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A socio-ecological model of the Segura River basin, Spain

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ABSTRACT

The Segura River basin in South-East Spain is home to aquatic and dry-land ecosystems of regional significance. Pressurised, over the course of the last five decades, by interests of agricultural origin, the basin is caught up in a persistent water crisis traversed by conflict and socio-ecological deterioration. This article presents a socio-ecological-system characterisation of the Segura River basin with a focus on the interactions between institutional performance and expectations on irrigation water supply. The contribution of this research is twofold: first, it provides a model that develops a conceptual articulation of a socio-ecological framework in the idiom of Systems Dynamics; second, it generates (both numerical and qualitative) policy-relevant insights into the basin's crisis, in a way that fully reflects its complexity. Our results indicate that ∼333.100 ha of drylands and agro-natural landscapes were lost to agriculture, and that groundwater overexploitation reached ∼500 Hm^3 within the 1960-2021 modelling horizon. Our work accurately models the pervasive impacts of intensive agriculture expansion in the Segura basin and portrays some of the socio-ecological consequences of the hydraulic paradigm in Spain, raising crucial doubts on the dominant forms of water governance in the region.

1. Introduction

Agriculture is one of the most relevant and apparent drivers of ecosystem transformation globally (Ramankutty et al., 2008). The trade-offs inherent to intensive agriculture, and propagated across the food production chain, not only contribute to the ecological deterioration of various habitats, but also constitute a tangible threat to the livelihoods of rural communities worldwide (Foley et al., 2005). Freshwater consumption is fundamental in framing the intricate juxtaposition, and intersection, of these agricultural trade-offs (Hoekstra and Chapagain, 2008), given the material and multi-scale dependency of (local) food deficits and (global) trade dynamics (Marchand et al., 2016; Seekell et al., 2017). To disentangle these intricate interdependencies, perspectives embracing the nontrivial (nonlinear) links between agriculture and water governance have been widely recommended (D'Odorico et al., 2018; Rosa et al., 2020).

We adopt a socio-ecological systems (SES) perspective, to investigate the problematics linked to the excessive growth of irrigated agriculture in the semiarid ecosystems of the Segura River basin in South-East Spain. Put differently, the effects of the unchecked expansion of irrigated agriculture in the Segura River basin, predicated on the local paradigm of water governance, constitute our research problem. Our research hypothesis states that the seemingly intractable problematics emanating therefrom can be better explained by means of a socio-ecological systems purview of the basin.

This improved understanding of the basin, we demonstrate, obtains from the possibilities that a SES framework offers to reason about the nonlinear connections between people and nature under conditions of water stress (Martinez-Fernandez et al., 2021; Preiser et al., 2018). Our model approaches nonlinearity in the form of feedback loops and cycles undergirding the system's dynamics, which we simulate in order to recuperate persistent and structural changes over the socio-ecological history of the basin. Our quantitative modelling pivots around the growth of irrigated agriculture across the basin based on the expectation

Abbreviations: SES, socio-ecological systems; TST, Tagus Segura Transfer; CHS, Confederación Hidrográfica del Segura; TIA, Total Irrigated Area; SRbSES, Segura River basin Socio-Ecological System.

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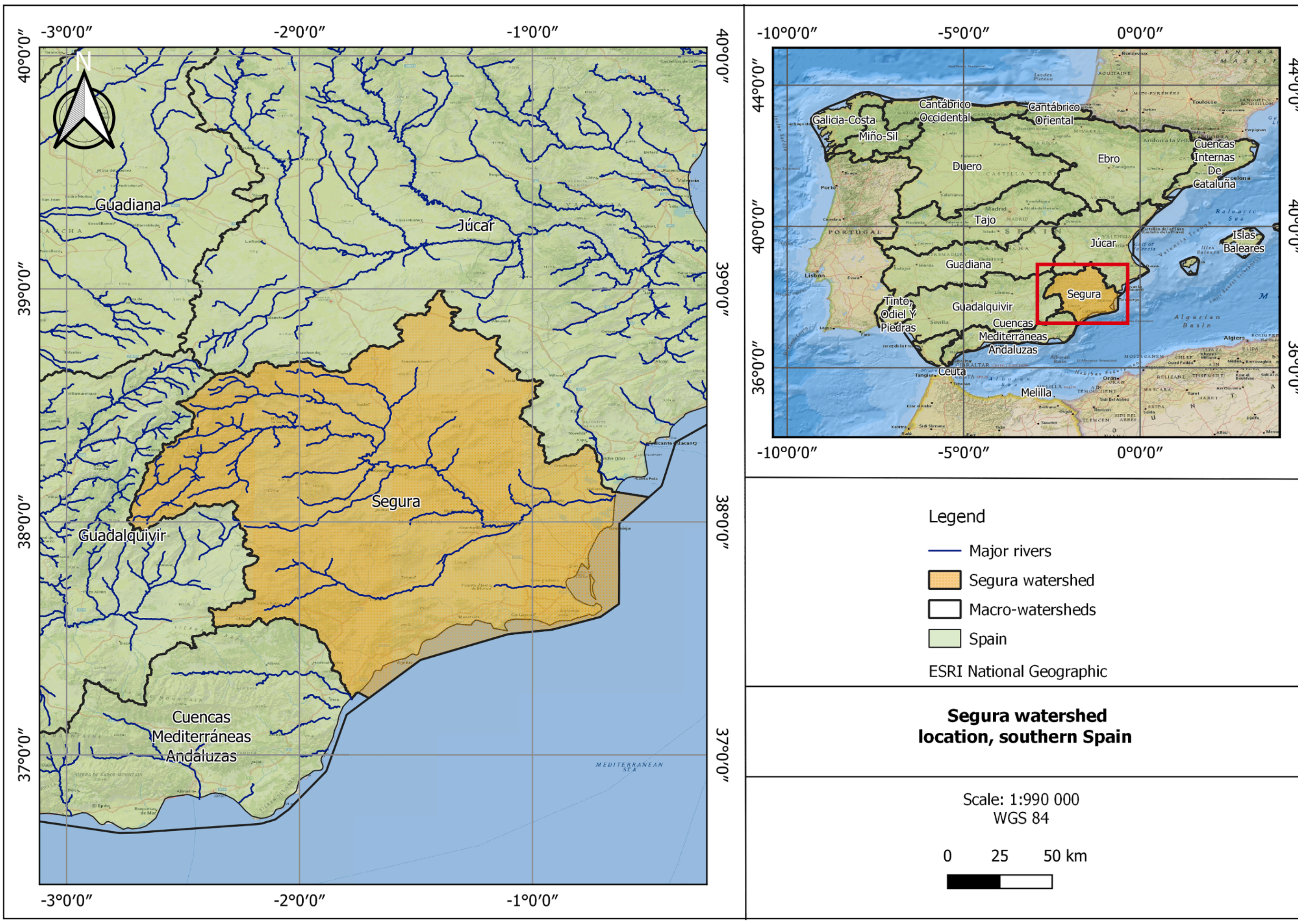

Fig. 1. Map of the Segura basin. Authors' elaboration using data from the *Ministerio para la Transición Ecológica y el Reto Demográfico, Spain.*

feedback loops triggered by the *Tagus-Segura Transfer* (*TST*) *project*, and further reinforced by the *Confederación Hidrográfica del Segura* (*CHS*).

To identify the role of the TST project, and to situate the testing of our modelling hypotheses, we discriminate the total irrigated area (TIA) across the basin into two groups: the *TST irrigated areas* (also referred to as the *TST jurisdiction*), comprising approximately 198.178 ha (CHS, 1998) with regularised water abstraction licenses issued between the 1970′s and 1998; and the *irrigated areas outwith the TST jurisdiction*, comprising approximately 135.000 ha (CHS, 2005) which should not have access to transferred water for irrigation, as per the current CHS normative, but whose numbers have steadily grown from the mid XXth century onwards. This institutional conundrum is at the heart of our model's nonlinear dynamics, helping us explain some of the main environmental impacts afflicting the basin. Namely, the pollution of water flows, groundwater overexploitation, and the transformation of drylands/agro-natural landscapes into irrigated lands.

The remainder of this article is structured in five sections. Section two provides a socio-ecological description of the Segura River Basin. Section three presents the conceptual and methodological underpinnings of our model. Section four reports the model's performance and results. These results are discussed in section five. Finally, the article concludes with a summary of our findings and an outline of policy recommendations.

2. The Segura River basin socio-ecological system

The Segura River raises in Jaén and flows southeast through semiarid lands of marls and clays (Fig. 1). The region is characterised by mild winter temperatures, high solar irradiance, and high potential evapotranspiration (CHS, 2022a). The average rainfall in the basin is 385 mm/year with great spatio-temporal variations across regions (CHS, 2015). The basin has a variable orography and a complex hydrogeological structure evidenced in many small and medium sized aquifers (CHS, 2013).

The interplay of ground and surface water, along with other biophysical attributes, sustain the ecology of the arid ecosystems which dominate the basin (Esteve-Selma, 2006; Esteve-Selma and Calvo, 2000). Among these, dry river or ephemeral streams are centres of endemism, as species must adapt to their extreme environmental conditions, and key in guaranteeing the livelihoods of local communities (Vidal-Abarca Gutiérrez et al., 2022; Vidal-Abarca et al., 2020).

The dynamics of transferred water and irrigation is also key to understanding the socio-ecology of the basin. The Segura basin receives water from the Tagus River through the TST project. Its construction began in 1970 and water started flowing out of the Tagus headwaters to the Segura in 1979 (Hernández-Mora et al., 2014). The volume of transferred water has neither met the original supply expectations nor the growing demand (Martinez-Fernandez and Esteve-Selma, 2000; Starke et al., 2017), thus inducing a "water imbalance" to which farmers have responded by diversifying water sources for irrigation; that is, by extracting water mainly from aquifers (Aldaya et al., 2019; Martinez-Fernandez et al., 2021).

We trace this gap in water provision – often termed, although a misnomer, "water deficit" – to the institutional pathologies typified in the literature as the 'hydraulic paradigm' (Hernández-Mora et al., 2014; Martinez-Fernandez et al., 2020; Saurí and del Moral, 2001;

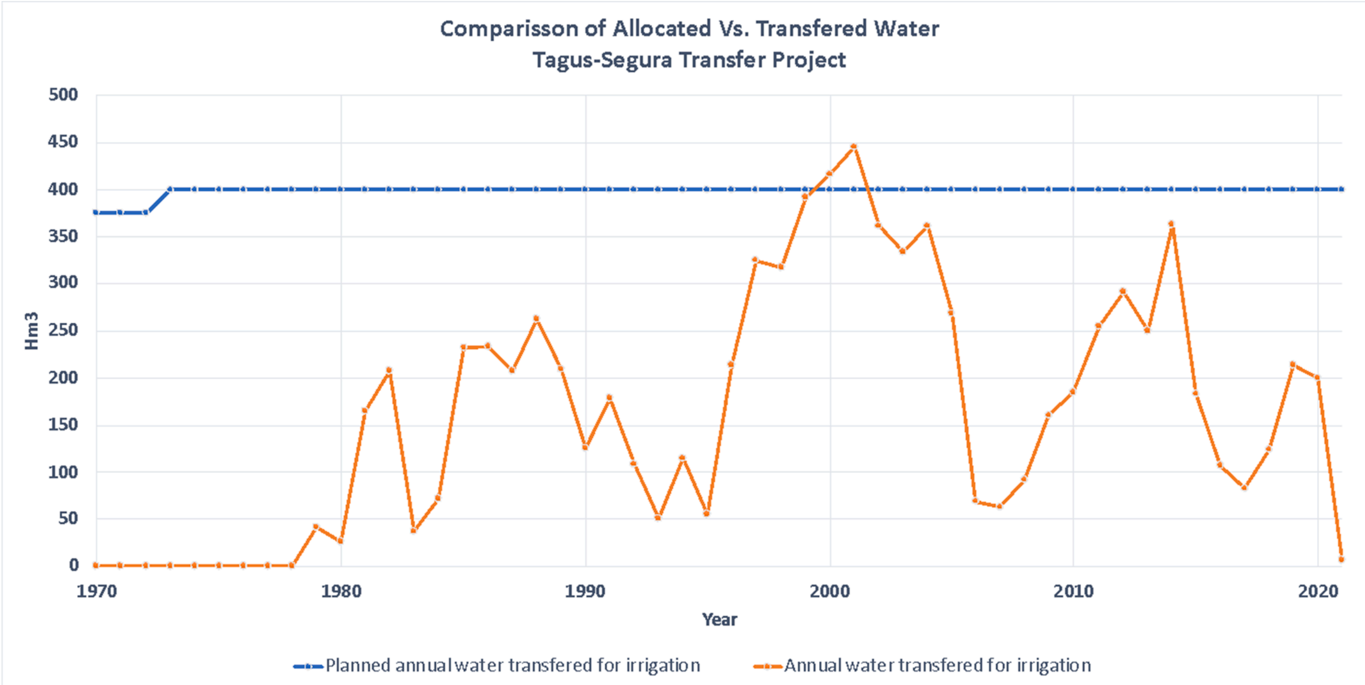

Fig. 2. Maximum planned allocated water Vs. Transferred Water from the Tagus to the Segura basin. Authors' elaboration based on CHS (2022b) data.

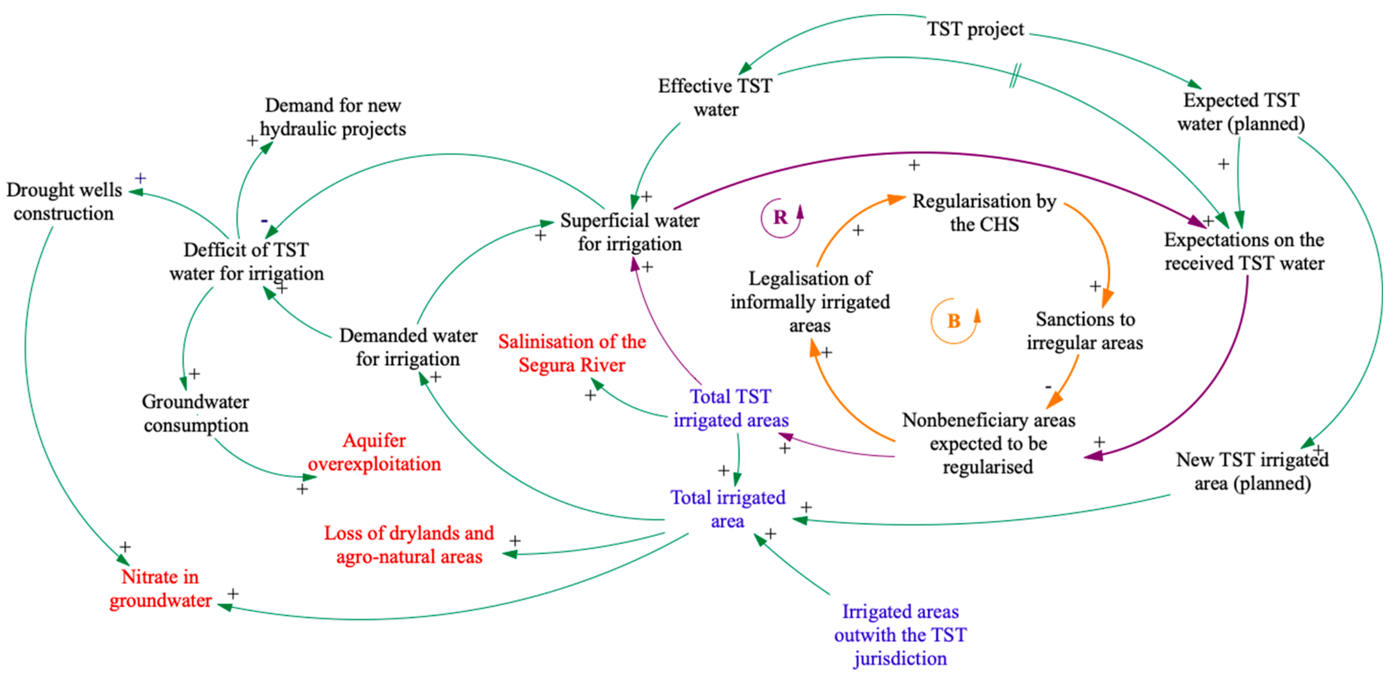

Fig. 3. Conceptual model underlying the SRbSES model. Authors elaboration.

Swyngedouw, 2015). The hydraulic paradigm refers to the recuperation of the late XIXth century *Regeneracionista* narrative into the Spanish dictatorship's mission to conquer a hard-dry landscape, i.e., "to correct all (natural) water imbalances", through hydraulic infrastructure (Lopez-Gunn, 2009; Swyngedouw, 2007). The paradigm's more immediate manifestations took shape in the form of large-scale, public-funded engineering enterprises, lacking both risk and viability assessments, and of a feeble water governance model based on a pseudo-technocratic, top-down approach (Swyngedouw, 1999). The less apparent consequences came in the form of a consolidated elite of technicians (irrigators, hydropower companies and public infrastructure developers) concentrating all relevant water policy decisions (Pérez Mezo and Díaz, 1999).

Intending to "correct" the "structural deficit" of the Segura River basin, the 1971 water decree set the maximum volume of transferred water to 385 Hm^3 /year by syphoning off the "surplus water" from the Tagus (see Fig. 2). This chapter in the hydraulic paradigm narrative was truncated by three concurring events: the self-reinforcing effect of the expectations on new water volumes, the resulting expansion of irrigated lands beyond the originally planned (Martinez-Fernandez et al., 2021; Sanchis-Ibor et al., 2017), and the depletion of water resources in the upper Tagus (Hernández-Mora et al., 2014).

Recognising and unravelling the role of the hydraulic paradigm in the expansion of irrigated agriculture is crucial to understanding the Segura River Basin as a SES. The paradigm subtends the ideation, materialisation, and shortcomings of the TST project, and, ultimately, helps identifying the drivers of the ecological deterioration of the basin. Moreover, it allows us to illustrate how the current governance model of the basin is conducive to the perpetuation of economic interests that are exploitive of and disconnected from the socio-ecological systems they rely upon.

3. Research methods

We approach the socio-ecological crisis of the Segura River basin from the perspective of Systems Theory. Using canonical dynamic system modelling methods (Lade et al., 2022; Sterman, 2000), we delineate the trajectory of a Segura River basin Socio-Ecological System (SRbSES). This approach allows for a regime-shift reading of the crisis, a reading uncovering the counter-intuitive impacts of managerial views on water governance which are often hidden behind dominant narratives.

Shifting current approaches to the governance of the SRbSES calls for renovated analytical perspectives on the complexities inherent to SES modelling. This work, in particular, is concerned with the non-linear properties of the SRbSES. We identify the feedback loops mobilising the systemic changes and perturbations leading to large, persistent, and unexpected reorganisation phenomena impacting, both, the structure and functioning of the SRbSES. We also make explicit the connections between our systems-dynamic model with agent- and network-based interpretations of the SRbSES, hoping subsequent research may look into the socio-ecological pathways towards a benign transition of the basin.

In this context, and as customary in the SES literature, the SRbSES can be fully characterised in terms of structure and function (Biggs et al., 2022; Folke, 2007). The structure of the SRbSES model is described by two types of constituting elements, to which we refer as variables or nodes. Water abstractors (whether formal TST users or not) and the CHS are depicted as *control variables*, or *performative nodes*; while the basin's ground and surface water networks, along with the more conspicuous ecological structure (at the landscape level) of the local semiarid ecosystem, are identified as *state variables* or *descriptive nodes*.

We recognise the SRbSES's dynamics in the coextensive behaviour of irrigated land expansion, and the historical patterns of water use. Characterised thusly the self-reinforcing mechanisms (i.e., non-linearity), the reactiveness (i.e., adaptiveness), and the environmental impacts of the water governance problematics introduced in Section 2 and identified elsewhere in the literature (e.g. Ibor et al., 2011; Martinez-Fernandez et al., 2008; Rupérez-Moreno et al., 2017), become apparent. In the language of SES theory, the SRbSES model can be considered an adaptive, complex, open subsystem of a larger Segura River SES.

3.1. Conceptual model – underlying hypotheses and assumptions

Fig. 3 illustrates the key factors and linkages of the SRbSES model. The model pivots around the total irrigated area in the basin, treated as the material consequent of the expectation formation and reinforcement mechanisms prompting inconsequential water abstraction practices, i.e., the hydraulic paradigm. Two key causal mechanisms govern the system's dynamics (i.e. the decision to irrigate/abstract water), and, by extension, the environmental impacts to the basin; namely: the expectation loop of transferred water volumes leading to the expansion of intensive agriculture (R loop), and the institutional feedback loop embodied by the CHS (B loop). In Fig. 3, these loops are signalled by the purple and orange self-enclosing arrows, respectively.

The B loop portrays the stages at which informal irrigated areas are formalised and further incentivised. The legalisation of informally TST irrigated areas is based solely on the CHS's recognition of the farmers' ability to use transferred water via water abstraction licenses (Martinez-Fernandez and Esteve-Selma, 2000). The legalised areas are subsequently incorporated into the CHS's official registry of beneficiaries, hence regularised (Ibor et al., 2011). At this stage, regularised abstractors become subjects of rights and responsibilities, i.e., objects of potential sanctions (even if retroactive). Nevertheless, sanctions are rarely forthcoming. Nor are the levels of officially announced/planned TST water supply actualised, fomenting higher expectations on the future availability of TST water for irrigation. The net effect is the sustained apparition of new informally irrigated areas.

The R loop describes the mechanisms leading to the formation of these expectations. The R loop portrays the articulation of the performative nodes around the volumes of demanded, planned, and effectively available water. In tracing the interconnectedness of these nodes, we recuperate the formation expectation mechanism from the contribution of surface water for irrigation and the inflated values of planned TST water. These expectations are only partially modified by current knowledge about the actual volumes of effectively transferred water, which are later amplified by the equivocal institutional efforts to correct the water imbalance. This is where both loops meet and complement one another.

We argue that the expansive drive of informal irrigation marks the point of articulation between the two loops, because the CHS's legalisation imperative cancels its own regulatory capacity, acting as a form of factual validation for higher, but insubstantial, expectations on the TST water volumes available for irrigation. In this sense, the apparition of new areas of informal irrigation also governs the SRbSES dynamics, via the TIA, and, ultimately, through the prevalence and severity of the ecological impacts associated with irrigated agriculture. This dynamics is operated through the juxtaposition, i.e., the quasi-nestling, of the two loops giving autonomy to the R loop, as though the B loop would imprint a momentum wherefrom the R loop could operate independently. We characterise the ensuing socio-ecological crisis, born out of this loop interconnectedness, by way of the overexploitation and pollution of groundwater, the loss of drylands and semi-natural areas, and the salinisation of the Segura River (signalled with red in Fig. 3).

3.2. A systems dynamic model of the Segura basin

The SRbSES dynamics is structured around three differential equations modelling changes in distinct areas of intensive irrigation across the basin, from 1960 to 2020. Eq. 1 describes changes in the irrigation areas originally planned as TST beneficiaries (A_t). Eq. 2 describes changes in nonbeneficiary areas expected to be regularised (N_t). Eq. 3 describes changes in the irrigated areas outwith the TST jurisdiction (I_t). We approximate the TIA as the summation of these three types of areas.

$$\Delta A_\tau = A_0\, \chi_{[E_{irr}\ (A_\tau)\leq 0]} + (NA_\tau - AA_\tau)\overline{\text{ir}}\chi_{[E_{irr}\ (A_\tau)\geq 0]} \tag{1}$$

$$\Delta N_\tau = E_{irr}\ [N_\tau] \left(\frac{A_o + E_{leg}[N_\tau]}{A_o}\right)\overline{ir}\chi_{[\tau<1998]} \tag{2}$$

$$\Delta I_\tau = (\overline{maxl} - TIA_\tau) \left(\overline{cr}\chi_{[\tau<1998]} + \ \overline{er}\chi_{[\tau\geq 1998]}\right) \tag{3}$$

Before moving forward, let us note that $\chi_{[K]} = 1$ if the condition K holds, and $\chi_{[K]} = 0$ in every other situation[1]; and that $\tau \in [1960,\ 2020]$. Eq. 1 aggregates the initial area of irrigated lands (A_0) to the difference between new irrigated areas (NA_t) and effectively irrigated areas (AA_t), as modulated by the expectations on the availability of water for irrigation ($E_{irr}[A_t]$). This difference is subsequently fine-tuned by a fixed annual ratio of land transformation ($\overline{\text{ir}}$), i.e., a modelling parameter.

Eq. 2 explains new irrigation areas through the joint contribution of two expectation mechanisms adjusted by a TST-dependent annual ratio

[1] $\chi_{[K]}$ acts as an indicator function with respect to K.

Table 1
Environmental impacts derived from the expansion of intensive agriculture. Authors' elaboration.

Impact	Equation[1]
Nitrate in groundwater (mg/l)	$\Delta Ng_\tau = (TIA_\tau * \partial_\tau * \overline{nr})$
Loss of dryland and natural landscape (ha)	$\Delta Ld_\tau = TIA_\tau - (I_{\tau_0} - A_{\tau_0})$
Salinisation of the Segura River (μS/cm)	$\Delta Sl_\tau = (N_\tau + A_\tau) * \overline{sr}$
Aquifer overexploitation (Hm^3/Year)	$\Delta AO_\tau = [(\overline{wr} - 1)\ TIA_\tau + (ow_\tau - os_\tau)]\chi_{[ow_\tau > os_\tau > 1 \text{ or } \overline{wr} > 1]}$

[1] $\overline{nr}$, $\overline{sr}$ and $\overline{wr}$ are model parameters.

Table 2
Goodness of fit test results. Authors elaboration.

Variable	Statistic Result **MAPE**	**NRMSE**
TIA	0,029 *(Highly Accurate)*	3,82% *(Excellent)*
TST	0,062 *(Highly Accurate)*	7,79% *(Excellent)*
Ng	1,09 *(Good)*	17,38% *(Good)*
Sl	0,04 *(Highly Accurate)*	7,82% *(Excellent)*

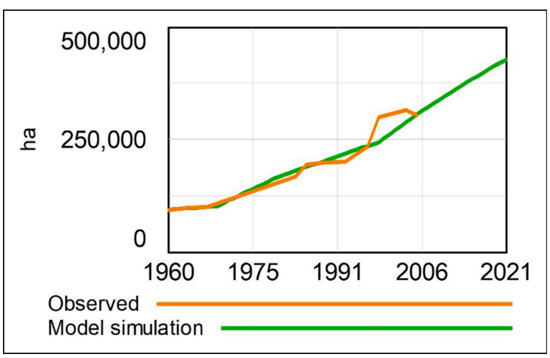

Fig. 4. Observed vs. simulated TIA. Authors elaboration, data from the SRbSES model.

of land transformation ($\overline{tr}$). One of these mechanisms formalises the B loop, using the smoothed value of TST irrigable (not-yet-regularised) lands to approximate the farmers' perceptions on water availability ($E_{irr}[N_t]$). The other mechanism models the change in legislation proper to the R loop ($eleg_t$), by smoothing the number of irrigable lands in process of regularisation ($E_{leg}[N_t]$).

Eq. 3 expresses that the change in the irrigated areas outwith the TST jurisdiction is the product of the annual ratio of land transformation (cr_t) and the difference between the maximum area of irrigable land ($\overline{maxl}$) and the total irrigated area in the basin (TIA_t). cr_t varies to reflect the impact of the Ebro Transfer announcement on the growth of irrigated land across the basin. cr_t takes the values $\overline{cr} = 0.0011$ throughout 1960-1998, and $\overline{er} = 0.013$ from 1999 onwards. In the next section we explain how these parameters were obtained, i.e., calibrated.

A succinct description of the equations governing the environmental impacts generated by the increase in irrigated lands derived from Eqs. 1–3 can be found on Table 1 (refer to Appendix A for details on the remaining variables of our model). To measure Nitrate in groundwater (Ng_τ) we multiplied the TIA_τ by ∂_τ (potential increase in nitrates[2]) and $\overline{nr}$ (annual nitrates influx). We quantify the loss of drylands and natural landscape (Ld_τ) as the difference between the TIA_τ and the net area of intensive irrigation in 1960 ($I_{\tau_0} - A_{\tau_0}$). We use the hydraulic conductivity as a proxy of salinisation (Sl_τ), being the product of the Total TST irrigated area ($N_\tau + A_\tau$) and an annual rate of soluble salts ($\overline{sr}$). The overexploitation of aquifers (AO_τ) is estimated as the difference between the aggregated volume of water use (which includes water uses distinct from irrigation (ow_τ)) and the aggregated volume of renewable water resources (which includes resources distinct from TST water (os_τ)). Based on the *Revisión del Plan Especial de Sequía* (CHS, 2018) we established a ratio of undersupplied irrigated areas ($\overline{wr}$), in order to compute the fraction of the TIA_τ exclusively dependent on groundwater. The ow_τ and os_τ values were retrieved from datasets reported by the CHS (CHS, 1998, 2015, 2022a, 2022b; for more details see Appendix C).

4. Results

We conduct structure-oriented tests to validate the SRbSES model; namely, dimensional consistency, extreme conditions, and goodness of fit tests. An additional sensitivity analysis complements the results of these tests. Overall, the SRbSES model demonstrates conceptual robustness and empirical aptness (for details see Appendix B).

The parametric coherence of the SRbSES model was corroborated through a two-stage sensitivity analysis, in the spirit of Schouten et al. (2012), comprising a 'One-At-a-Time' assessment (OAT) of the model at threshold/limit values, and Monte Carlo simulations ranging over a wider spectrum. The OAT allows for a rapid evaluation of the effects extreme parameter values have on the model's target variables, for each one of the 13 model parameters.[3] The Monte Carlo simulations (MC) use uninformative priors, i.e. uniform distributions, over a Latin Cube partition of the (parametric) event space, to attain a simultaneous/global exploration of the relevant parameters[4] (Banos-Gonzalez et al., 2018; Uusitalo et al., 2015). Our results indicate a low to moderate response of the target variables to changes in the corresponding parameters (sensitivity metrics for both OAT and MC procedures can be found in Appendix B). In other words, the model's outputs are robust to changes in parameter values within the model.

The dimensional consistency test is oftentimes seen as an empirical check on a model's coherence. The test determines whether the right- and left-hand sides of each equation (i.e., Eqs. 1–3) are consistent with respect to the measuring units of their empirical counterparts. All our dynamic variables preserve metric consistency, i.e., the SRbSES model is metric-invariant with respect to ha/year units.

Of a distinct nature is the extreme-condition test where the system's behaviour is probed under a set of conditions different from its underlying modelling assumptions. This set of conditions gives way to the following test scenarios: the expectations on transferred water for irrigation are ineffectual; there is no increase in TST planned areas; unplanned TST areas are not regularised; there is no increase in either planned or unplanned TST areas; and neither the TST nor the Ebro Transfer are deemed impactful. None of the constraints in these scenarios disprove the SRbSES's functioning (for details see Appendix B), and the ratio of the number of successful (i.e., synthetically valid) scenarios to the product of the number of dynamic and total variables is relatively low (0.0029)[5], thus providing evidence of modelling correctness.

We approach the goodness of fit test as a probing into the model's capacity to replicate observed irrigation patterns across the Segura basin

[2] The difference between the accumulated Nitrate in groundwater for the previous year and the maximum quantity of Nitrates reported for the Campo de Cartagena by the CHS.

[3] The set of target variables comprises the 'Total TST irrigation area', 'Total irrigated area in the Segura basin', 'Aquifer overexploitation', 'Nitrate in groundwater' and 'Salinisation of the Segura river'.

[4] Those with a sensitivity coefficient equal or higher than 50%.

[5] This is the value of the Reality Check Index computed by Vensim, a metric used to approximate modelling adequacy.

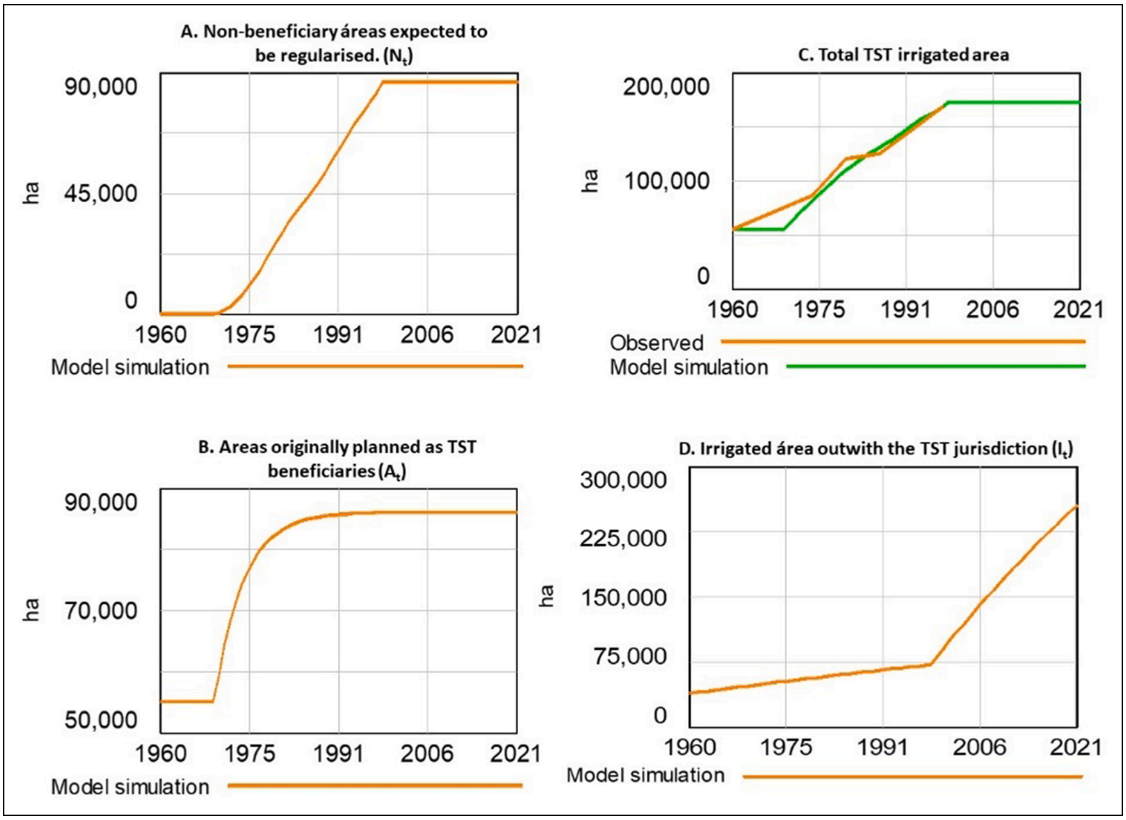

Fig. 5. Changes in irrigation areas simulated with SRbSES: A. Simulated N_t. B. Simulated At. C. Irrigated TST area (N_t+A_t). D. Simulated $I_{t.}$ Authors elaboration, data from the SRbSES model.

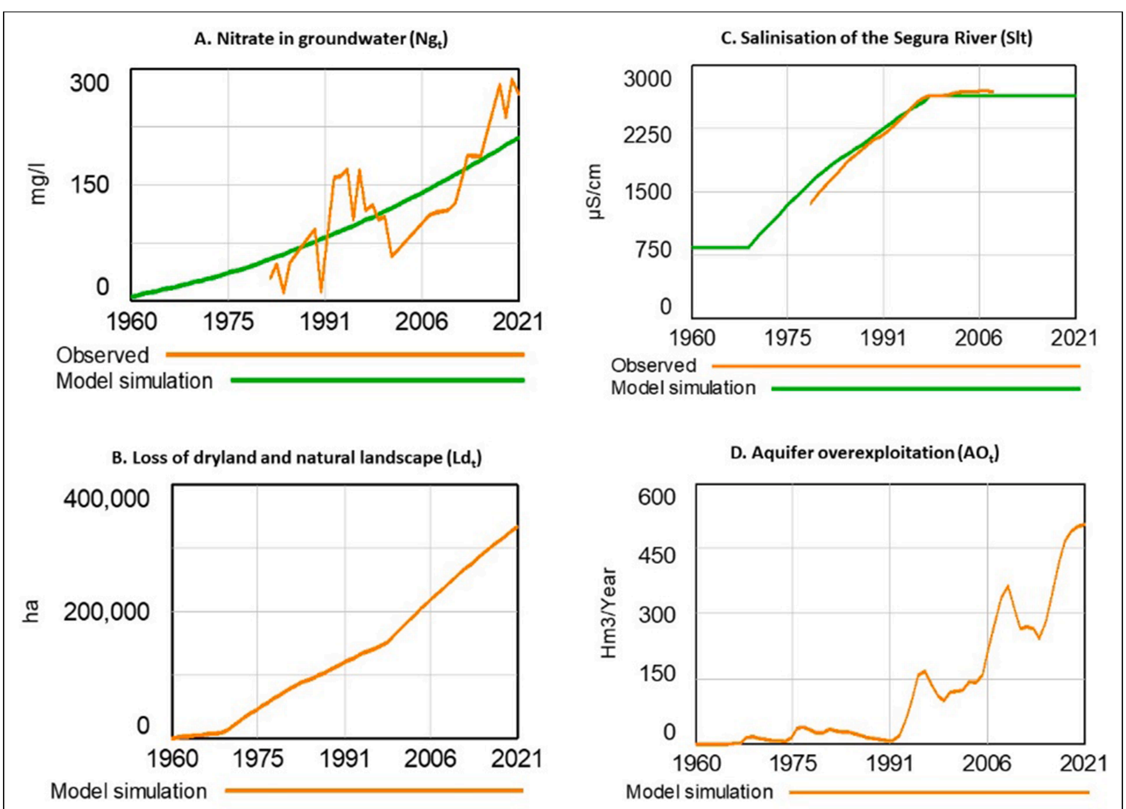

Fig. 6. Environmental impacts of the growth of intensive irrigation in the SRbSES: A. Nitrate in groundwater (Ng_t). B Loss of dryland and natural landscape (Ld_t). C. Salinisation of the Segura River (Sl_t). D. Aquifer overexploitation (AOt). Authors' elaboration, data from the SRbSES model.

Table B1
Historical Fit results. Authors' elaboration, data from the SRbSES model.

Variable	N	R^2	MAPE	MSE	RMSE	Bias (U^M)	Variation (U^S)	Covariation (U^C)	NRMSE
Total Tagus-Segura Transfer project irrigated area	5	0.966	0.062	77976776	8830.446	0.263	0.062	0.675	7.79%
Total Irrigated Area in the Segura basin	8	0.981	0.029	71742616	8470.102	0.154	0.069	0.777	3.82%
Salinisation of the Segura River	19	0.995	0.045	9022.121	94.985	0.515	0.429	0.056	7.17%
Nitrate in groundwater	13	0.613	1.090	2305.205	48.0126	0.092	0.729	0.179	1.38%

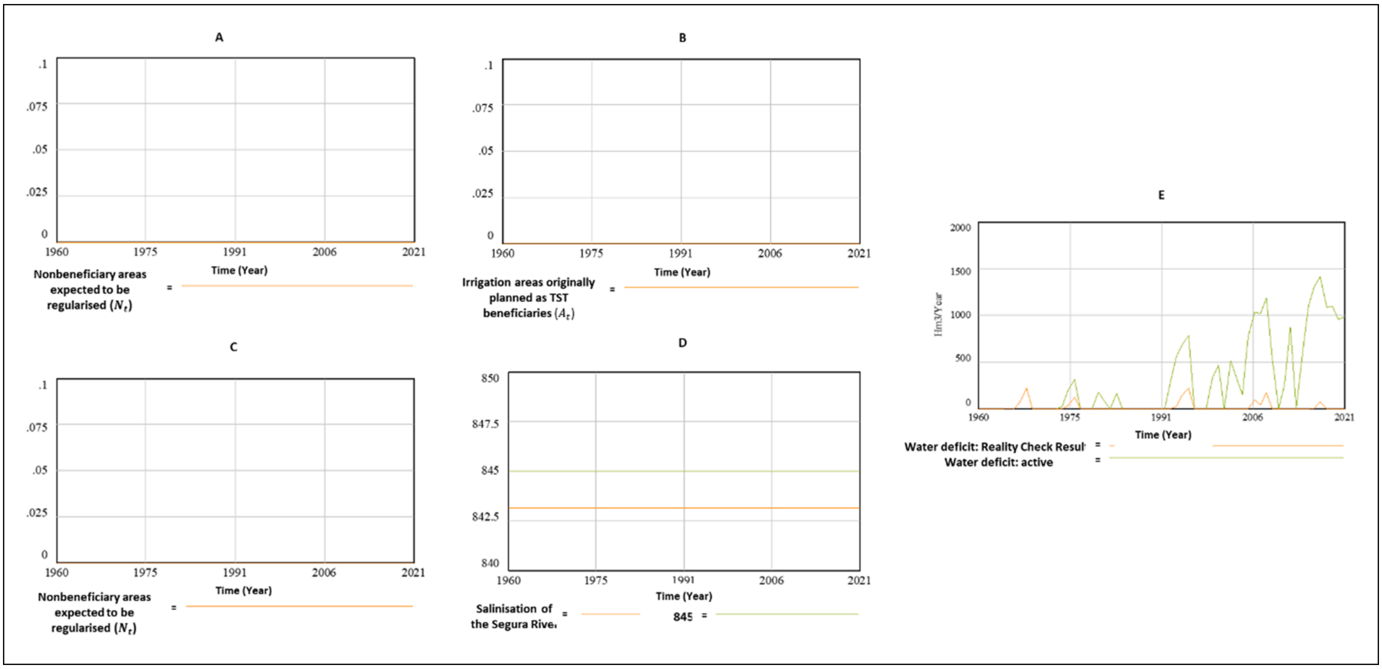

Fig. B1. Reality Check Results. A. Expectations on transferred water for irrigation are ineffectual; B. There is no increase in TST planned areas; C. Unplanned TST areas are not regularised; D. There is no increase in either planned or unplanned TST areas; E. Neither the TST nor the Ebro Transfer are deemed impactful. Authors' elaboration, data from the SRbSES model.

Table B2
OAT results. Authors' elaboration, data from the SRbSES model.

Parameter	Total TST irrigation area	Total irrigated area in the Segura basin	Aquifer overexploitation (smoothed)	Nitrate in ground water	Salinisation of the Segura River
Annual ratio of land transformation ($\overline{tr}$) associated to nonbeneficiary areas expected to be regularised	68.34	20.14	50.32	19.86	68.19
Base increase ratio (cr_t)	0.00	5.62	14.05	7.02	0.00
Time delay for assessing lands status	7.11	2.11	5.24	2.02	7.11
Annual ratio of land transformation ($\overline{ir}$)	0.00	0.00	0.00	0.00	0.00
Time to assimilate changes in the water received	9.72	2.87	7.03	3.69	9.48
Ebro Transfer irrigable to irrigation transformation ratio ($\overline{er}$)	0.00	36.77	71.89	10.82	0.00
Nitrate ratio	0.00	0.00	0.00	71.89	0.00
Salinisation ratio	0.00	0.00	0.00	0.00	99.96
Crop undersupply ratio	0.00	0.00	85.20	0.00	0.00
Maximum potential irrigation area in Segura basin	0.00	64.40	126.46	24.26	0.00
Maximum potential nitrate	0.00	0.00	0.00	24.14	0.00
Net irrigable area that was planned to be attended by TTS	49.91	14.52	36.41	19.86	49.98
Segura basin net water per hectare	72.98	21.55	164.11	20.93	72.93

(See Table 2). We use the *Mean Absolute Percentage Error* (MAPE) (Goh and Law, 2002) and the *Normalised Root Mean Square Error* (NRMSE) (Andarzian et al., 2011; Granderson and Price, 2012; Sepaskhah et al., 2013) statistics to assess the accuracy of the simulations and to quantify the typical size of the associated errors, respectively. MAPE values below 10% are considered 'highly accurate', those between 10% and 20% are 'good', while those between 20% and 50% are deemed 'reasonable' (Lewis, 1982). NRMSE values range from 0% to 10% when the results are 'excellent', between 10% and 20% when they are considered 'good', and 'fair' when they vary from 20% to 30% (Granderson and Price, 2012; Sepaskhah et al., 2013).

As per $MAPE_{TIA} = 0.029$ and $NRMSE_{TIA} = 3{,}82\%$, the SRbSES model

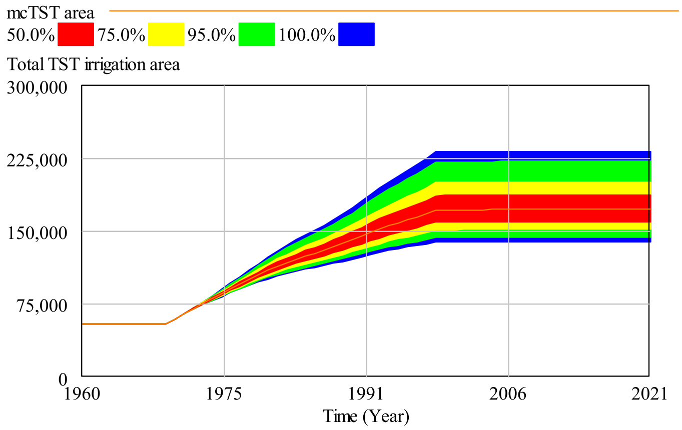

Fig. B2. MC results for the Total TST irrigation area under the simultaneous variation of its sensitive parameters (Annual ratio of land transformation $(\overline{ir})$ and Segura basin net water per hectare). The different colours refer to the 50, 75, 95 and 100% percentiles of the 200 runs. Authors' elaboration, data from the SRbSES model.

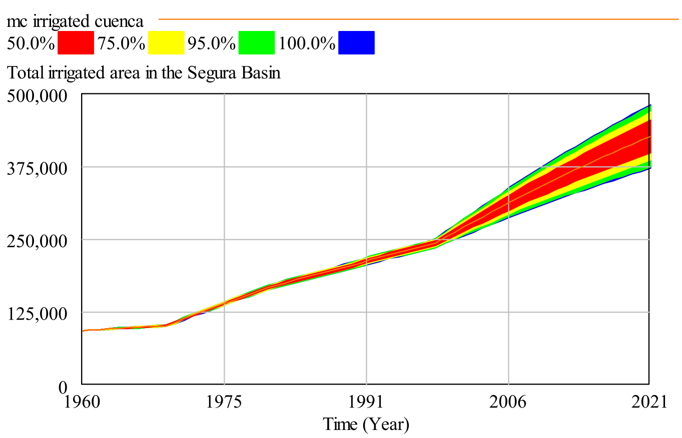

Fig. B3. MC results for the Total irrigated area in the Segura basin under the simultaneous variation of its sensitive parameter (Maximum potential irrigation area in the Segura basin). The different colours refer to the 50, 75, 95 and 100% percentiles of the 200 runs. Authors' elaboration, data from the SRbSES model.

not only can accurately replicate the TIA's historical trend but can also guarantee small deviations from the observed data (See Table 2). Fig. 4 illustrates this by retracing changes in the TIA from the relatively low and steady levels of the mid 1960′s/early 70′s, when the intensively irrigated surface of the basin reached the 125.000 ha, to the steep transition beyond the 299.500 ha and 427.000 ha thresholds observed in the 90′s and the 2020′s.

$MAPE_{TST} = 0.062$ and $NRMSE_{TST} = 7,79\%$ indicate a good fit to the observed data (i.e., Total TST irrigated area (Fig. 5C)). Fig. 5A and B show the simulated behaviour of the planned and unplanned areas, which are distinctly addressed at a conceptual level by the SRbSES (see Fig. 3). Fig. 5C illustrates the role of the TST in explicating the increase in areas under intensive irrigation (i.e., $A_t + N_t$) from 1973 to 1998, and how the new water demands are progressively carried over to other water sources (Fig. 5D).

Fig. 6 shows the environmental impacts linked to the expansion of intensive irrigation. Conceptually, these impacts act as points of articulation with other socio-ecological subsystems. In this sense, they are conceived of as throughputs of the SRbSES model, thus mediating the causal relation between the expectation-formation mechanisms associated with the TST, and the ecological degradation of the SRbSES (see Section 3). For this reason, our modelling approach is not focused on a

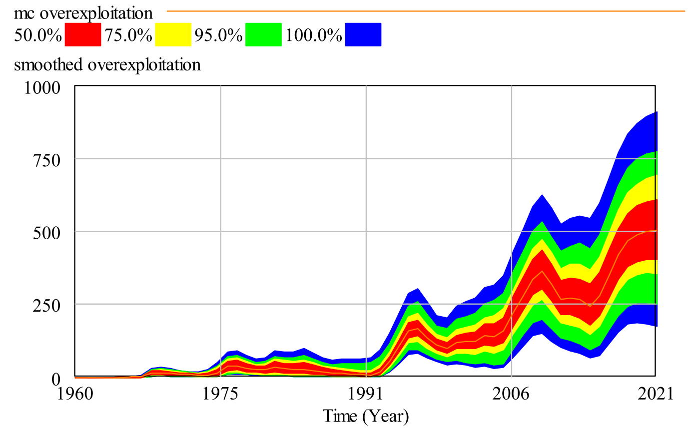

Fig. B4. MC results for the Aquifer overexploitation (smoothed) under the simultaneous variation of its sensitive parameters (Annual ratio of land transformation $(\overline{ir})$, Ebro Transfer irrigable to irrigation transformation ratio $(\overline{er})$, Crop undersupply ratio, Maximum potential irrigation area in Segura basin and Segura basin net water per hectare). The different colours refer to the 50, 75, 95 and 100% percentiles of the 200 runs. Authors' elaboration, data from the SRbSES model.

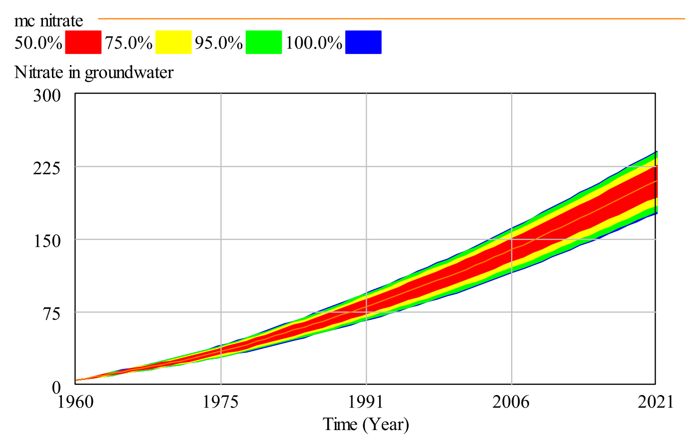

Fig. B5. MC results for the Nitrate in groundwater under the simultaneous variation of its sensitive parameter (Nitrate ratio). The different colours refer to the 50, 75, 95 and 100% percentiles of the 200 runs. Authors' elaboration, data from the SRbSES model.

detailed representation of the biophysical dynamics subtending each one of the impacts.

Fig. 6A and C compare the simulated behaviour of nitrates in groundwater and water salinity (by means of the hydraulic conductivity at 20ºC) against the datasets obtained from local monitoring stations. The simulated levels of nitrates in aquifers describe a trajectory smoother than that of the empirical data series retrieved from the CA07NI-44 hydrometric station located in the Campo de Cartagena (CHS, 2022c), which is evidenced in $MAPE_{Ng} = 1.09$ and $NRMSE_{Ng} = 17,38\%$ (See Table 2); however, the general trend is aptly modelled as per $R^2 = 0.613$ and direct inspection of Fig. 6A, wherefrom the well-documented nitrification phenomenon obtains (ranging from almost nil to over 200 mg/l of nitrates by the end of the simulation). The hydraulic conductivity of the Segura River, approximated with observations from the *SE0912M063* hydrometric station (CHS, 2022e), is more aptly replicated by the SRbSES with $MAPE_{SI} = 0.04$and $NRMSE_{SI} = 7,17\%$ (Table 2), in which case the 1970′s to mid-90′s plateau is obtained at 2690μS/cm.

Fig. 6B andD portray the loss of drylands/agro-natural landscapes (computed as the total transformed area over the simulation period) and

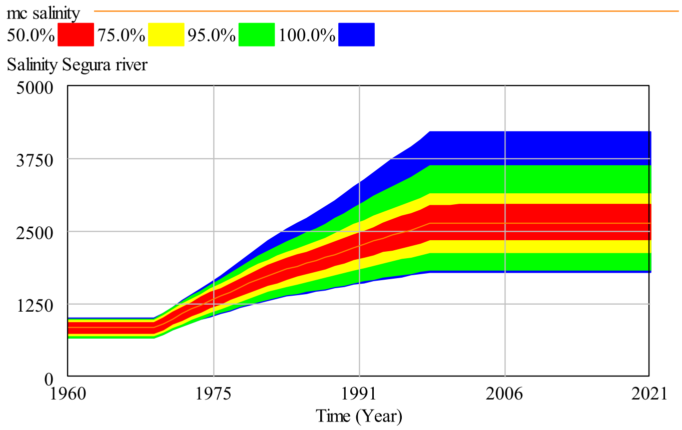

Fig. B6. MC results for the Salinisation of the Segura River under the simultaneous variation of its sensitive parameters (Annual ratio of land transformation ($\overline{\text{tr}}$) associated to nonbeneficiary areas expected to be regularised, Salinisation ratio and Segura basin net water per hectare). The different colours refer to the 50, 75, 95 and 100% percentiles of the 200 runs. Authors' elaboration, data from the SRbSES model.

Table B3
Results of the general sensitivity analysis (MC) showing the VC for each target variable. Author's elaboration, data from the SRbSES model.

Target variable	Sensitive parameters	Variation Coefficient
Total TST irrigation area	Annual ratio of land transformation ($\overline{\text{ir}}$) Segura basin net water per hectare	0.47
Total irrigated area in the Segura basin	Maximum potential irrigation area in the Segura basin	0.23
Aquifer overexploitation (smoothed)	Annual ratio of land transformation ($\overline{\text{ir}}$) Ebro Transfer irrigable to irrigation transformation ratio ($\overline{\text{er}}$) Crop undersupply ratio Maximum potential irrigation area in Segura basin and Segura basin net water per hectare	0.91
Nitrate in ground water	Nitrate ratio	0.27
Salinisation of the Segura River	Annual ratio of land transformation ($\overline{\text{tr}}$) associated to nonbeneficiary areas expected to be regularised Salinisation ratio Segura basin net water per hectare	0.54

aquifer overexploitation across the basin. These data series are synthetic and produced under the assumption that the TIA punctuates their comportment. Over the complete timeframe, the natural and dryland loss reaches a value well over 300.000 ha. Finally, aquifer overexploitation intensifies from 1990′s onwards, reaching around 500 Hm^3/year by the end of the simulation period.

5. Discussion

This paper illustrates the socio-ecological basis of the degradation of the Segura River basin through a principled systems-theoretic approach. We assemble a socio-ecological system of the Segura River basin (the SRbSES model) around two expectation formation mechanisms and assess its dynamics. Our contribution is twofold: first, from a theoretical point of view, our model offers the first system-dynamics articulation of the Segura River basin; second, it provides a policy-relevant account of the basin's socio-ecological crisis. This section delves deeper into the connections between these contributions, drawing from our results in Section 4, with an emphasis on the SRbSES′s capacity to inform water governance.

At a conceptual level, the SRbSES pivots around the B and R loops introduced in Section 3, which model the expectation formation mechanisms (i.e., institutional contradictoriness and unfounded projections of water availability, resp.), we argue, explain the overgrowth of intensively irrigated lands. The results in Section 4 support this claim and motivate a more elaborate explanation of the TIA's trend and its ecological effects, in terms of the contradictions inherent to the hydraulic paradigm.

5.1. The SRbSES model: institutional performance, expectations on water availability, and the overgrowth of intensively irrigated areas across the Segura River basin

Our simulations indicate that the TST kick-starts the ever-positive trend of the TIA over the 20 years following the *secano*-to-intensive-irrigation transition[6] (see Figs. 4 and 5), and that this trend is currently sustained by the farmers' expectations on upcoming hydraulic projects (See Fig. 5A). An impetus made possible by the overexploitation of groundwater. Less succinctly, intensive agriculture is pervasive across the basin, and agriculture drives water use and prompts the development of hydraulic projects, prefiguring the matter-of-factly commodification of surface/ground water and its retroactive justification (Martinez-Fernandez and Esteve-Selma, 2005, Martinez-Fernandez and Esteve-Selma, 2000). This is how the hydraulic paradigm unfurls.

To appreciate this, we provide a detailed account of loop R with respect to our more abstract rendition in Section 3. The TST project not only marked the transformation of the basin's landscape but reinforced the notion that money can buy water. Put differently, the TST, quite literally, substantiated and sanctioned that water supply is only dependent on one's willingness or ability to pay, as if it were a "private good". Even before becoming operational, the TST project (including channels, dams, pumping, roads, etc.) fomented high expectations on a new water source that eventuated in an inconsequential *secano*-to-irrigation crop conversion (del Moral Ituarte, 2007), as our results show (Figs. 4 and 6B). Furthered by the belief that fully productive lands were a precondition for gaining access to the transferred water, regardless of individual water rights arrangements (Ibor et al., 2011), this process eventuated in the sustained growth of irrigated areas belonging to nonbeneficiaries, from 1973 to 1998 (Fig. 5A).

Once in operation, the TST project struggled to supply water in the quantities originally projected (Fig. 2), while pressurised to guarantee irrigation water to an expansive number of beneficiaries. The structural nature of the ensuing water imbalance could be identified as early as 1998, when the '*Plan de Cuenca*' unveiled the gravity of the imbalance (CHS, 1998). From 1992 to 1995, after a protracted period of severe drought, the CHS stopped regularising informal water abstractors, confirming that the transferred water could not be used to irrigate new croplands therefrom (Martinez-Fernandez and Esteve-Selma, 2005, 2004a). The SRbSES model evinces this occurrence in Fig. 5A, where the smoothing of the TIA's trend signifies the halt in the regularisation process of the *de facto* TST-irrigated lands from 1998 onwards. It is in this sense, that we claim that the CHS regulatory capacity is countered by their (market-like) role as water supplier.

The water imbalance triggered the demand for new hydraulic projects, more prominently, for a new transfer scheme to syphon water from the Ebro River as consigned in the 1998 *Libro Blanco del Agua* (Martinez-Fernandez et al., 2020). Just like the TST two decades before, the Ebro transfer set in motion a (new self-reinforcing) expectation mechanism driving the expansion of irrigated lands above and beyond the pre-existing TST ones (Albiac et al., 2006).

[6] Also known as dryland farming, *secano* is practiced in areas where annual potential water evaporation exceeds annual precipitation; a condition associated with semiarid environments (Peterson, 2018).

New croplands cropped up, but the Ebro transfer was never built, and the total water imbalance deepened (Fig. 5D). This is an exemplar of the phenomena for which loop B accounts, and which, ultimately, loop B in conjunction with loop R retroactively explain, alongside the ecological maladies commonly associated with the Segura River. These maladies include a wide range of environmental impacts linked to the pollution of water flows, groundwater overexploitation, and the transformation of drylands/agro-natural landscapes into irrigated lands (Martinez-Fernandez et al., 2021).

5.2. The SRbSES in crisis: the unaccounted impacts of intensive irrigation

Aquifer nitrification (Fig. 6A) and overexploitation (Fig. 6D), the salinisation of the Segura River (Fig. 6B), and the loss of drylands/agro-natural landscapes (Fig. 6C) are the more apparent effects brought about by the interplay of loops B and R in the SRbSES model. The increments of the TIA link up these expectation formation mechanisms to the ecological deterioration of the basin. This is how the SRbSES model allows us to trace some of the material consequences of a failing, albeit prevalent, water governance model founded upon the hydraulic paradigm.

In 2019 the regional government of Murcia declared 14 inland and one coastal water bodies as vulnerable (Orden 23 de Diciembre de 2019) due to a concentration of nitrates above the 50 mg/l cap stipulated by the EU normative (Council Directive 91/676/EEC, 1991). In 2020 the CHS reported the existence of 23 groundwater bodies polluted with nitrates, out of the 63 sampled across the basin (García Mariana, 2020). Of concern is not only that this type of groundwater pollution reappears in agriculture as, e.g., groundwater becomes unsuitable for irrigation unless denitrified (BOE 148, 2018), but also that nitrification contributes to the eutrophication of nearby wetlands (Steffen et al., 2015). To elucidate the causal mechanisms underpinning these problematics in the Segura River basin we successfully reproduced the readings of the CA07NI-44 hydrometric station located in the Campo de Cartagena (CHS, 2022c), via the simulated (over)growth of the TIA.

Intensive irrigated agriculture dominates the basin's (landscape) mosaic on account of the –transferred and otherwise sourced – water made available by the advent of the TST and the farmers' capacity to artificially uphold profitable quantities of food exports with synthetic fertilisers (Pedreño et al., 2022). Nitrogen fertilisers are oftenest favoured for intensive farming as they promote the rapid growth of plants and encourage the unsullied development of foliage and fruits (Segura and Pedreño, 2006). Foster and Custodio (2019) further suggest that the rate at which nitrates in irrigation-water infiltrate permeable soil profiles is slower than the rate of water-table depletion (attributable to excessive abstraction), and that the accumulation of nitrates makes diffuse groundwater pollution a tangible threat to the basin. We incorporate these considerations by connecting TIA increments, provoked by the interactions between loops B and R, to the expansion of (over)fertilised areas. Inexpensive and soluble, Nitrogen fertilisers pollute both superficial and ground water bodies, as the SRbSES model attests.

Two of the most prominent consequences of these alterations in the Nitrogen – and Phosphorus – biogeochemical cycle(s) are the excess of nutrients of aquatic ecosystems (eutrophication) and, the concomitant, accumulation of phytoplankton (Paerl et al., 2014; Zhang et al., 2004). This overgrowth is often conducive to algal blooms, which reduce the amount of available oxygen and sunlight along any given water column, eventuating in the death of other autotrophic and heterotrophic species (from small crustaceans to fish) (Eugercios Silva et al., 2017; le Moal et al., 2019). Along the Segura River Basin, these impacts are variously perceived as the eutrophic crisis of the Mar Menor lagoon (Álvarez-Rogel et al., 2020; Martinez-Fernandez et al., 2014), the largest coastal water body in the Western Mediterranean, and a biodiversity and tourism hotspot.

Although a dedicated study of the Mar Menor ecological collapse is beyond the scope of this paper, we would like to tersely outline the more recent events marking the timeline of the crisis. Ever since the early 2000′s, scientists have denounced the anthropic origin of the lagoon's eutrophication[7] (e.g. Lloret et al., 2005; Martínez-Fernández & Esteve-Selma, 2003; Pérez-Ruzafa et al., 2002); in 2016 algae finally tainted the Mar Menor green (e.g. Jimeno-Sáez et al., 2020; Martinez-Fernandez et al., 2017); in 2019 and 2021 the algal bloom precipitated the mass die-off of aquatic biota (e.g. Guerrero-Gómez et al., 2022). The more than apparent links of these processes to intensive irrigation in the Campo de Cartagena derived in a series of conflicts between agriculture promotors and lagoon activists, which has taken a new turn after legal personhood was granted to the Mar Menor in 2022 (known as the ILP, see Vadillo, 2022).

The salinisation of the Segura River is concurrent with the nitrification of the basin. This is another environmental impact that the SRbSES model illustrates via R-and-B loop interactions (see Fig. 3). As with the nutrient excess problematics, the salinisation of the Segura River is accounted for by successfully reproducing the behaviour of the *SE0912M063* hydrometric station (CHS, 2022e). Our results in Fig. 6C indicate that even though the salinisation process seemed to have reached a plateau in the late 1990′s, the current levels are not ecologically commendable. These findings corroborate the work of Estévez et al. (2019) in showing that the salt build-up along the Segura River shifts from slight, in the middle basin, to heavy concentrations in the lower basin. This is an alarming result, for the salinisation of freshwater is directly linked to the deterioration of the inorganic nitrogen removal and carbon storage properties of aquatic environments, as well as to increments in toxic sulphides, which feedback the physiological stress in wetland biota initiated by the salinisation process itself (Herbert et al., 2015).

As pointed in Section 3, the expansive trend of the TIA has also had a sizable impact on the quality and quantity of abstracted groundwater. Driven by un-checked expectations on water availability, the regularisation of informal irrigation, and the assimilation of pumping techniques (all of them symptoms of the hydraulic paradigm which the B loop models), farmers have historically tried to make up for the TST deficit with the abstraction of groundwater (Fig. 6D). The SRbSES model reproduces the growing reliance on aquifers over the last 50 years. Our results coincide with the overall trend identified in other works (Custodio et al., 2016; Rupérez-Moreno et al., 2017). Note that the latest official report (i.e., the volume of abstracted groundwater in 2015 published by the CHS) is less than one standard deviation away from the SRbSES simulated value – i.e. 207 Hm^3/year (CHS, 2015) vs. 280.5 Hm^3/year, respectively.

As a contradistinctive qualification of our results, let us also point to recent publications claiming that the TST project contributes to the replenishment of aquifers, via infiltration, and that the substitution of transferred water, with irrigation water from (more) saline sources, could accelerate the degradation of the basin's soils (Morote et al. (2020) and Morote et al. (2017)). These works are based on secondary literature, mostly public policy documents, and various ethnographic interventions with relevant stakeholders. Paradoxically, we interpret such claims as illustrative or symptomatic of our diagnosis, for the antecedents to their conclusions outline the expectation-formation narrative conceptualised through loops R and B. A closer look at our results show that aquifer overexploitation is largely coeval with the development of the TST project. That is, the overall trends of aquifer overexploitation fluctuate within the 10 Hm^3 and 40 Hm^3 in the early stages of the project, and the 1995 and 2007 peaks of overexploitation follow the deflationary expectations triggered by concomitant but spurious hydraulic projects which made aquifers the more reliable, if not the only, source of irrigation water.

[7] The increase of Nitrates has been attributed to intensive irrigated agriculture, while Phosphates have been associated with wastewater coming from malfunctioning treatment plants, between 1980's and the 2000', and industrial pork farms more recently.

Correlated with the expansion of intensively irrigated agriculture throughout the basin is the loss of drylands/agro-natural areas, amounting to a loss of 333.100 ha by 2021 (Fig. 6B). Habitat fragmentation due to land-use changes has been identified as one of the main causes of terrestrial biodiversity loss globally (Haddad et al., 2015; Hanski, 2015). In South-East Spain this phenomenon is a threat to the conservation of semiarid and arid ecosystems (Peñas et al., 2011), even in protected sites (Martínez-Fernández and Esteve-Selma, 2004b). Several works have been continually reporting the severe effects of habitat loss of protected and endangered ibero-african species such as *Periploca angustifol* (vegetal endemism) and *Testudo graeca* (terrestrial tortoise) (Martinez-Fernandez et al., 2021), as well as a continuous decay of steppe-birds populations (e.g. *Chersophilus duponti, Tetrax tetrax, Pterocles orientalis and Burhinus oedicnemus*) (Caballero et al., 1996; Esteve-Selma, 2006; Esteve-Selma et al., 1995).

We interpret the results of the SRbSES model as evidence of the continual deterioration of the basin, due to iterative cycles of unrevised expectations on the amount of available water for irrigation, and to the coextensive loops of reinforcing institutional leniency. These findings suggest three main avenues of future research. Namely, a critical assessment of the 'hydraulic mission' via the SRbSES, a supersystem extension of the SRbSES, and its prospective refunctioning.

Furthering the critical insight of the SRbSES model requires taking a closer look at its core feedback mechanisms, under a more historiographic rendition of the prevalent water governance lineaments. As our results show, the interrelation between the B and R loops not only explain the growth of the TST irrigated areas, but also reflect the shortcomings of the Spanish 'hydraulic mission'. This prefigures a site to expand our understanding of the identified loops in the unfolding of similar socio-ecological problematics in the region, such as those raised by the Ebro Transfer and private desalinisation plants.

A larger Segura basin SES model can be produced by augmenting the model with other subsystems. In particular, it would be fruitful to couple the SRbSES model with spatial modelling techniques to explore the interplay between aquifers, precipitation, and agricultural practices. These efforts could give a better account of the uncertainties associated with our findings and contribute to a more informed understanding of the basin's superficial-ground water dynamics, e.g., explicating the observed fluctuations of nitrates in groundwater which the current version of the SRbSES model correctly approximates in the aggregate (see Section 4).

Finally, in the face of new regulations aiming at reducing the amount of transferred water (CHT, 2022), exploring the prospective and predictive potential of the SRbSES model is an imperative. The model's explanatory capacity can be strengthened by including individual stakeholders (e.g., reworking the SRbSES as an agent-based model) to elucidate alternative/lower-level responses of the system to the adoption of new water governance lineaments (e.g., the modelling of the occurrence of the ILP). This would require a revision of the CHS's role (s), as well as the explicit recognition of the interactions between agriculture and water governance entities substantiated in decentralised decision-making and coordination structures. We anticipate, also drawing evidence from the literature (see Oliveira et al., 2022; Pahl-Wostl, 2019), that these exploratory reflections around the SRbSES model hold a transformative potential of the current paradigm towards a collective approach to water governance.

6. Conclusions

The degradation of the Segura River Basin is one of the many manifestations of the prevalent, sectoral, infrastructure-oriented approach to water (and agriculture) governance. This approach is consistent with the praxis and narratives of the 'hydraulic mission', an ideology of technological and economic development based on the domination of nature through the control and exploitation of water ecosystems (Molle et al., 2009). In a quite explicit fashion, the hydraulic mission's precepts in Spain have incarnated into what is locally termed the hydraulic paradigm. Our research simulated the reverberations of the paradigm's pervasiveness in terms of the excessive expansion of irrigated agriculture, and its impacts on the semiarid and riverine ecosystems proper to the basin. Our systems-theoretic (i.e., SES) approach is conducive to an explicit modelling of the socio-ecological feedbacks explicating the structural and functional changes configuring the basin's deterioration, which we consider informative for the water governance of the basin.

Our results show that the expectations on new hydraulic projects and the regularisation of informal water uses, even if just nominally, exceeded the total irrigated area in the basin, in the early 1970′s and the late 1990′s, to unsustainable but persistent levels of water requirements. We characterise these events as a self-reinforcing TST water demand/extraction mechanism leading to the expansion of intensive agriculture (R loop), and as an institutional feedback loop portraying the CHS's leniency in fulfilling its role (B loop). The two loops are at the core of our SRbSES model (see Section 3) explaining the behaviour of the total irrigated area over the last 50 years, reaching 427.000 ha for 2021, and the extent of the associated environmental impacts. According to the model, nitrates in groundwater range from almost nil to over 200 mg/l for 2021, while overexploited in ~500 Hm^3 for the same year; the hydraulic conductivity at 20°C reaches a plateau at 2690µS/cm in the mid-90′s; and the loss of drylands/agro-natural landscapes to irrigated agriculture added up to 333.100 ha by 2021.

The SRbSES model demonstrates that the socio-ecological deterioration of the Segura basin is acute and calls for a profound change in the way water governance lineaments are conceived and effected. Drawing on our results, we argue that a long-term system's perspective on the inapparent behavioural links between irrigated agriculture and institutional performance could counteract the socio-ecological deterioration of the basin. A key leverage point in the articulation of this new perspective is concerned with the role of the CHS. The CHS could reshape its monitoring and controlling (passive) mission, into an active praxis of waterscape transformation conscious of the influence it exerts on water abstractor groups who anticipate the CHS's directives. Thus oriented, we foresee that the role of the public may also change towards the creation of distinct spaces of engagement, coordination, and, hopefully, cooperation, where the governance of the basin becomes an instance of collective transformation.

CRediT authorship contribution statement

Paula Andrea Zuluaga-Guerra: Data curation, Formal analysis, Methodology, Software, Validation, Conceptualization, Writing – original draft, Writing – review & editing. **Julia Martinez-Fernandez:** Conceptualization, Formal analysis, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing. **Miguel Angel Esteve-Selma:** Methodology, Supervision, Writing – review & editing. **Jampel Dell'Angelo:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Two of the co-authors, Julia Martínez and Miguel Ángel Esteve, act as invited editors of the special issue: "Modelling socio-ecological systems. Understanding the dynamics of water, agricultural and rural systems".

Data availability

Data will be made available on request.

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Appendix A. Description of the SRbSES model

Variable Name and Description
Announced TST water (Hm3/Year) = IF THEN ELSE((Time>1969:AND: Time<1979),385,0) **Description:** This variable is set at 385 Hm^3/year and is active between 1969 and 1978. When the TST project was announced the project promotors promised a volume of 385 Hm^3/year. **Reference:** Boletín Oficial del Estado 148, 1971. Ley 21/1971, de 19 de junio, sobre el aprovechamiento conjunto Tajo-Segura., BOE-A-1971-778.
Annual ratio of land transformation (cr_t) associated to outwith the TST jurisdiction (1/Year) = IF THEN ELSE(Time<1998, Base increase ratio (cr_t), Ebro Transfer irrigable to irrigation transformation ratio ($\overline{er}$)) **Description:** The cr_t varies to reflect the impact of the Ebro Transfer announcement on the growth of irrigated land across the basin. The cr_t takes the values $\overline{cr} = 0.0011$ throughout 1960-1998, and $\overline{er} = 0.013$ from 1999 onwards. These were calculated by calibration.
Annual ratio of land transformation ($\overline{tr}$) associated to nonbeneficiary areas expected to be regularised (1/Year) = 0.0595 **Description:** Annual ratio for the transformation of expectations of irrigable area into new unplanned irrigated lands. Estimated by calibration with observed data of total irrigated TST area.
Areas of informal irrigation legalised in the current policy cycle (ha) = SMOOTH (Nonbeneficiary areas expected to be regularised, Time delay in assessing land legal status) **Description:** There is a process for regularising irrigated areas, we defined a 5 years period for the CHS to process the request and approved it.
Segura basin net water per hectare (Hm3/ha/Year) = 0.005288 **Description:** Average net water per hectare in the Segura basin. Source: R2, page 170Original name: Segura basin net water per hectare
Crop undersupply ratio (Dmnl) = 0.46 **Description:** According to the CHS there 46% of the crops are undersupply. **Reference:** CHS, 2018. Revisión del Plan Especial de Sequías. Demarcación Hidrográfica del Segura. Memoria.
Expected TST water (Hm3/Year) = Announced TST water input+ Received TST **Description:** Before the 1970 (pre TST hydraulic works) this variable has a value of cero. Between 1969 and 1978 the value of the variable corresponds to the Announced TST; from 1979 onwards it corresponds to the values of Received TST.
Difference between new irrigated areas (NA_t) and effectively irrigated areas (AA_t) (ha) = New irrigated areas - Effectively irrigated areas **Description:** This variable is used for calculating the areas originally planned as TST beneficiaries' stock.
Estimated groundwater overexploitation (Hm3/Year) = Water deficit- Uncovered water deficit **Description:** The water deficit is covered through the use of non-renewable groundwater resources, thus, it represents the estimated groundwater exploitation in the Segura basin.
Expectations on irrigable land by TST (ha) = SMOOTH(Irrigated area fully covered by actual TST transfer, Time to assimilate changes in the water received) **Description:** It is calculated as the irrigated area fully covered by the TST project with a 5-years smoothing period, since there is a time lag between the TST water reporting and the expectations of farmers.
Increase in nitrates (mg/l/Year) = Total irrigated area in the Segura Basin * Potential increase in nitrate* Nitrate ratio **Description:** Annual increase in nitrate content in the groundwater
Increase of irrigated areas outwith the TST jurisdiction (ha/Year) = Annual increase ratio of irrigated areas outwith the TST jurisdiction * Potential area to be transformed into new irrigated lands **Description:** Annual increase of irrigated areas outwith the TST jurisdiction.
Increase in irrigation areas originally planned as TST beneficiaries (ha/Year) = IF THEN ELSE(Time>1972, Difference between new irrigated areas (NA_t) and effectively irrigated areas (AA_t) * Annual ratio of land transformation ($\overline{ir}$),0) **Description:** Areas originally planned as TST beneficiaries that are actually transformed each year. This variable is active from 1972, when the first planning documents defining TST beneficiaries were issued. **Reference:** CHS, 1998. Plan Hidrológico de la cuenca del Segura. Memoria.
Increase of nonbeneficiary areas expected to be regularised (Nt) (ha/Year) = Legalisation expectations* Expectations on irrigable land by TST * Annual ratio of land transformation ($\overline{tr}$) **Description:** Annual transformation of lands into unregularised TST irrigated areas.
Initial value of irrigated TST area (ha) = 55107

(*continued on next page*)

(*continued*)

Variable Name and Description
Description: Irrigated lands that were planned to be TST beneficiaries and that were already installed. Estimated according to the total TST area for 1974 and the proportion of partially attended /total TST area for 1980.
Reference: CHS. 2022b. Históricos. Postrasvase Tajo-Segura [WWW Document]. URL https://www.chsegura.es/es/cuenca/infraestructuras/postrasvase-tajo-segura/historicos/ (accessed 5.17.22).
Initial value of Nitrates in groundwater (mg/l)
= 5
Description: Our modelling assumption is that values in 1960 were very low.
Initial value of irrigated areas outwith the TST jurisdiction - 1960 (ha)
= 38782
Description: The total area of irrigated lands in 1960 is estimated through the lineal interpolation of the area reported between 1956 and 1963. Since part of this area is already included in the areas originally planned as TST beneficiaries (in the sense that the already existing irrigated areas would later be partially covered through the TST), the value of this variable is calculated as the difference between the total irrigated area in the basin in 1960 and the estimated area that later would be partially covered by the TST water.
Initial value of nonbeneficiary areas expected to be regularised (ha)
= 0
Description: The value of this variable is 0 as these areas were not planned.
Legalisation expectations (Dmnl)
= IF THEN ELSE(Time<1998,(Initial value of irrigated TST area+ Areas of informal irrigation legalised in the current policy cycle/ Initial value of irrigated TST area,0)
Description: Dimensionless indicator to represent the expectations for legalising unregularised TST lands. When there are no legalised areas with respect to planned areas, it takes a value of 1. As legalisation increases, the indicator also does until 1998, when CHS stopped the regularisation of new irrigated areas to be attended by TST.
Maximum potential irrigation area in Segura basin (ha)
= 951150
Description: According to R13, total area in Segura basin is 1,902,500 ha. According to CHS (2007), "Around 50% of the basin is not adequate for irrigation as it corresponds to mountain areas occupied by forests and shrublands. These lands correspond to the agronomic class 6, which includes the non-irrigable areas", thus we calculated that the maximum irrigable area (beyond legal, economic or environmental considerations) is 0,5*1902500 = 951,150 ha.
Reference: CHS. 2007. Estudio General sobre la Demarcación del Segura
Maximum potential nitrate (mg/l)
= 500
Description: This value corresponds to the maximum registered value for Nitrates in the Campo de Cartagena according to the CHS reports.
Nitrate ratio (mg/l/ha/Year)
= 1.9e-005
Description: Annual contribution of Nitrates per hectare of irrigated lands to the cumulated Nitrates content in groundwater. Estimated by calibration.
Water uses distinct from irrigation (ow_τ) **(Hm3/Year)**
= EXTERNAL_DATA(2.0)
Description: Net water uses in the Segura basin different from agriculture.
Reference: CHS, 2022c. Proyecto de Plan Hidrológico de la Demarcación Hidrográfica del Segura (Revisión de tercer ciclo: 2022-2027). Anejo III. Usos y Demandas.
Water resources distinct from TST water (os_τ) **(Hm3/Year)**
= EXTERNAL_DATA(2.0)
Description: All the water resources, different from the TST, that are available in the Segura basin (with the exception of non-renewable groundwaters).
Reference: CHS, 2022c. Proyecto de Plan Hidrológico de la Demarcación Hidrográfica del Segura (Revisión de tercer ciclo: 2022-2027). Anejo III. Usos y Demandas.
Annual ratio of land transformation ($\overline{\mathbf{ir}}$) **(1/Year)**
= 0.2
Description: Ratio modulating the growth of irrigation areas originally planned as TST beneficiaries (A_t). Estimated by calibration of total TST area with observed values.
Net irrigable area that was planned to be attended by TTS (ha)
= 86105
Description: It corresponds to the net irrigable area, this is, the gross irrigable area minus the non-productive area. The gross irrigable area which was planned to be attended by TST corresponds to the first value of this variable, as established in 1974 (CHS, 2022). The non-productive areas in Segura basin is 15% of gross irrigable area, which is estimated in average in Segura basin as 15% of gross irrigable area (CHS, 1998).
Reference:
CHS. 2022b. Históricos. Postrasvase Tajo-Segura [WWW Document]. URL https://www.chsegura.es/es/cuenca/infraestructuras/postrasvase-tajo-segura/historicos/ (accessed 5.17.22).
CHS, 2018. Revisión del Plan Especial de Sequías. Demarcación Hidrográfica del Segura. Memoria.
Potential area transformable into new irrigated lands (ha)
= Maximum potential irrigation area in Segura basin- Total irrigated area in the Segura Basin
Description: Area that can be still converted into irrigated lands in Segura basin.
Irrigated area fully covered by actual TST transfer (ha)
= Expected TST water/ Segura basin net water per hectare
Description: We calculate the number of hectares that can be fully irrigated according to the water received from the TST.
Potential increase in Nitrates (mg/l)
= MAX((Maximum potential nitrate - Nitrate in groundwater)/ Maximum potential nitrate,0)
Description: Tis variable guarantees that Nitrates level maintain within the maximum registered level of Nitrates (See Maximum potential nitrate variable for details)
Received TST water (Hm3/Year)
= EXTERNAL_DATA(2.0)

(*continued on next page*)

(*continued*)

Variable Name and Description
Description: Approved TST for irrigation in origin (Bujeda).
Reference: CHS. 2022b. Históricos. Postrasvase Tajo-Segura [WWW Document]. URL https://www.chsegura.es/es/cuenca/infraestructuras/postrasvase-tajo-segura/historicos/ (accessed 5.17.22).
Salinisation ratio (μS/cm/ha)
= 0.01
Description: Contribution of TST irrigated lands (per hectare) to the salinisation of the Segura river. Estimated by calibration.
Time delay for assessing lands status (Year)
= 5
Description: Average time required for CHS to assume the unplanned new irrigated areas as official TST perimeters. Estimated by calibration of TST total irrigated area.
Time to assimilate changes in the water received (Year)
= 5
Description: Years that are needed for a farmer to change the mindset. Number of years for changing the expectations on how much water they will receive and, therefore, how much unplanned irrigated areas can be established.
Total irrigation net water demand (Hm3/Year)
= Total irrigated area in the Segura Basin* Segura basin net water per hectare
Description: Total irrigation net water demand in Segura basin.
Aggregated volume of water use (Hm3/Year)
= Total irrigation net water demand+ Water uses distinct from irrigation (ow_τ)
Description: Calculated by considering all the water uses in the Segura basin.
Aggregated volume of renewable water resources (Hm3/Year)
=Received TST+ Water uses distinct from irrigation (ow_τ)
Description: Calculated by considering all the renewable water resources in the Segura basin.
Uncovered water deficit (Hm3/Year)
= Water deficit* Crop undersupply ratio
Description: Water deficit that is not covered through groundwater overexploitation.
Water deficit (Hm3/Year)
= IF THEN ELSE(Aggregated volume of water use > Aggregated volume of renewable water resources, Aggregated volume of renewable water resources - Aggregated volume of water use,0)
Description: Estimated water deficit in the Segura basin.

Vensim functions:

- IF THEN ELSE (cond, tval, fval): "Returns first value (tval) if condition (cond) is true; second value (fval) if condition is false. cond must be a Boolean expression or an expression or variable that can be interpreted as Boolean (i.e., taking a value of 0 or 1). Only the value returned is evaluated, so the other value could be an expression that would lead to an error." (Ventana, 2022a).
- SMOOTH: "Is commonly used to take time averages and represent expectations. It is different from LN, EXP and IF THEN ELSE in that it has time behavior built into it. That is, if you know what value x takes on then you can compute EXP(x), but just knowing x does not tell you the value of SMOOTH(x,4), you also need to know what value the SMOOTH previously had. This is because the SMOOTH function has a level implicitly built into it." (Ventana, 2022b).

References:

Ventana. (2022a). *IF THEN ELSE Function. User Guide - Vensim Introduction & Tutorials*. http://vensim.com:/documentation/fn_if_then_else.html.
Ventana. (2022b). *SMOOTH Function. User Guide - Vensim Introduction & Tutorials*. https://www.vensim.com:/documentation/20480.html.

Appendix B. SRbSES Model Validation

1. Model Fit

1.1. Model simulation beyond temporal limits

To determine the coherence of the SRbSES model, i.e., whether the model's results become ineffectual with respect to the modelling specifications (Jørgensen and Fath, 2011), we extend the temporal span of the simulations to the 1960-2100 timeframe. Over this time span we expect to detect any anomalous behaviour of our main target variables.

1.2. Dimensional consistency test

This test checks whether the dimensions of the model variables correspond to the units that meaningfully encode the model's simulations (Barlas, 1996). We inspect the dimensional consistency of the right- and left-hand sides of each equation through the "Units Checking" built-in function in Vensim (Ventana, 2022a).

1.3. Historical fit

This test verifies the model's capacity to replicate patterns readily identifiable in the observed data (Martinez and Richardson, 2013; Solecki and Oliveri, 2004). We use Theil's inequality statistics (1966) for this effect: the Mean Absolute Error (MSE), the Normalised Root-Mean-Squared Error (NRMSE), and the Mean Absolute Percentage Error (MAPE).

We compute the MSE (Eq. 6) according to Goh and Law (2002) and Oliva (2003). As per Goh and Law (2002), Theil's (1966) statistic can be alternately derived from unequal means, unequal variances, or imperfect correlation. For this reason, it is commendable to decompose the MSE (Eq. B1) into simulated and actual series with respect to three distinct components (Eqs. B2-B4): the sample bias (U^M), its unequal variation (U^S), and the analogous unequal covariation (U^C).

$$MSE = \frac{1}{N}\sum_{t=1}^{N}(S_t - R_t)^2 \tag{B1}$$

$$U^M = (\overline{S} - \overline{R})^2 / MSE \tag{B2}$$

$$U^S = (S_s - R_R)^2 / MSE \tag{B3}$$

$$U^C = 2(1-r)S_s S_R / MSE \tag{B4}$$

We indicate the simulated and reported (observed) values of the SRbSES model as S and R, respectively. $\overline{S}$ and $\overline{R}$ are their average values, and S_s and S_R represent their standard deviations. r is the correlation between simulated and observed data. N is the number of observations, and S_t and R_t denote simulated and observed values at time t.

The NRMSE (Eq. B6) is computed in accordance with Andarzian et al. (2011), Granderson and Price (2012) and Sepaskhah et al. (2013). The notation is as before.

$$RMSE = \left[\sum_{i=1}^{N}\frac{(S_i - R_i)^2}{N}\right]^{0.5} \tag{B5}$$

$$NRMSE = 100\frac{\sqrt{1/N\sum_{i=1}^{N}(S_i - R_i)^2}}{R_{max} - R_{min}} \tag{B6}$$

The RMSE (Eq. B5) and the NRMSE (Eq. B6) quantify the typical size of the error in the simulations. The NRMSE provides a measure of the relative difference between simulated and observed data (Andarzian et al., 2011; Sepaskhah et al., 2013). NRMSE values range from 0% to 10% when the results are excellent, between 10% and 20% when they are considered good, and deemed fair when they vary from 20% to 30% (Ibid).

The MAPE (Eq. B7) is a measure of accuracy when fitting time series for trend estimation. MAPE values below 10% are considered 'highly accurate', those between 10% and 20% are said to be 'accurate', while those between 20% and 50% are deemed 'reasonable' (Goh and Law, 2002; Lewis, 1982).

$$MAPE = \frac{\Sigma_t |R_t - S_t / R_t|}{N} \tag{B7}$$

We conducted the Historical Fit test for 4 of our variables (Table B1).

1.4. Extreme conditions test

The extreme conditions test evaluates the model's behaviour under a set of conditions different from the underlying modelling assumptions. We use Vensim's *Reality Check* function to assess the SRbSES model (Ventana, 2022b) under extreme conditions, for it has been shown to be informative in testing socio-ecological dynamic models (Li et al., 2012; Vidal-Legaz, 2011).

The test conditions give way to the following test scenarios: the expectations on transferred water for irrigation are ineffectual (Fig. B1A); there is no increase in TST planned areas (Fig. B1B); unplanned TST areas are not regularised (Fig. B1C); there is no increase in either planned or unplanned TST areas (Fig. B1D); and neither the TST nor the Ebro Transfer are deemed impactful (Fig. B1E). For these five scenarios the Reality Check Index value was of 0.0029 and the Closeness score is 100% on 5 measurements.

2. Sensitivity Analysis

The parametric coherence of the SRbSES model was corroborated through a two-stage sensitivity analysis, in the spirit of Schouten et al. (2012), comprising a 'One-At-a-Time' assessment of threshold/limit values (OAT), and Monte Carlo simulations (MC) ranging over a wider spectrum.

The sensitivity index $T_{i,j}$, of the target variable i to changes in the parameter j, is calculated as follows (Jørgensen and Fath, 2011):

$$T_{i,j} = \left(\frac{OM_{i,t} - Om_{i,t}}{Ob_{i,t}}\right) \Big/ \left(\frac{PM_j - Pm_j}{Pb_j}\right) * 100 \tag{B9}$$

Where j; $OM_{i,t}$ and $Om_{i,t}$ are the maximum and minimum values of the target variable i at time t. $Ob_{i,t}$ represents the base (default) model value of the target variable i at time t. PM_j and Pm_j are the maximum and minimum values of the parameter j, respectively, and Pb_j is the initial value of the parameter j.

The range of each parameter was set to move ±20% around its default value (Ford, 1990; Taylor et al., 2010). Banos-Gonzalez et al. (2018) suggest the parameters to be classified into five categories in accordance to : insensitive ($T_{i,j}$=0%), low sensitivity ($T_{i,j}$ <10%), moderate sensitivity (10%≤ $T_{i,j}$ <50%), high sensitivity (50%≤ $T_{i,j}$ <100%) and very high sensitivity ($T_{i,j}$ ≥100%).

For each target variable i, the parameters showing high or very high sensitivity were selected for the general sensitivity analysis. We use the Latin Hypercube method as the sampling technique upon which to run the MC (Hekimoglu et al., 2010), ensuring an adequate exploration of the parameter space within a reasonable number of iterations (Ford and Flynn, 2005), i.e., 200 epochs per simulation.

The Variation Coefficient (VC) of each target variable was computed as:

$$VC_{i,t} = \left(\frac{OM95_{i,t} - Om95_{i,t}}{\overline{O}_i}\right) * 100 \tag{B10}$$

Where $VC_{i,t}$ represents the relative variation of the target variable i respect to its mean value at time t using 95% confidence bounds (Ford and Flynn, 2005). $OM95_{i,t}$ and $Om95_{i,t}$ are the maximum and minimum values of the i target variable at time t using 95% confidence bound, and $\overline{O}_i$ is the mean value of the target variable i. Each target variable i was classified in one of the following three categories (Banos-Gonzalez et al., 2018): low response ($VC_{i,t}$ <50%), moderate response (50%≤ $VC_{i,t}$ <100%) and high response ($VC_{i,t}$ ≥100%).

2.1. Sensitivity analysis results

The details of the OAT results are shown in Table B2. The sensitivity index was estimated for the 13 model parameters in relation with the 5 target variables. Most parameters show low to moderate sensitivity to the target variables.

The results of the MC for each target variable under the simultaneous variation of its sensitive parameters (sensitive index ≥50%) can be seen in Figs. B2 to B6.

Table B3 shows the results of the general sensitivity analysis. Only those parameters showing high or very high sensitivity, as per the Sensitivity Index, are used to compute the VC values.

The target variables present a low to moderate response to changes in the parameter values (Table B3). Three out of the five target variables show a low response (variation coefficient below 50%), and the remaining but a moderate response (variation coefficient between 50% and 100%).

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Appendix C. Water uses and water resources in the Segura Basin

Table C1, Table C2

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Table C1
Non-TST water resources in the Segura River Basin (SB). (1) Known as “Ramblas” in Spanish; (2) Renewable water resources in the SB; (3) No-TST water resources for the SB. Authors elaboration.

Final year of the hydrological year	Superficial water input period (final year)	Year of publication	Superficial water input value	Renewable groundwater	Rio Segura Drain	Coastal aquifers and intermittent water channels **(1)**	Evaporation in reservoirs	**Renewable water (2)**	Non-TST resources for irrigation and urban uses outside the SB	Negratin Transfer	Desalination	TST for urban uses in the SB	**Total water resources used in the SB (3)**	Estimated overexploitation	Comments
-	-	1960	400	600	50	30	60	**860**	30	0	0	0	**830**	-	The most recent value is used as the initial value. (CHS 1998). Except for known values: Until 1980, Negratin and TST = 0
-	-	1980	400	600	50	30	60	**860**	30	0	0	0	**830**	-	
1997	41-90	1997	400	600	50	30	60	**860**	30	17	0	103	**950**	210	Non-TST resources for irrigation and urban uses outside the SB (CHS, 1998 pg. 145)
2012	81-06	2012	-	-	-	-	-	**817**	-	17	139	103	**1076**	-	-
2015	81-2012	2015	-	-	-	-	-	**854**	-	17	158	103	**1132**	-	Total water resources used in the SB (CHS, 2015, pg. 190-191)
2019	91-2018	2019	845		150		60	**635**	-	17	305	103	**1060**	-	-

Table C2
Non-TST water uses in the Segura River Basin (SB). (1) Without towns of the Júcar Basin; (2) Direct MCT (Mancomunidad de los Canales del Taibilla) supply to industries + supply from groundwater wells; (3) Consumption; (4) Indirect reuse (water coming from urban and industrial returns into the river) + direct reuse; 5) Reference year for demand (the year with the most updated value). Authors elaboration.

Final year of the hydrological year	Superficial water input period (final year)	Year of publication	MCT Aba + small industries in the SB **(1)**	Industrial **(2)**	Non-MCT towns	Cattle	Golf	Energy **(3)**	No-agrarian gross demand	Reused water within the SB **(4)**	**Non-agrarian consumption in the SB**	Year in the series **(5)**	Comments
-	-	1960	172	23	-	-	-	-	195	141	**54**	1960	When there is no data, the most recent value was used (CHS 1998).
-	-	1980	172	23	-	-	-	-	-	-	-	-	-
1997	41-90	1997	172	23	-	-	-	-	195	141	**54**	1990	Reused waters = all the urban waste water plus the estimated network mean lost (126+57), multiplied by the proportion that corresponds to the SB (0,77) (CHS, 1998 pg. 146). CHS (1998), except the TST supply in the SB, that corresponds to CHS (2015)
2012	81-06	2012	167	9	18.5	-	11.34	0.0053	205.8453	143	**62.8453**	2010	Golf value is for 2012 and aba value is for 2010. CHS (2015)
2015	81-2012	2015	171	9.1	18.1	-	11,34	0.0053	197.9853	140.1	**57.8853**	2012	CHS 2015
2019	91-2018	2019	181.76	8.5	17.86	11.21	11.2	0.0053	230.5353	147	**83.5353**	2019	The urban demand is for 2019. CHS (2022a, 2022b)

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