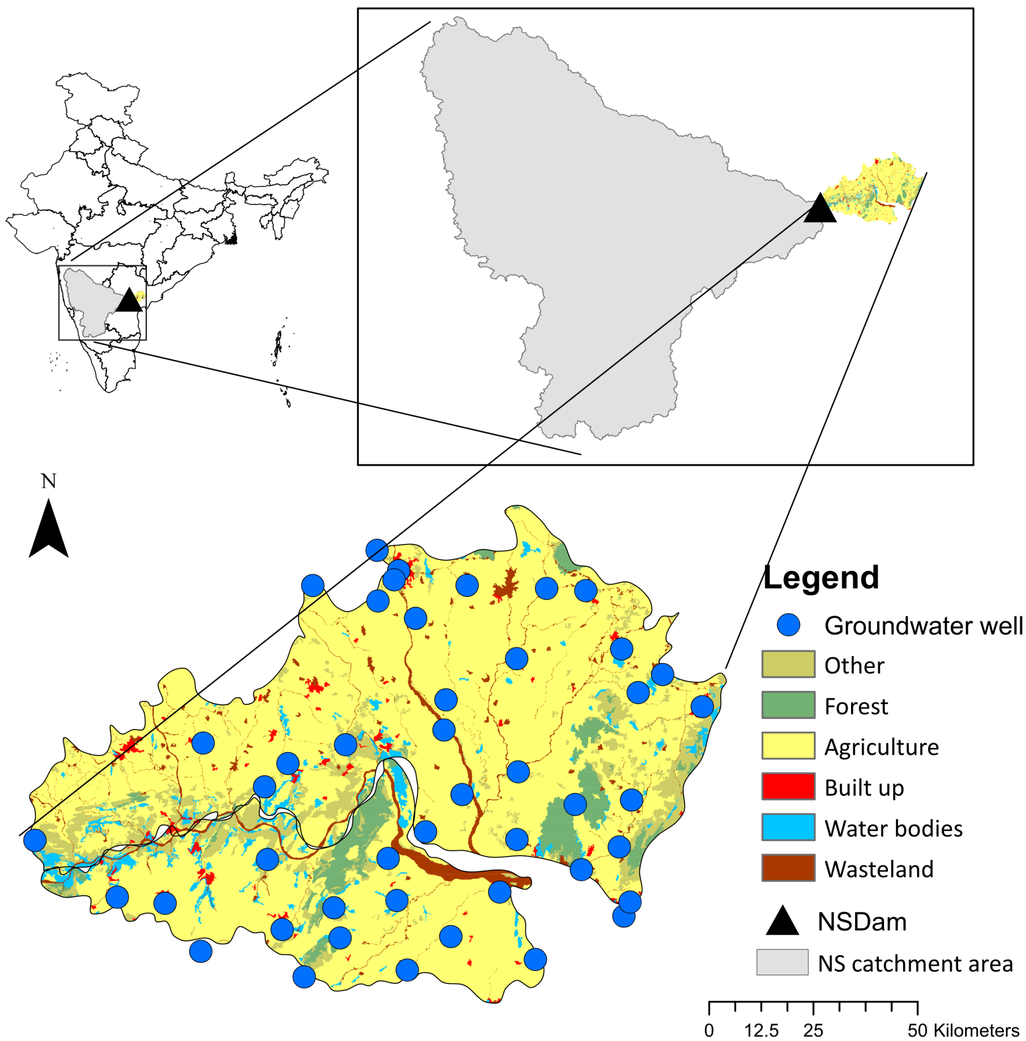

Figure 1. The Nagarjuna Sagar reservoir, its catchment area, and command area. Land-use pattern in the command area is shown where majority is agriculture. The location of ground water wells is shown in blue circles.

3.1.1 Reservoir Module

The reservoir model tracks the water balance dynamics of reservoir via Equation 1.

$$s_t = s_{t-1} + q_t - d_t - re_t \tag{1}$$

In Equation 1, s_t is the storage in the reservoir, q_t is the inflow to the reservoir, d_t is water released for satisfying multisectoral demands and re_t is the excess water released downstream. Subscript t is the timestep. The model is simulated on a monthly timescale. Without any stakeholder elicitation, water is released assuming a rational decision maker. First, demand related releases are made, then excess water is released if s_t exceeds 95% of live storage capacity of the reservoir. These releases are monitored for high flow failures defined by the maximum release in the historical data for a given time period.

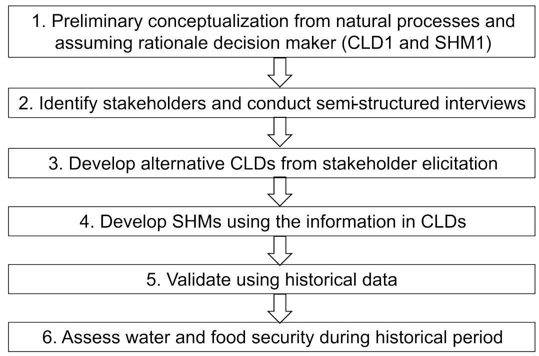

Figure 2. The methodological framework for developing alternative CLDs and SHMs from first principles and stakeholder elicitation. This is followed by validation using historical data.

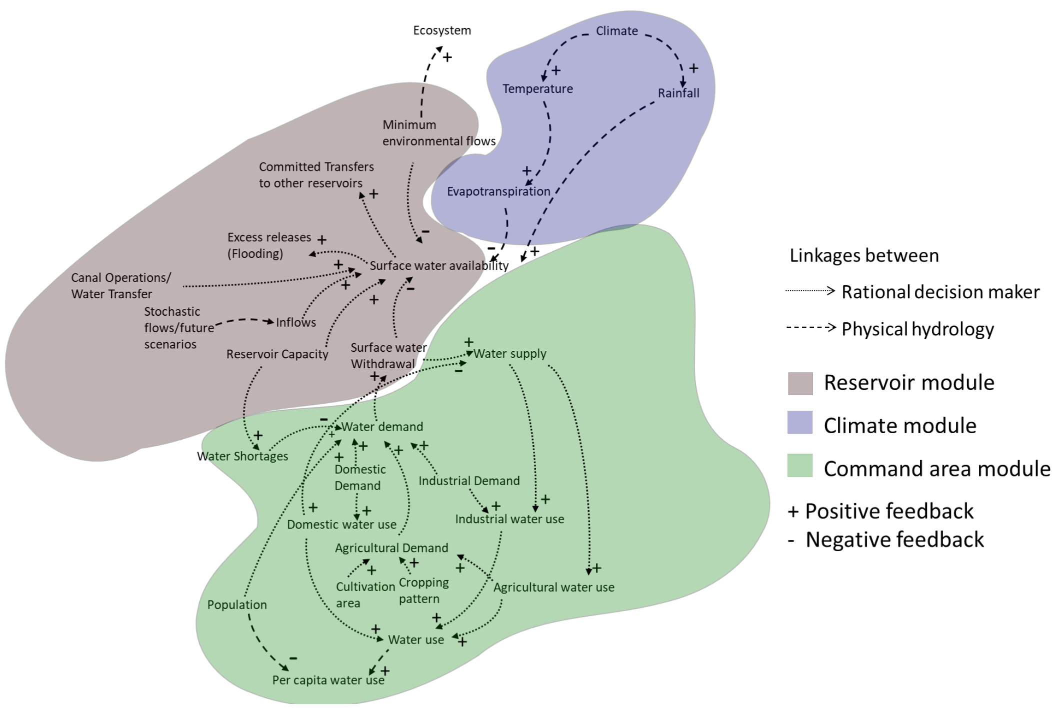

Figure 3. CLD1 showing the preliminary conceptualization of the NS reservoir system with three main components: the reservoir operation module, the command area module and climate module.

3.1.2 Command area module

This module specifies demands that are to be satisfied from reservoir releases and groundwater pumping. Demands are estimated for domestic, agricultural and industrial sectors as a function of time. Agricultural demands depend upon crop type, cropping area and net irrigation requirements, which are estimated using historical observations for 1968-2013 (Gaur et al., 2008; Venot, Reddy, & Umapathy, 2010; EPTRI, 2008). Domestic demand is based on population (Jones & O'Neill, 2016) and per capita demand. In absence of data, the industrial demands are assumed equal to domestic demands. Supplementary Figure S3 shows the demand patterns for 1968-2013. Cropping is sown in two major seasons Kharif (July to November) and Rabi (December to April). Type of crops in Kharif season are rice, groundnut, sorghum, grams, cotton, chilli, and in Rabi season are groundnut, sorghum and grams. Cropping pattern is 25%, 12%, 10%, 29%, 17%, and 6%, for crops rice, groundnut, sorghum, grams, cotton, chilli in both seasons.

3.2 Stakeholder Elicitation

We apply a stakeholder elicitation approach to characterise the role of human decision making in managing water resources. Inputs from stakeholders can help identify and characterise water management decisions of different stakeholders and incorporate their insights into the model structure (Bhave et al., 2018, 2020; Jacobs & Buijs, 2011). This is especially relevant for multi-stakeholder systems such as large multi-purpose reservoirs because interactions between hydrological, infrastructural, and human behavioral dimensions are complex, and capturing such interactions may be crucial to simulate conditions accurately (Jacobs & Buijs, 2011). Here, we divided stakeholders into three groups based on their role in decision-making related to the NS reservoir. Group 1 comprised of government decision makers who take decisions regarding reservoir management such as state irrigation departments. Group 2 comprised of water users in the study area, including municipal bodies that manage water for Hyderabad and farmers in the project's command area. Decisions of stakeholders from the second group are affected by the decisions/actions of the first group. Group 3 comprised of stakeholders concerned about the riverine ecosystems such as non-governmental organizations (NGOs).

We use semi-structured interviews to elicit responses to specific questions of the interviewer (the first author) and to allow for a more organic discussion that yields information on other dimensions that could help improve the relevance of the CLD for this complex system. These interviews were conducted between May and July 2019; 8 with the first group, 9 with the second group and 4 with the third group. Interviews were conducted in person at the stakeholder's workplace, with due consent and anonymity, and lasted between 30 minutes to 1 hour. Each interview started with an informal social discussion and a brief introduction to research goals and interview style. Questions were open-ended and based on a pre-interview questionnaire. The pre-interview questionnaire included questions on water availability, cropping patterns, tackling water deficits, challenges related to managing water resources, water transfers, prioritization of donor and recipient basins, groundwater withdrawals, and other alternatives (Supporting material S1). We conducted interviews in two languages, Telugu (regional language) and English, as per the convenience of the stakeholder (the interviewer is proficient in both languages). Starting with questions common to all stakeholders we fine-tuned the interview to the type of stakeholder and the information we sought from them. For example, the question on stakeholder's opinion on positive and negative consequences of a possible water transfer were discussed in terms of water supply perspective for water users and in terms of the ecological perspective of NGO representatives. Questions related to water demand changes under land use/cropping pattern change were discussed in detail with water users and decision makers but not with NGO representatives.

3.3 SHM validation measures and water security indicators

Models can be validated in two ways: outcome validation and structural validation (Aghaie et al., 2021). With outcome validation one can assess the model results whereas with structural validation one can assess whether the structure of model agrees with different opinions. As discussed previously, validating SHMs has been difficult due to intangible variables in the model, limited data availability and lack of protocol for SHMs. Here, we validate the different SHMs using multiple measures. We use outcome validation for SHM performance, where we use observed historical data on reservoir storage, groundwater levels, and the ratio of surface water consumption to groundwater abstraction.

We also identify five indicator variables that represent water security in the study region as well as the extent to which sustainable limits for water use are approached. These are:

(i) Blue water withdrawal exceedance (WWE): Following the procedure suggested by Steffen et al. (2015), we quantifies the limits of blue water use for the Krishna River at NS. First, the natural inflows to the reservoir are classified into low flow, intermediate flow, and high flow months using the variable monthly flow method (Pastor et al., 2014). We then define blue water withdrawal limits using a conservative estimate of 25%, 40%, and 55% of mean monthly flow for low, intermediate, and high flow months, respectively. These are the freshwater use boundaries following guidelines in Steffen et al. (2015). When water withdrawal exceeds the blue water withdrawal limit, the difference between these two is defined as WWE.

(ii) Minimum environmental flow (MEF) satisfaction: MEF requirements for instream ecology are set at 30% of the historical flows as per the recommendations of Smakhtin (2006). MEF limits are estimated at a daily time step by applying the 30% threshold to mean daily flow value across all years. Then, simulations of water released downstream of the reservoir are compared against these daily thresholds to identify whether MEF was satisfied or not. This information is condensed into a reliability metric that quantifies the relative number of days in a time horizon MEF requirements were met.

(iii) Demand deficits: Demand deficits are estimated as the difference between estimated water demands and water released for demand satisfaction, aggregated across the entire time horizon.

(iv) Downstream releases: Downstream releases are analyzed to ascertain whether extreme inflows may lead to releases causing channel erosion and other damages downstream of the reservoir.

(v) Groundwater levels: the output from the groundwater module is visualized to understand the trajectory of groundwater levels in the command area of the reservoir.

4 Results

4.1 Stakeholder elicited CLDs and SHMs

Semi-structured interviews reveal key interactions that were not included in CLD1. First, farmers highlighted how groundwater supplements surface water irrigation water provided by the NS reservoir. Second, reservoir authorities revealed certain rules-of-thumb that are followed in filling and spilling the reservoir, instead of a demand-based rule. Third, interviews revealed that there is a governance time scale of 5 years at which major decisions related to reducing demands following water saving techniques or identifying alternative water sources or utilizing reservoir's dead storage, may be taken for regions undergoing prolonged shortages of water (interviewee X quotes "In case of continuous droughts the focus should be on decentralized management like farm ponds and rainwater harvesting, which takes around 5 years to be implemented. Rainwater Harvesting Theme Park was constructed in Hyderabad to create awareness on rainwater harvesting and groundwater recharge."). On the other hand, interview Y quoted "Based on water availability in the previous year, we decide the crop area and cropping pattern for the current year. There are instances where we reduce the crop area by a small amount to account for deficits of previous year", indicating that farmers may react to deficits that occur even for a single year, albeit with a smaller margin of demand reduction.

Using such insights, we develop CLDs 2 and 3 (Figure 4). Instead of adding all the elicited information into a single updated CLD, we added information methodically to CLD1 by categorizing the responses from stakeholders resulting in CLD2 and CLD3. This exercise is performed to understand the value of information in a model structure at monthly timestep. For example, first any obvious omissions to the system, such as unaccounted groundwater pumping or rules-of-thumb followed by reservoir operators, are included in CLD2. Next, we include water user behavior changes in the most complex version of the CLD. Various elements of these CLDs are grouped into different modules, highlighted using background color in Figure 4. Thus, the groundwater and consumer modules are added to CLD1 after stakeholder inputs. Each module is then translated into a model by using adequate equations and parameterizations, these are detailed in Sections 4.1.1 and 4.1.2. Note that while stakeholder inputs were used to develop the CLDs, process related equations and parameterizations were primarily derived from author's understanding of qualitative stakeholder inputs. Table 2 lists the process differences between CLDs 1, 2, and 3; Table 3 lists the parameters in the models. After stakeholder elicitation, the reservoir operations are altered to additionally include a rule of thumb to empty the reservoir in by April (SHM2 and SHM3). To this end, we estimate the reservoir storage in the beginning of December and release one-fourth of that volume every month until April to empty the reservoir. Also, reservoir is allowed to completely fill in the months of August and September to maintain maximum storage of 95% of live capacity.

We would like to note that this process will vary depending upon the study area and nature of stakeholder involvement for each study. However, the main idea is to develop multiple model structures and include stakeholder information in a systematic manner to enable testing using multiple modules.

Table 2. Difference between the CLDs. CLD2 and CLD3 are constructed from CLD1 after incorporating stakeholder inputs.

	CLD1 (author developed)	CLD2 (stakeholder elicited)	CLD3 (stakeholder elicited)
Reservoir module	Release based on water availability in the reservoir	CLD1 along with the goal to empty the reservoir at the end of summer and fill the reservoir in monsoon based on reservoir operator inputs.	Same as CLD2
Command area module	Farmers irrigate as per demands	Farmers irrigate as per demands	Farmers irrigate as per updated demands on adapting to deficits
Consumer module	Farmers demand do not respond to experienced water deficits	Same as CLD1	Farmers adapt to experienced deficits. Two adaptation options are included based on whether the experienced deficits are short-term or long-term
Groundwater module	None included as it is assumed farmers exclusively depend upon reservoir water	Included to simulate conjunctive use of surface and groundwater in the command area as per the inputs from the farmers	Same as CLD2

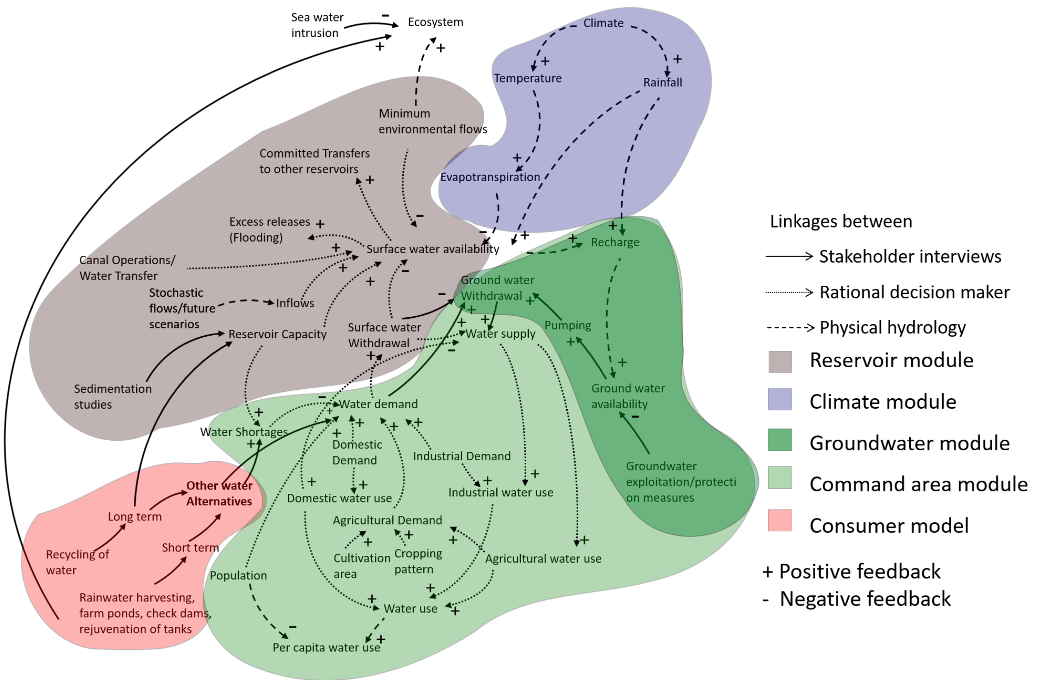

Figure 4. Fully developed stakeholder elicited CLD (CLD 3) for NS reservoir. CLD 2 includes the groundwater module (CLD2 shown in Figure S4 of supporting information). CLD3 additionally includes a consumer water use module. We depict three types of linkages; derived from physical hydrology (dashed lines), from an assumed rational decision maker (dotted lines), and from stakeholder interviews (solid lines). Colors represent different modules of the system - reservoir module is shown in purple, climate module is shown in blue, consumer module is shown in pink, command area module is shown in light green, and groundwater module is shown in dark green. Positive feedbacks are shown by the + sign and negative feedbacks by the - sign.

4.1.1 Groundwater module

The groundwater heads are simulated assuming the entire command area as a single control volume. We use a lumped parsimonious water balance model that simulates groundwater head as function of rainfall (P_t in m), pumping (Qp_t in m^3) and a lateral outflow term (Equation 2). The model is based on the recent model by Elangovan et al. (2021), which has shown promising application to the urban region of Hyderabad, also serviced by the NS reservoir. Here we include an additional lateral outflow term that allows us to capture the effect of subsurface groundwater fluxes, which are unobservable.

$$h_t = h_{t-1} + \frac{r * (P_t)}{S_y} - \frac{Q_{p_t}}{S_y * A} - \alpha h_{t-1} \tag{2}$$

In Equation 2, h_t is the groundwater level at time t in m, r is recharge factor, S_y is specific yield, A is aquifer area in m^2. r varies between 0 and 1, α determines the lateral flux from the aquifer as a fraction of aquifer head and varies between 0 to 1. Simulated groundwater heads are compared against Theisson-polygon averaged groundwater heads using all the observation wells in the command area. 70% of the data is used for calibration of parameters while the remaining 30% data is used for validation (Table 3). When water released from reservoir fails to satisfy demands, it triggers pumping in the command area for SHM2 and SHM3. Pumping volumes are set equal to the unmet demand and is bounded by 200 Mm^3. This is the upper limit of pumping in the command area based on developed infrastructure (Venot et al., 2007).

4.1.2 Consumer Water Use Module

The consumer model simulates end user's water use behavior as elicited from interviews. It adapts demands based on deficits in demand satisfaction in previous years (Equation 3-4).

$$ad_t = \begin{cases} ad_t & ad_{t-12} = 0 \\ ad_t - min(ad_{t-12}, \phi) & df_{t-12\times m} > 0 \quad m = 1 \\ ad_t - min(2 \times ad_{t-12}, k\phi) & df_{t-12\times m} > 0 \quad m \in [1, ..., 5] \end{cases} \tag{3}$$

$$df_t = d_t - ad_t \tag{4}$$

In Equation 3-4, ad_t is the actual demand, d_t is the water released for demand satisfaction, and df_t is the deficit at time t, k and ϕ are demand reduction and multiplier for reduction parameters fixed from literature and earlier studies on India in case of short-term and long-term deficits. A deficit is classified as long-term when water users face five consecutive years of water shortages for that month, other deficits are classified as short-term. In short-term (long-term) deficits, water users reduce their demands equal to (twice of) the experienced deficit of the prior year, or 62.5 Mm^3 (125 Mm^3), whichever is smaller. Here, ϕ is equal to 62.5 and value of k is 2. The upper limits on demand reduction for long-term deficits are largely consistent with other studies (Bhave et al., 2018; Ashoori et al., 2017; Nechifor & Winning, 2018). The upper limit for short-term deficits was set at half that for long-term deficits. In case of long-term deficits, reservoir operator adaptation is also considered by increasing the reservoir storage capacity utilizing water from dead storage. NS reservoir storage capacity of 5,733 Mm^3 is increased by 500 Mm^3 during long-term deficits with a maximum limit of 6840 Mm^3.

Table 3. List of parameters in SHMs developed

Parameter	Unit	Description	Module	Data/calibration
r	-	Recharge factor	Command area	Calibrated
Sy	-	Specific yield	Command area	Calibrated
b	m	Maximum depth of groundwater	Command area	Calibrated
α	-	Lateral outflow fraction	Command area	Calibrated
ϕ	Mm^3	Demand reduction value	Consumer water use	Data from literature
k	-	Multiplier for demand reduction	Consumer water use	Data from literature

4.2 Calibration and Validation of SHMs

4.2.1 Groundwater module

We divide the period of available groundwater levels (2007-2013) into a calibration (2007-2011) and validation (2011-2013) period to estimate four parameters (recharge coefficient r, specific yield Sy, lateral outflow fraction α, and maximum depth of groundwater b) for the groundwater module in SHM2 and SHM3. We calibrate the parameters using the Nondominated Sorting Genetic Algorithm II (NSGA-II, (Deb et al., 2002)) that minimizes two objective functions: Nash Sutcliffe Efficiency and mean absolute error. The calibration is carried out using an open source python toolbox, REGSim toolbox developed by Elangovan et al. (2021). Two values each of r and α are defined for monsoon and non-monsoon season following recommendations by Elangovan et al. (2021) for this region. The pumping volumes are set equal to unmet demand from surface resources and is bounded by 200 Mm^3 based on infrastructure available in the region (Venot et al., 2007). The model attains NSE of 0.76 (0.84) and 0.76 (0.85) for SHM2 and SHM3, respectively in the validation (calibration) period (Figure S2 in Supporting Information S1). The optimal parameter value for Sy is 0.048, r is 0.12 (monsoon) and 0.19 (non-monsoon), α is 0.07 (monsoon) and 0.1 in (non-monsoon) and b is 11.73 m.

For the validation period (2007-2011), we find a general agreement on seasonality and overall year-to-year trends for groundwater with groundwater levels rising during monsoons (June-July-August-September) due to increased recharge and falling during the pre-monsoon period (Figure 5a). Dry season fall (January to April) is primarily due to increased demand triggered by lower water supply from the NS reservoir and low recharge. Groundwater levels also fall in the post-monsoon months due to high demands for the Rabi cropping season (October to March). SHM2 and SHM3 tend to under-predict the groundwater depletion during the dry months from January to June in 2012 and 2013. These are also periods of low reservoir storages triggers by low inflows, that likely resulted in over-extraction of groundwater resources and/or non-linear lateral flow dynamics.

4.2.2 Reservoir storage levels and relative usage of surface and groundwater for irrigation

When comparing reservoir storage observations (2000-2013) against simulated, we note a correlation coefficient (Pearson) between observed and simulated monthly storage values are 0.57, 0.85 and 0.87 for SHM1, SHM2, and SHM3, respectively (Figure 5b). We note a strong improvement in model performance when information on reservoir operation obtained from elicitation is included (SHM2 and SHM3). A substantial decrease in storage during the multi-year drought of 2002-2004 is observed across all SHMs (Venot, Reddy, & Umapathy, 2010). SHM2 and SHM3 simulations show substantial difference in simulated peak storage values post 2004 because the consumer water use module in SHM3 lowers demands following the drought, resulting in greater storage values. Incidentally, these higher values are more in agreement with observations, even in the validation period.

We also compare ability of SHMs to capture relative contributions of groundwater and surface water by simulating the ratio of respective volumes utilized for irrigation and comparing with observations (Figure 5c). The observed values of ratio of area under irrigation from surface water to groundwater in the NS command area for 2001-2002, 2002-2003 and 2005-2006, are 1.03, 0.12, and 3.56, respectively (Venot, Reddy, & Umapathy, 2010). The corresponding ratio of simulated values for volume of water utilized from surface water to groundwater for SHM2 (SHM3) are 6.08 (6.08), 3.02 (3.02), 26.07 (24.82), respectively. Both SHM2 and SHM3 demonstrate the ability to simulate the observed reduction in the ratio of surface water to groundwater for 2001-2002 and 2002-2003. Also, an increase in the utilization ratio was noted for both SHM2 and SHM3 when comparing 2002-2003 with 2005-2006, which is consistent with observations. These trends are also meaningful considering that 2002-2003 was a drought year, thus more reliance on groundwater is expected for 2002-2003 resulting in lower ratios. Note that the absolute values are different due to incommensurable variables used in the ratio estimation, i.e., volume for simulated data and area for the observed data.

4.2.3 Water security for environment and human well-being

We now compare the inferred water and ecological security states of the NS reservoir and its command area across the three model structures for the simulation period 1968-2013 (Figure 6). Demands increase significantly with time, mainly during 1968-1982 and are stabilized by year 1983 (Supplementary Figure S3). So, this time period is divided into pre- and post-demand stabilization for the years 1968-1982 and 1983-2013 respectively.

The mean annual volumes of water withdrawal exceedances (WWE) for SHM1, SHM2, and SHM3 are 5.21 Bm^3, 6.34 Bm^3, and 6.29 Bm^3, respectively (Figure 6a). This implies that the limits of sustainable blue (surface) water withdrawals are exceeded more frequently and by a greater magnitude by SHM2 and SHM3 where a rule to empty the reservoir at the end of summer and fill the reservoir in monsoon is followed by the reservoir operators. These exceedances are observed in the monsoon season for SHM2 and SHM3, where water is extracted to store in the reservoir. Whereas, in the case of SHM1, water is released downstream based on water availability, which is proportional to the natural flows reducing the water withdrawal exceedance. WWE for SHM1 is high during post-demand stabilization (5.96 Bm^3) compared to pre-demand stabilization (3.71 Bm^3) due to increase in demands and thereby increase in water withdrawal for demand satisfaction. Furthermore, WWE are high for SHM1 compared to SHM2 and SHM3 during the drought period (2001-2002), with values of 3.86 Bm^3 (2.59 Bm^3, 2.59 Bm^3) for SHM1 (SHM2, SHM3). This is due to the role played by conjunctive use of surface water and groundwater for SHM2 and SHM3, whereas demand satisfaction for SHM1 solely depends on the surface water withdrawal, exceeding the withdrawal limits.

We find substantial differences in inferred water demand deficits across the three model structures. SHM3 that incorporates adaptive behavior of water users results in mean annual deficits of 0.69 Bm^3. SHM2 that does not incorporate such adaptation results in greater deficit volume of 0.72 Bm^3 when compared to SHM3. Deficits are not observed for SHM1 except during drought periods (mean annual deficit of 0.28 Bm^3) due to its nature of operation of reservoirs to satisfy demands based on water availability. We see continuously increasing demand deficits in the historical period of NS reservoir due to increase in water demands and reduced water availability in the reservoir accounted by rapid upstream developments (Figure 6 c). Deficit during pre-demand stabilization period is zero for all SHM structures; 1.09 Bm^3 (1.04 Bm^3) for SHM2 (SHM3) during the post-demand stabilization period. These deficits increase by 86% during the drought period (2001-2002) with annual deficit of 2.03 Bm^3 (1.94 Bm^3) for SHM2 (SHM3). This suggests that demand deficits increase irrespective of model structure with SHM3 resulting in less deficit compared to SHM2.

Groundwater levels are observed to be the same for both SHM2 (annual mean depth of 6.47 m) and SHM3 (annual mean depth of 6.48 m) except with a small variation during the post drought years of 2004-2006 (Figure 6b). Mean annual depth of groundwater level is the same in pre-demand stabilization period for SHM2 and SHM3 with depth of 6.63 m, which reduces in the post-drought stabilization to 6.38 m (6.4 m) for SHM2 (SHM3). This shows reduced groundwater levels with increase in demands and higher level for SHM3 compared to SHM2 due to consumer adaptation. Also, groundwater abstraction is slightly higher for SHM2 during post drought period (5.91 m and 5.95 m for SHM2 and SHM3 for years 2004-2006) due the compound effect of increasing demands in the command area of the NS reservoir and not adapting to changes in water availability. We find a significant role of the consumer module that updates demand based on perceived long-term deficits in SHM3 but not in SHM2 when comparing groundwater levels. Between 2001 and 2005 (drought and post-drought periods), we observe a considerable difference in water demands. This is a period of reduced inflows, where the adaptation behavior of consumers to reduce demands becomes apparent. These lower demands in turn result in lower deficits, leading to reduced groundwater abstractions (Figure S5).

Thus, overall SHM3 suggests higher groundwater levels when compared to SHM2. The difference in average annual demands between SHM2 and SHM3 is 429 Mm^3, which translates to a difference in deficits of 152 Mm^3. Groundwater restores rapidly for SHM3 compared to SHM2 with a maximum difference in depth of 0. 2 m (20 mm) occurring in February 2004, which is a 5% improvement for SHM3 compared to SHM2.

We track downstream releases from NS reservoir for future flood occurrences that may lead to socio-economic damages to populations residing downstream as well as ecological damages from changes in channel geomorphology (Figure 6d). We find that a few instances of high flow releases across different SHMs. However, the differences between SHM model structures are negligible for this variable. We find a significant reduction in downstream releases for post-demand stabilization period (12 Bm^3) compared to pre-demand stabilization (23 Bm^3). So, downstream releases reduce with time with lowest during the drought period (1.89 Bm^3). The NS reservoir fails to satisfy minimum environmental flows (MEF) irrespective of model structures (Figure 6e). However, SHM1 generally yields lower MEF values than SHM2 and SHM3. Historical mean annual MEF for SHM3 (SHM2) is 0.50 (0.52) suggesting that socio-economic development in the command area could adversely affect downstream flows. Satisfaction of minimum environmental flow reliability also reduces with time (reliability of 0.56 and 0.47 in pre- and post-demand stabilization period respectively for SHM3), performing worse during the drought period (reliability of 0.21 for SHM3). Increase in deficits are consistent with low releases downstream and reduced reliability of satisfaction of MEF.

5 Discussion

We evaluate multiple structures of SHMs as an initial attempt to illustrate the uncertainties associated with conceptual model development and model structure. The command area of the recipient basin is predominantly cultivated by small and marginal farmers (Figure S1 in Supporting Information S1), where marginal farmers cultivate up to one hectare, and small-scale farmers cultivate between one and two hectares. The different CLDs and SHMs in this study do not always capture the different priorities of different farmers, nor the range of different demand reduction methods that may apply for different sizes of land holdings. For instance, farm ponds may be applicable for larger land holdings while farmers with smaller land holdings may depend on the canal-based surface water supply. We also assume a uniform aquifer, which is a necessary simplification, but may mean that heterogeneity in groundwater availability and extraction, and its implications may not have been sufficiently captured. Few issues identified by stakeholders in the CLDs, such as seawater intrusion, are not quantified in the SHM, because given the physiographical location of the study region, these impacts are considered relatively less important. These limitations illustrate a key issue with modelling human-water interactions, which is that all interactions and feedbacks may not be captured in the CLDs and SHMs. Exploration of the parametric uncertainty associated with the SHM, sediment assessment, and potential impacts of alternative short-term and long-term water management measures are beyond the scope of this study, but could be explored in future studies.

Explicit and implicit choices associated with system boundaries also have implications. For instance, while stakeholders could provide much information about the NS reservoir and command areas, insights regarding interventions outside basin could influence the system are not captured. These include the proposed Polavaram Vijayawada link to transfer water from the Godavari basin to the Krishna basin, and potential upstream changes in irrigation demand through interventions like the Kaleswaram project. Such large scale interventions could affect water availability and demand dynamics besides complex interactions with exogenous factors like climate change, along with uncertainties associated with their future management.

We find that long drought has substantial impact on the systems model. In case of low inflows, releasing for demand satisfaction instead of storing water in the reservoir may worsen the impact of drought, suggesting the need for reservoir operators to proactively manage reservoir storage to satisfy water demand. However, capturing reservoir operator behaviour is difficult. For instance, during the drought period of 2002-2004 (Figure 5), though the operator did not get sufficient inflows to raise the reservoir storage, they chose to release water through the canals which the SHM model developed does not capture, and warrants more research. This drought also reveals profound changes in the system resulting in equifinality between adaptation of reservoir operators and water users. Both adapt dynamically and isolating their individual impacts within a complex system is challenging. Increase in storage levels post-drought could be due to lower demands (adaptation by water users) or risk-averse behavior of the operator. Adaptation by water users (farmers) is considered by reduction of demands and also found in earlier studies (Venot, Reddy, & Umapathy, 2010; Venot, Jella, et al., 2010; Molle et al., 2010; Kakumanu et al., 2019). Adaptation of reservoir operators is hard to quantify as their adaptation behavior is not explicitly characterized. However, in SHM3, we consider farmer adaptation by reduction of demands and a logical reservoir operator adaptation by increasing the water stored in the reservoir (utilizing small amount of water from dead storage) which resulted in a good validation of post-drought water availability. Such adaptation of reservoir operator is not included in the literature. Stakeholders involved in reservoir operation did not explicitly reveal adaptation, but suggested the need to adapt policies during post-drought periods and included as part of structural modification. Information on unpredictable, complex behavior of reservoir operators, and legislative policies on actions during drought period were not established during elicitation. Overall, more detailed analysis on multiple working hypothesis are needed on how humans respond to prolonged droughts.

One key concern associated with irrigation water demand change is the effect on downstream water availability, especially for riparian ecosystems. SHMs tools provide more value when stakeholder inputs are used to identify the linkages, linkages and feedbacks (O'Keeffe et al., 2018). In our discussions stakeholders identified better observation networks, remotely sensed information, and constant monitoring of water-related parameters, especially streamflow and water distribution through canals, for better understanding of the system. For instance, canal water may not always reach the tail-end of the command area, sometimes due to over extraction by users in head or middle reaches, for which better observations would be useful. Also, complex quantitative and qualitative information available anecdotally, from newspapers and interactions with stakeholders could provide useful insights. Stronger two-way flow of information between modelers and stakeholders could help include and assess a wider range of issues, and help develop management systems that support greater equity in the distribution of water, enhanced protection of riparian ecosystems, and wider societal goals.

6 Conclusion

In this study, we develop socio-hydrologic models for large scale reservoirs in irrigation dominated command areas of a major multi-purpose water resources project. There are several unique features of this setting: 1) the conjunctive use of surface and groundwater in the command areas of the reservoirs, 2) the lack of standard norms for reservoir operations beyond existing government regulations on prioritization of water releases, and 3) hydroclimatic variability of the Indian summer monsoon that may result in multi-year droughts triggering demand adaptation behavior in farmers. The project and its overall setting are indicative of several such projects in developing countries. We have attempted to capture the feedbacks between water availability and water use using the method of semi-structured interviews. Our results highlight the value of including demand adaptation behavior by farmers in reservoir operation models to accurately understand the water security conditions in the project's command area in the aftermath of multi-year droughts. We also show that model outputs can be sensitive to varying levels of stakeholder inputs, and highlight the importance of independent validation of socio-hydrological models.

This study provides a useful methodological framework for understanding how to consider, conceptualize, characterize, and assess different aspects of human-water interactions to support better management of water resources in the future. The application of the model provides a significant planning and management avenue for exploring different model structure for the historical period with a possibility to analyze for future changes in climate and socio-economic conditions. We show why it is necessary to develop SHMs of different levels of complexity and with different inputs, project the system's state at larger scales, and explore uncertainties in human-water interactions.

One of the crucial facets of this study is stakeholder elicitation, where we include the attitudes and preferences of the stakeholder in the SHM framework using three different formulations of the CLD. We find better performance of the SHM which includes stakeholder information in terms of annual demand deficits for different structures of SHM. We propose and use a methodology for the development of the structure of socio-hydrological models from quantitative data and their validation with the available observed ground data. Overall, the dynamics of the system's state variables are impacted by the varying inputs from stakeholders about the complex interactions, and the consequent representation in the models. Further research may include using the developed SHMs to explore further interactions of this system with upstream regions and with neighboring basins, assessing adaptive behavior of water users under a wider range of climate change projections, and assessing the impact of different structures of SHMs.

7 Open Research

The hydrological data is obtained from Srivastava et al. (2009); Pai et al. (2014). The land use data is obtained from Roy et al. (2016). Data and codes to reproduce the results are uploaded to a GitHub repository (https://github.com/ssaiveena/shm.git) (Sunkara, 2023).

Acknowledgments
Sai Veena and Riddhi Singh are funded by DST-SERB early career research award number ECR/2015/000355. The authors thank the Central Water Commission (CWC) and the Irrigation and CAD Department, Telangana, for providing the data. Ajay Bhave is funded by the Water Security and Sustainable Development Hub funded by the UK Research and Innovation's Global Challenges Research Fund (GCRF) [Grant No. ES/S008179/1].

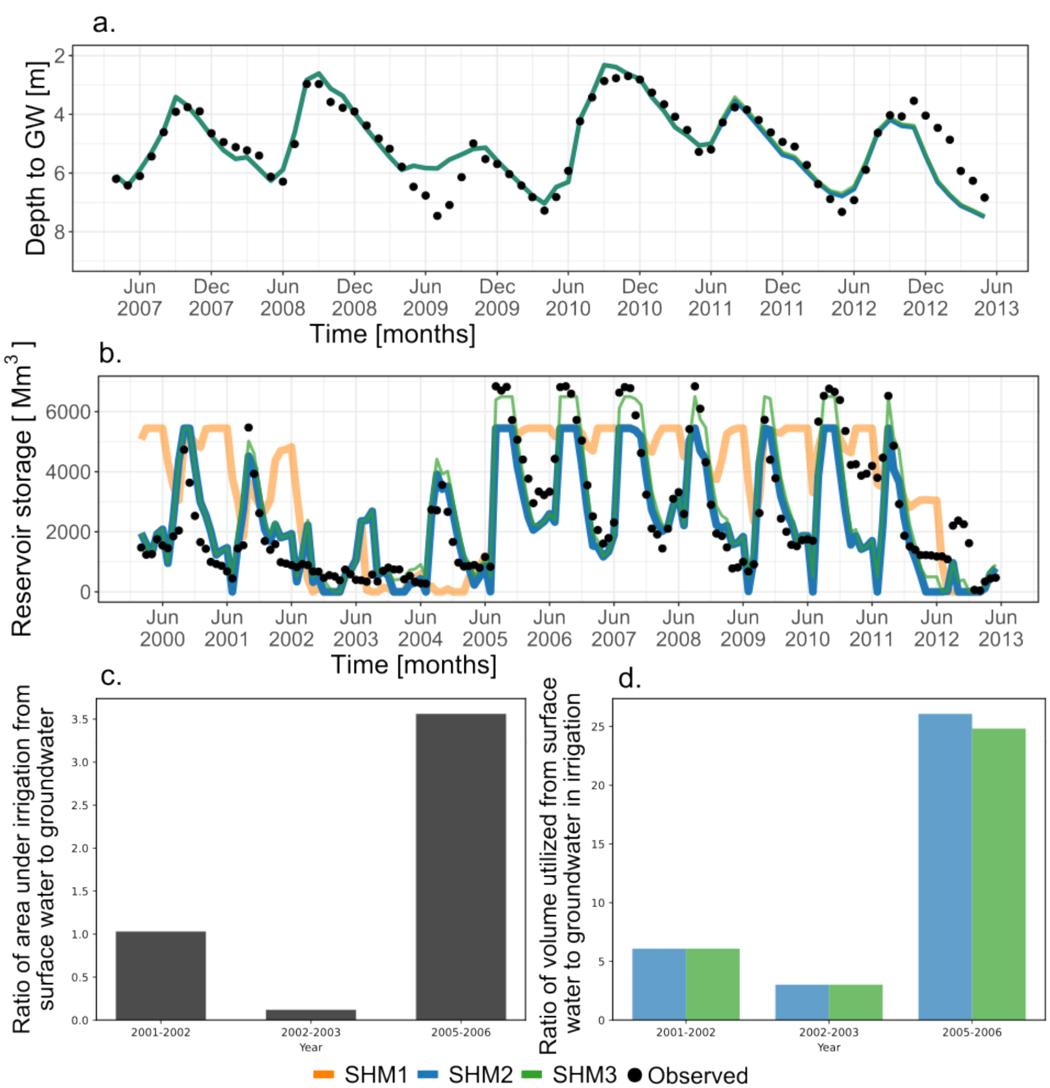

Figure 5. (a) Depth to groundwater in the command area of the NS reservoir for the calibration (2007-2011) and validation (2011-2013) periods as simulated by SHM2, and SHM3. Calibration is used to identify five groundwater process parameters: two seasonal recharge coefficients, specific yield, two coefficients for lateral flux, and depth to bedrock. (b) Monthly live storage [Mm^3] in the NS reservoir for 2000-2013 as simulated by SHM1, SHM2, and SHM3. Observed values are shown by black circles while simulations are shown by solid colored lines.(c) Ratio of surface to groundwater utilized. Here, observed data is the ratio of areas whereas for SHM data is ratio volume of water utilized.

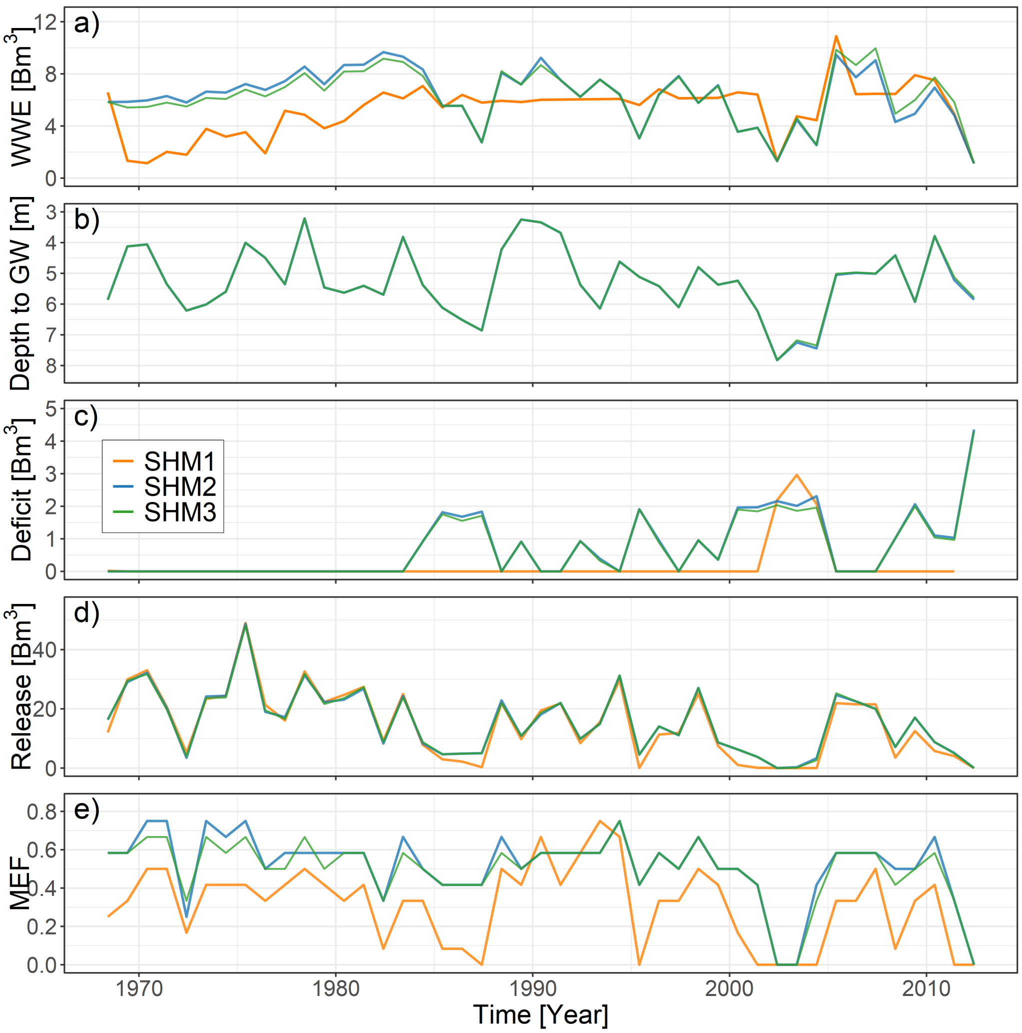

Figure 6. Historical (1968-2013) values of annual a) water withdrawal exceedance (WWE, Bm^3), b) Depth to groundwater [m], c) demand deficits [Bm^3], d) reservoir downstream releases [Bm^3], and e) satisfaction of minimum environmental flows (MEF) for the NS reservoir.

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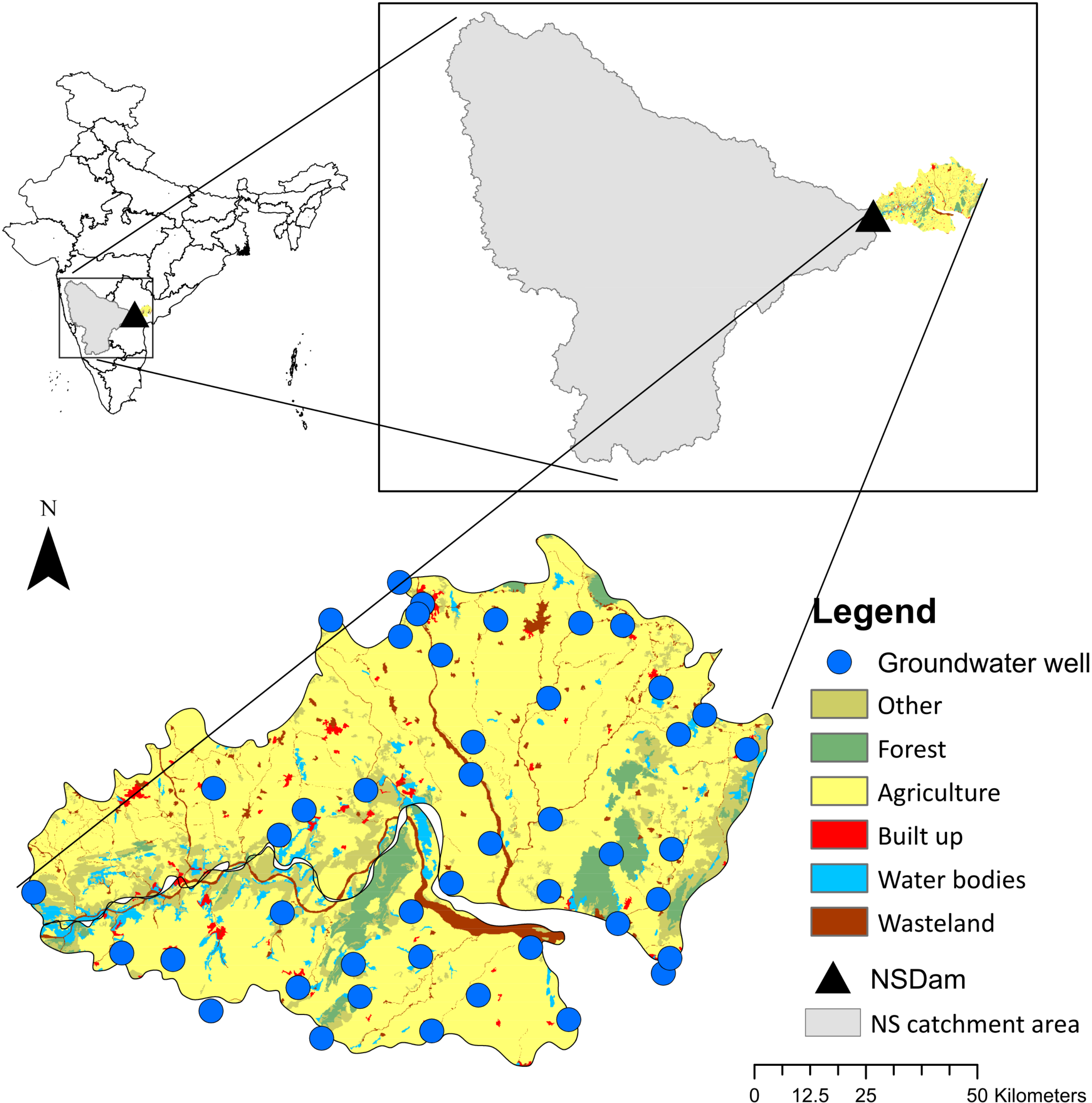
Figure 1.



N
Legend
Groundwater well
Other
Forest
Agriculture
Built up
Water bodies
Wasteland
NSDam
NS catchment area
0
12.5
25
50 Kilometers

Figure 2.

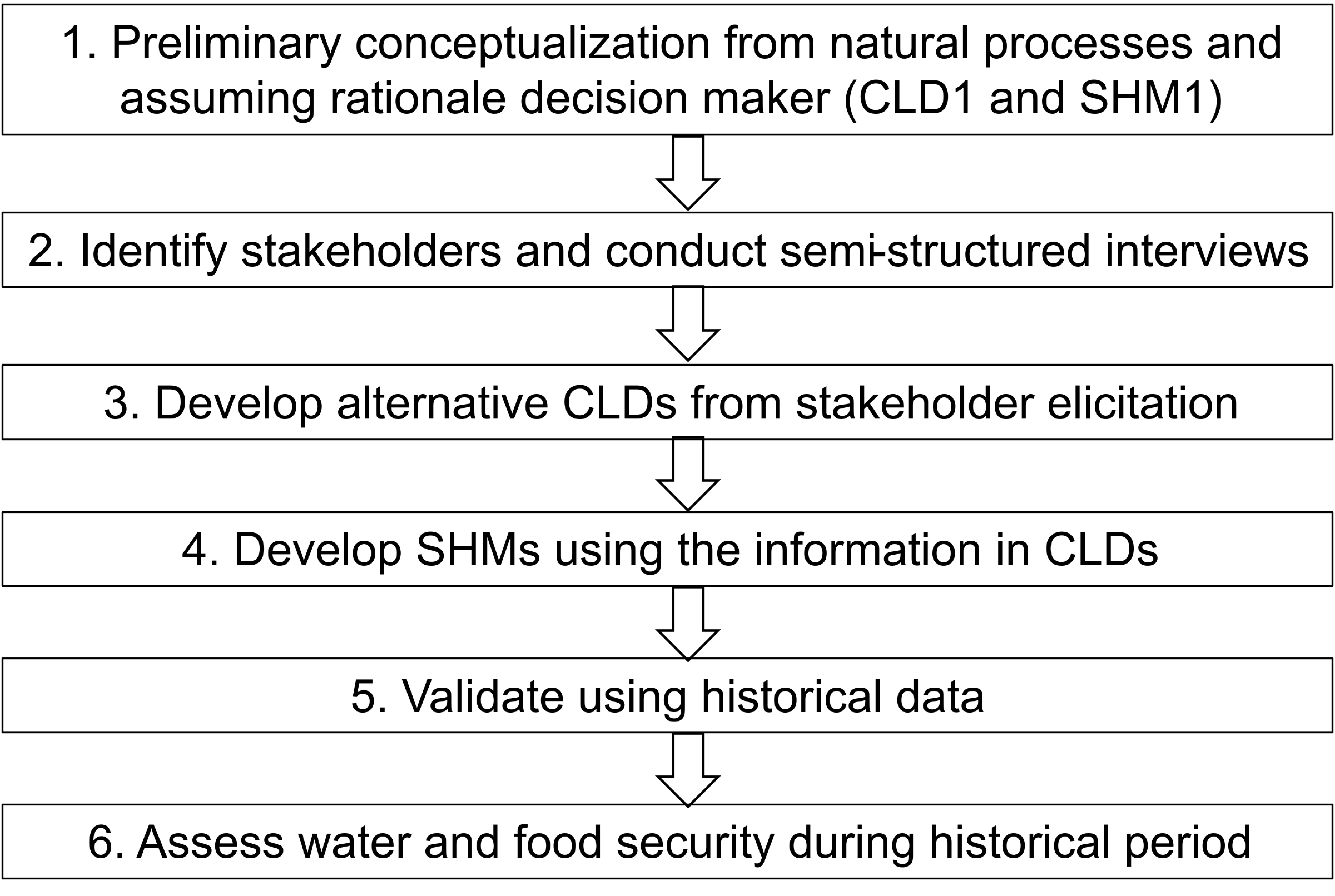

1. Preliminary conceptualization from natural processes and assuming rationale decision maker (CLD1 and SHM1)
2. Identify stakeholders and conduct semi-structured interviews
3. Develop alternative CLDs from stakeholder elicitation
4. Develop SHMs using the information in CLDs
5. Validate using historical data
6. Assess water and food security during historical period

Figure 3.

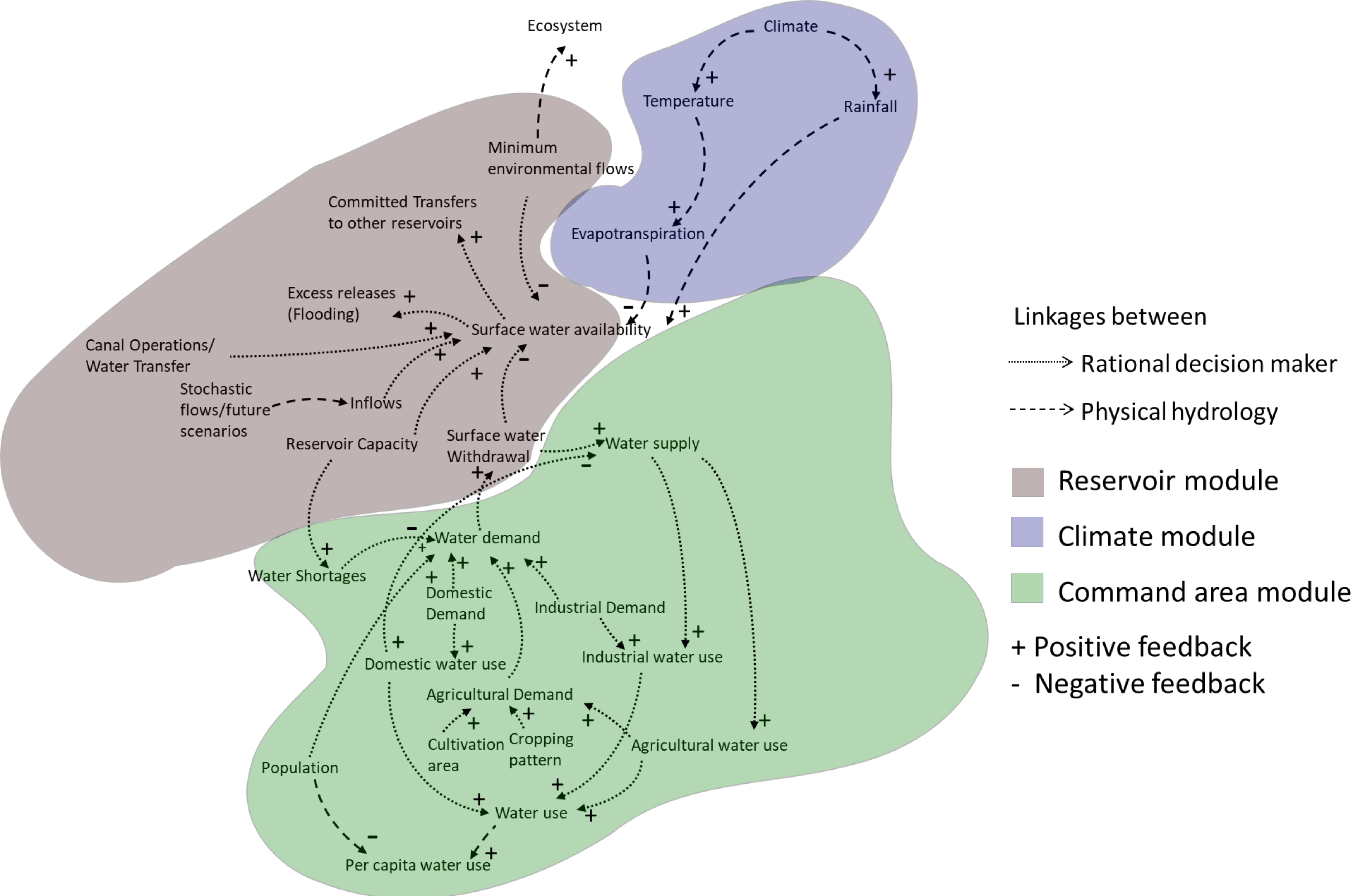
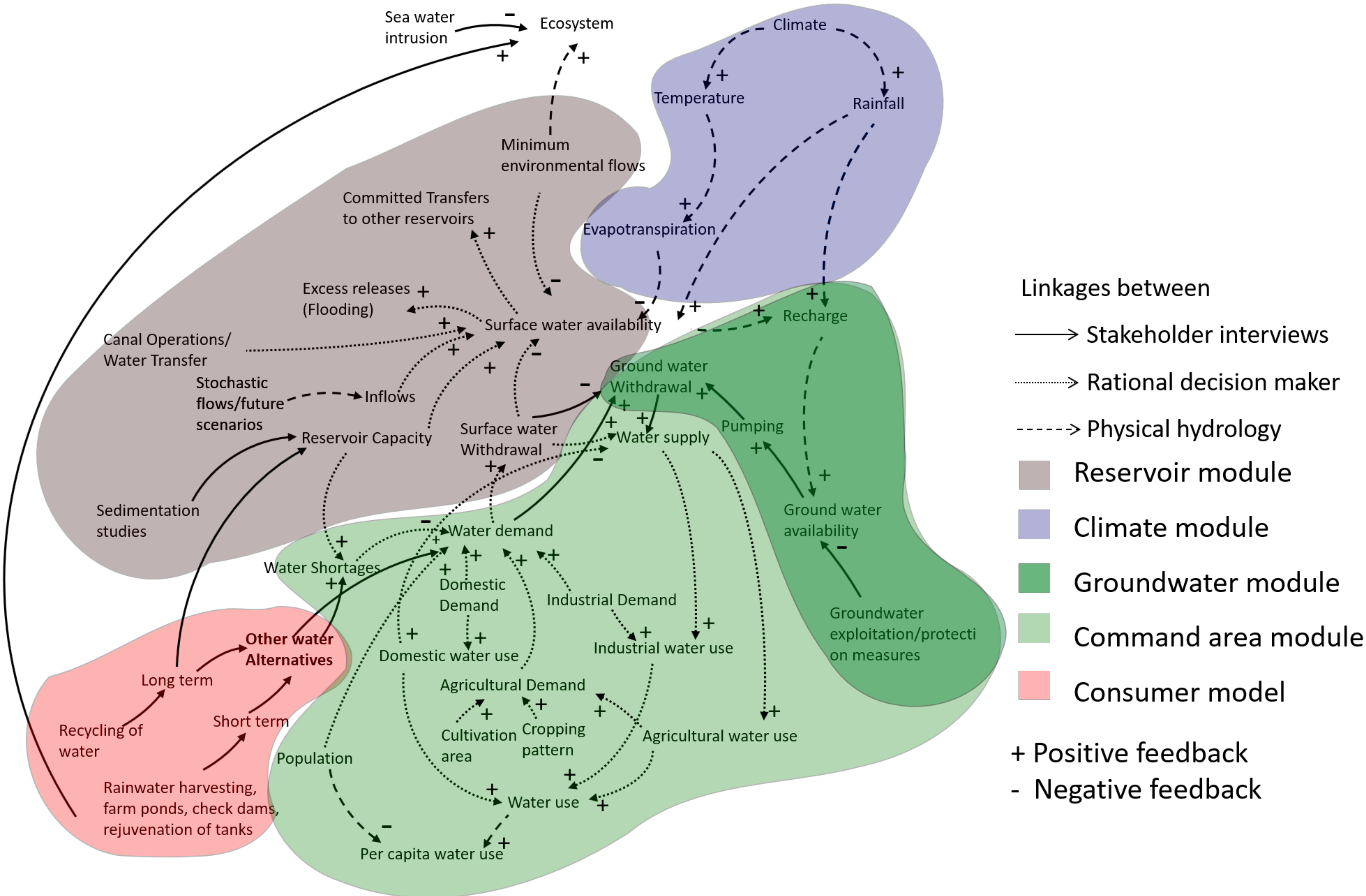

Ecosystem
Climate
Temperature
Rainfall
Minimum environmental flows
Committed Transfers to other reservoirs
Evapotranspiration
Excess releases (Flooding)
Surface water availability
Canal Operations/ Water Transfer
Stochastic flows/future scenarios
Inflows
Reservoir Capacity
Surface water Withdrawal
Water supply
Water demand
Water Shortages
Domestic Demand
Industrial Demand
Domestic water use
Industrial water use
Agricultural Demand
Cultivation area
Cropping pattern
Agricultural water use
Population
Water use
Per capita water use
Linkages between
Rational decision maker
Physical hydrology
Reservoir module
Climate module
Command area module
+ Positive feedback
- Negative feedback

Figure 4.



Sea water intrusion
Ecosystem
Climate
Temperature
Rainfall
Minimum environmental flows
Committed Transfers to other reservoirs
Evapotranspiration
Excess releases (Flooding)
Surface water availability
Recharge
Canal Operations/ Water Transfer
Stochastic flows/future scenarios
Inflows
Ground water Withdrawal
Reservoir Capacity
Surface water Withdrawal
Water supply
Pumping
Sedimentation studies
Ground water availability
Water demand
Water Shortages
Domestic Demand
Industrial Demand
Groundwater exploitation/protection measures
Other water Alternatives
Domestic water use
Industrial water use
Long term
Agricultural Demand
Recycling of water
Short term
Cultivation area
Cropping pattern
Agricultural water use
Population
Rainwater harvesting, farm ponds, check dams, rejuvenation of tanks
Water use
Per capita water use
Linkages between
Stakeholder interviews
Rational decision maker
Physical hydrology
Reservoir module
Climate module
Groundwater module
Command area module
Consumer model
+ Positive feedback
- Negative feedback

Figure 5.

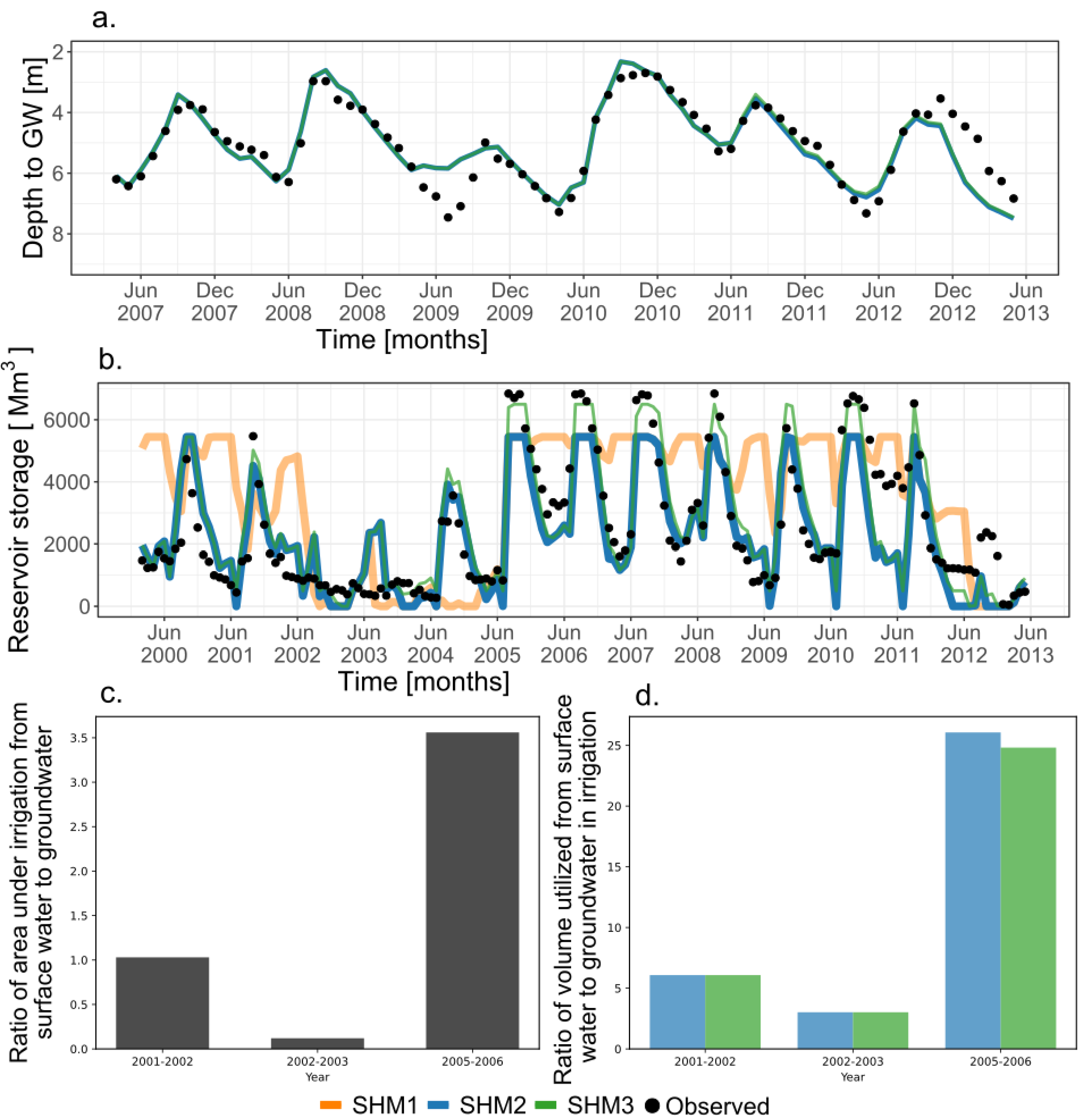
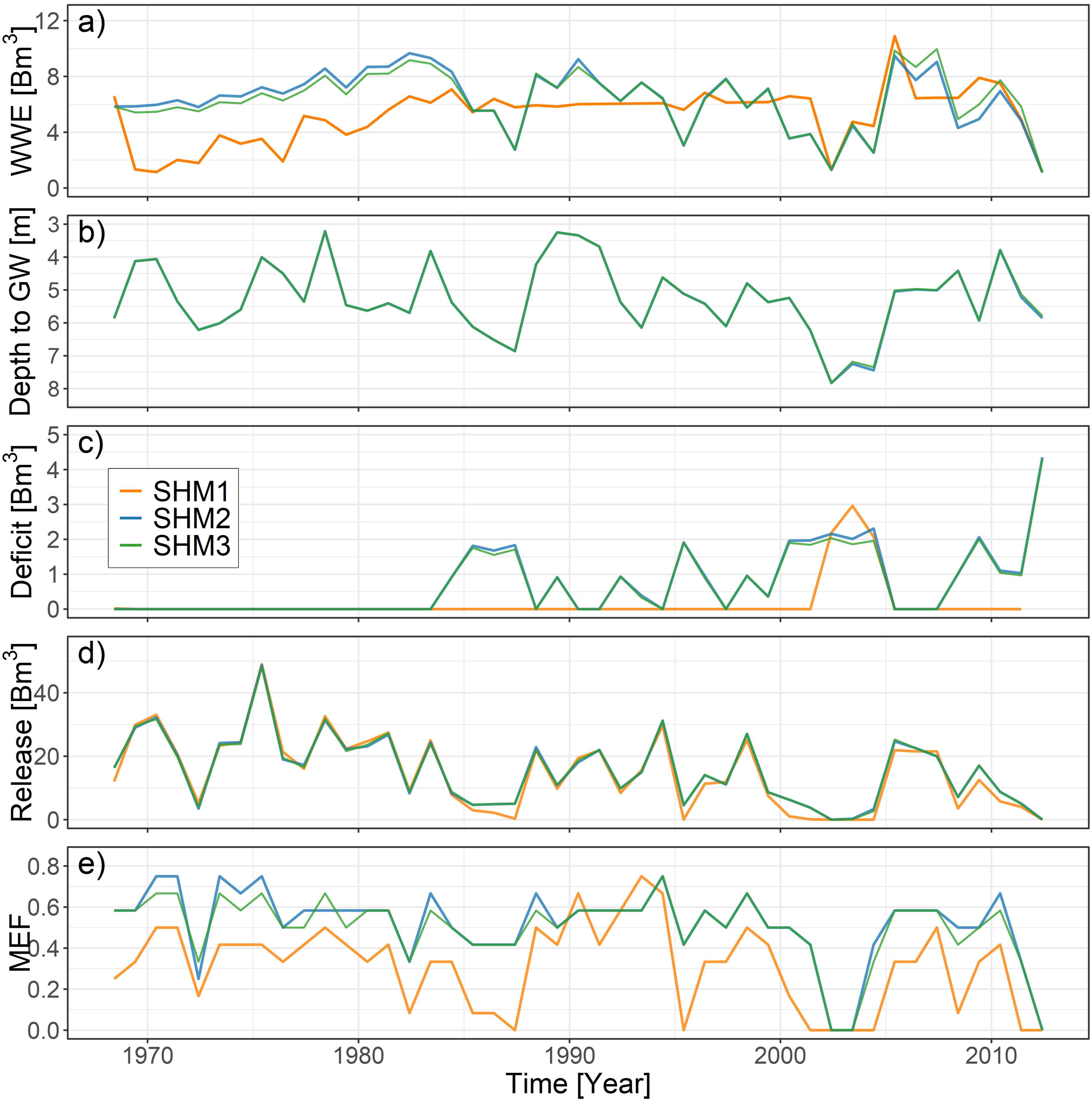

a.
Depth to GW [m]
2
4
6
8
Jun 2007
Dec 2007
Jun 2008
Dec 2008
Jun 2009
Dec 2009
Jun 2010
Dec 2010
Jun 2011
Dec 2011
Jun 2012
Dec 2012
Jun 2013
Time [months]
b.
Reservoir storage [Mm3]
0
2000
4000
6000
Jun 2000
Jun 2001
Jun 2002
Jun 2003
Jun 2004
Jun 2005
Jun 2006
Jun 2007
Jun 2008
Jun 2009
Jun 2010
Jun 2011
Jun 2012
Jun 2013
Time [months]
c.
Ratio of area under irrigation from surface water to groundwater
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
2001-2002
2002-2003
2005-2006
Year
d.
Ratio of volume utilized from surface water to groundwater in irrigation
0
5
10
15
20
25
2001-2002
2002-2003
2005-2006
Year
SHM1
SHM2
SHM3
Observed

Figure 6.



a)
WWE [Bm3]
0
4
8
12
b)
Depth to GW [m]
3
4
5
6
7
8
c)
Deficit [Bm3]
0
1
2
3
4
5
SHM1
SHM2
SHM3
d)
Release [Bm3]
0
20
40
e)
MEF
0.0
0.2
0.4
0.6
0.8
1970
1980
1990
2000
2010
Time [Year]