

1 **Socio-hydrologic Modeling to Understand and Mediate the Competition for Water**
2 **between Agriculture Development and Environmental Health:**
3 **Murrumbidgee River Basin, Australia**

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34 **Abstract**

35

36 Competition for water between humans and ecosystems is set to become a flash point in
37 the coming decades in many parts of the world. An entirely new and comprehensive
38 quantitative framework is needed to establish a holistic understanding of that
39 competition, thereby enabling the development of effective mediation strategies. This
40 paper presents a modeling study centered on the Murrumbidgee River Basin (MRB). The
41 MRB has witnessed a unique system dynamics over the last 100 years as a result of
42 interactions between patterns of water management and climate driven hydrological
43 variability. Data analysis has revealed a pendulum swing between agricultural
44 development and restoration of environmental health and ecosystem services over
45 different stages of basin scale water resource development. A parsimonious, stylized,
46 quasi-distributed coupled socio-hydrologic system model that simulates the two-way
47 coupling between human and hydrological systems of the MRB is used to mimic and
48 explain dominant features of the pendulum swing. The model consists of coupled
49 nonlinear ordinary differential equations that describe the interaction between five state
50 variables that govern the co-evolution: reservoir storage, irrigated area, human
51 population, ecosystem health, and environmental awareness. The model simulations track
52 the propagation of the external climatic and socio-economic drivers through this coupled,
53 complex system to the emergence of the pendulum swing. The model results point to a
54 competition between human ‘productive’ and environmental ‘restorative’ forces that
55 underpin the pendulum swing. Both the forces are endogenous, i.e., generated by the
56 system dynamics in response to external drivers and mediated by humans through
57 technology change and environmental awareness, respectively. Sensitivity analysis
58 carried out with the model further reveals that socio-hydrologic modeling can be used as
59 a tool to explain or gain insight into observed co-evolutionary dynamics of diverse
60 human-water coupled systems. This paper therefore contributes to the ultimate
61 development of a generic modeling framework that can be applied to human-water
62 coupled systems in different climatic and socio-economic settings.

63 **Keywords:** socio-hydrology, modeling, co-evolution, pendulum swing, irrigation,
64 ecosystem health, competition for water, Murray-Darling Basin, Australia.

65 **1. Introduction**

66

67 The world is facing severe water management challenges, in the context of population
68 growth, degradation of poorly distributed resources and the considerable uncertainties
69 posed by the effects of climate change (Falkenmark and Lannerstad, 2005; Wagener *et*
70 *al.*, 2010). The rapid rates of change that the water cycle and the environment are likely
71 to experience as a result of increasing human impacts (e.g., anthropogenic climate
72 change, land use and land cover changes) requires prediction and management
73 frameworks that capture the coupling between, and feedbacks across, engineered, natural,
74 and social systems (Sivapalan, 2011; Savenije *et al.*, 2014). In many parts of the world
75 such as Australia, climate change and the need to provide water, food and other amenities
76 for a growing population have posed major challenges for water management (UNEP,
77 2007). Increased water extraction for agriculture in many parts of Australia has resulted
78 in mounting pressure on, and degradation of, riparian environments. Planned cutbacks in
79 water allocation for irrigation to alleviate environmental degradation have resulted in a
80 sharper focus on the economic livelihood of rural Australia. This is clearly evidenced by
81 the heated debate over water use in the Murray-Darling Basin in eastern Australia where
82 competition for water resources between humans and ecosystems has come to the fore in
83 recent times (ABC, 2010; Roderick, 2011). Not surprisingly then, there is a critical need
84 for new theoretical and quantitative frameworks (Ostrom, 2009; Gleick and Palaniappan,
85 2010; Grafton *et al.*, 2013) to understand and mediate the competition for water between
86 humans and the environment through generating new understanding of how they coexist
87 and interact.

88

89 Of the many interacting processes in the earth system, human processes are now the
90 dominant drivers of change in water, nutrient, and energy cycles, and in landscape
91 evolution (Vitousek *et al.*, 1997; Crutzen and Stoemer, 2000; Röckstrom *et al.*, 2009;
92 Vörösmarty *et al.*, 2010; Zalasiewicz *et al.*, 2010). Rapid population growth and
93 increased appropriation of freshwater supplies means that hydrologic and human systems
94 are now intrinsically coupled. Human settlement patterns, economic production and
95 demographics are related to the availability of freshwater services as growing human

96 populations alter natural water systems to suit social needs. Human management of the
97 water cycle results in enormous complexity in coupled human-hydrological systems,
98 spanning both physical infrastructure and the economic, policy and legal frameworks
99 governing water availability, use and pricing. Explicitly confronting hydrological
100 predictions in the context of human behavior poses challenges towards quantification of
101 hydrological systems in terms that are meaningful within economic or policy
102 frameworks.

103

104 With the continued expansion of the human footprint, not only are landscape properties
105 changing, but there is also potential for new forms of hydrological behavior to arise due
106 to exceedance of known or previously unknown thresholds (Zehe and Sivapalan, 2009;
107 Kumar, 2011). Hydrological predictions must therefore be based on explicit accounting
108 of both changes in landscape structure as well as the possibility for new dynamics that
109 might emerge from such human-environment interactions (Kallis, 2007; Kallis, 2010).
110 Patterns of human modification in the landscape are themselves phenomena to be studied
111 and interpreted, so we can more deeply understand the consequences of human
112 intervention in the past, and better plan engineered responses to future challenges.
113 Wagener *et al.* (2010) have called for a new paradigm for hydrologic science that
114 includes human-induced changes as integral to the overall hydrologic system. To address
115 these challenges Sivapalan *et al.* (2012) and Sivapalan *et al.* (2014) have proposed the
116 sub-field of socio-hydrology with “a focus on the understanding, interpretation and
117 prediction of the flows and stocks in the human-modified water cycle at multiple scales,
118 with explicit inclusion of the two-way feedbacks between human and water systems”.

119

120 **Murrumbidgee (Australia) Case Study**

121

122 This paper presents a socio-hydrologic modeling study centered on the Murrumbidgee
123 River Basin (MRB) (Figure 1), a sub-basin of the much larger Murray-Darling Basin.
124 The Murray-Darling Basin has recently witnessed heated debate over water use as a
125 result of heavy competition for water resources between humans and ecosystems
126 (Roderick, 2011). Data analysis carried out by Kandasamy *et al.* (2014) using data from

127 the Murrumbidgee River Basin has revealed a “pendulum swing” between an exclusive
128 focus in the initial stages on water extraction for food production, and later efforts to
129 mitigate and reverse the consequent degradation of the riparian environment. The basin
130 witnessed a rapid rise in population in the early decades, amid increasing concerns of
131 salinity and declining ecosystem services. It was able to sustain the growth in population
132 and agricultural production by first increasing reservoir storage capacities and then
133 through investments in infrastructure and technologies that helped to control soil salinity
134 and algal blooms, such as efficient irrigation systems, barrages and upgraded sewage
135 treatment plants. Yet, in the end, it was unable to curb the eventual decline in population
136 and in agricultural production that began around 1990.

137

138 The decline in water available for the environment and its ultimate degradation as a
139 consequence led to the rise of the notion of the “environmental consumer” in the basin
140 (Kandasamy *et al.*, 2014). This implied a change in preferences of the population within
141 the basin and of the society at large towards a better environment. The system reached the
142 stage whereby inhabitants of the MRB, and especially in the wider society, were no
143 longer solely driven by the income that agriculture generated if it came at the cost of
144 environmental degradation. They reached the point where they were willing to give up
145 water consumption to achieve improved environment quality and to satisfy environmental
146 demands. Such a change in the values and norms of individuals within the basin and in
147 the wider society resulted in a different dynamics between agricultural production and
148 environment quality (Chen and Li, 2011; Sivapalan *et al.*, 2014). The changing values
149 and norms, via changes in the dynamics of human consumption and environment quality,
150 fed back to changes in the delivery of ecosystem services. Overall, the rise and the fall of
151 population and crop production led to a spatio-temporal pendulum swing that is best
152 illustrated by the area planted with rice within the basin (see Figure 4c in Kandasamy *et*
153 *al.*, 2014; see also Sivapalan *et al.*, 2012).

154

155 With this paper we aim to demonstrate that socio-hydrologic modeling can be used as a
156 useful tool to study and explain observed co-evolutionary dynamics of coupled human-
157 water systems. This paper thus represents an attempt to explore through numerical

158 simulation the main drivers of the “pendulum swing” observed in the Murrumbidgee. We
159 present a stylized, quasi-distributed and coupled socio-hydrologic system model that
160 explicitly includes the two-way coupling between humans and nature (e.g., the
161 hydrologic system), including evolution of human values/norms relating to water and the
162 environment. We use it to mimic broad features of the observed pendulum swing
163 described by Kandasamy *et al.* (2014), and in so doing generate insights into the
164 dominant drivers (both exogenous and endogenous) of the trajectory of co-evolution of
165 the coupled human-water system, and in this way to develop a broad theoretical
166 framework that may potentially be transferable to other systems in different climatic and
167 socio-economic settings. This modeling work also contributes to efforts aimed at
168 developing generic model frameworks for coupled socio-hydrologic systems that involve
169 a competition for water between humans and the environment (Elshafei *et al.*, 2014).

170

171 **2. Model Description**

172

173 Kelly *et al.*, (2013) described a wide class of approaches to modeling coupled human and
174 environmental systems and suggested a framework for choosing an approach that is
175 suitable for the problem at hand. In the area of socio-hydrology, there have been several
176 recent efforts at developing simple conceptual (or stylized) models of coupled human-
177 water systems. For example, Di Baldassarre *et al.* (2013a,b) developed a simple, dynamic
178 human-flood model to represent the interactions and feedbacks between hydrological and
179 social processes in context of urban flooding. Liu *et al.* (2014) likewise proposed a
180 coupled human-water system model to mimic the competition for water between humans
181 and the environment in the Tarim River Basin in Western China. Srinivasan (2013)
182 presented a coupled human-water system model in the context of urban water supplies in
183 the city of Chennai, India. These models belong to a class of system dynamics models
184 with a rich history of modeling the coupled dynamics of human populations, economic
185 growth and general resource availability at a variety of spatio-temporal scales (Forrester,
186 1971; Cuypers and Rademaker, 1974; Hoekstra, 1997; Vörösmarty *et al.*, 2000; Turner,
187 2008; Davies and Simonovic, 2011). Alternatively, although with some subtle
188 differences, there have been efforts at developing coupled conceptual water and

189 economic system models (also known as hydro-economic models) in the context of basin
190 scale water allocation (Pande *et al.*, 2011), groundwater management (Pulido-Velazquez
191 *et al.*, 2006), and agricultural water management (Knapp *et al.*, 2003; Maneta *et al.*,
192 2009). Another layer of complexity can be added to these approaches by invoking the
193 principles that underpin how individuals organize themselves (Greif and Laitin, 2004;
194 Pande and Ertsen, 2013), accounting for changing values and norms (Sivapalan *et al.*,
195 2014), or allowing for changing structure of coupled human water systems and how it
196 affects the resulting dynamics (Kallis, 2007; Kallis, 2010). The degree of belief in the
197 coupled dynamics simulated by these approaches is enhanced by also explicitly modeling
198 the feedbacks between economic growth, population size and also technology change,
199 where applicable (Eicher, 1996; Pande *et al.*, 2014). The model presented in this paper
200 goes some ways towards combining the strengths of these previous attempts at socio-
201 hydrological modeling.

202

203 Before we present the details of the model of the Murrumbidgee basin system, however,
204 it is pertinent to present the motivation and scope of the modeling framework being
205 presented. At this early stage simplified equations are used to model the main drivers in
206 the catchment, i.e., hydrology, irrigation, ecology and population size. As discussed later,
207 the governing equations have ‘intuitive’ basis in the relevant literature and their
208 parameters are calibrated to mimic the data trends. It is acknowledged up front that the
209 predicted timings and magnitudes will not exactly match actual occurrences in the past,
210 yet the simulated trends or patterns are consistent with those observed. This paper aims to
211 show that a socio-hydrologic modeling framework might be used to study complex
212 coupled human-water systems. The main goal of the model development is therefore to
213 demonstrate that despite complex interactions, the dominant patterns can be reproduced.
214 Yet another objective of model development is to trigger further study of the
215 complexities of human water interactions, especially the governing equations and
216 associated constitutive relationships. This will expand the possibility of implementing
217 socio-hydrological models, guide future decisions on catchment water management, and
218 communicate to the practicing engineer/basin manager the potential and value of socio-
219 hydrology.

220

221 **2.1 Model Domain**

222

223 The MRB is located in south-eastern Australia, has a drainage area of 85,000 km², and
224 forms part of the iconic Murray-Darling Basin (Figure 1). The headwaters of the
225 Murrumbidgee River are located in the Snowy Mountains in the east, from where the
226 river flows west towards the outlet, which is at the confluence with the Murray River.
227 Much of the agricultural activity happens downstream (i.e., west) of Wagga Wagga. For
228 this reason, the study domain is restricted to the area of the MRB west of Wagga Wagga
229 (as shown in Figure 2, with drainage area of 60,000 km²). The measured discharge at
230 Wagga Wagga is therefore the main water inflow to the system, supplemented by rain
231 that falls over the study domain. In order to mimic internal relocation of humans and
232 associated agricultural activity, the model domain on the MRB is notionally divided into
233 three equal sub-regions or settlements denoted here as upstream, middle stream and
234 downstream (Figure 2). The aim here is merely to demonstrate the working of the model
235 and not to correlate well with observed irrigation areas (see Figure 1). The geomorphic
236 properties are assumed to be the same for the three settlements (i.e., they have same
237 catchment area and the area available for irrigation).

238

239 **2.2 Governing Equations**

240

241 The model consists of five coupled nonlinear ordinary differential equations that describe
242 the interaction between state variables that govern the co-evolution: reservoir storage
243 (hydrology), irrigated area, size of the human population, a measure of ecosystem health
244 and an indicator of changing environmental awareness within society.

245

246 The hydrology equation represents water storage, irrigation water use and river discharge
247 variations from a water balance perspective. The irrigation equation simulates the
248 dynamics of the irrigation area per capita subject to water availability, technology change
249 and environmental degradation. The population equation tracks the dynamics of
250 population size through internal growth, migration from outside, and internal (both

251 upstream and downstream) relocation. The ecology equation simulates water storage in
252 notional riparian wetlands located downstream of the study region (i.e., downstream of
253 the downstream section) that are episodically recharged by river flow during high flow
254 events. The environmental awareness equation tracks the dynamics of community
255 sensitivity to the degradation of ecosystem health, here exclusively focused on the health
256 of riparian wetlands.

257

258 Explicit inter-connections are built in between these five principal equations through
259 assumed constitutive relationships that allow for the relevant feedback mechanisms (both
260 positive and negative) to operate. The first three equations (irrigation area, population
261 size, reservoir storage) are developed for each sub-region separately (upstream, middle
262 stream, downstream). Humans are allowed to internally relocate between these sub-
263 regions (in both directions), water is exchanged only in the downstream direction and
264 obviously no exchange of irrigation area is allowed. The last two equations (ecosystem
265 health and environmental awareness) are applicable to the wetlands only, and are
266 therefore system-wide equations. Details of each of the five model components and their
267 interconnections are presented next. Note that in this study, the constitutive relationships
268 that are used to link the governing equations are not prescribed; rather, both their
269 functional forms and associated parameter values are obtained by calibration. The
270 functional forms and parameters were adjusted based on expert knowledge, combined
271 with calibration, and was governed by two contrasting modeling demands. The first is the
272 need for realistic relationships between variables. The second is the aim to keep the
273 formulation as simple as possible. Details about these are therefore only presented as part
274 of the results section.

275

276 **Irrigation Equation**

277

278 In this study, irrigation activity is expressed in terms of irrigated area *per capita*. This
279 helps to separate the effect of population size, the dynamics of which is treated separately
280 (see later). The governing equation for irrigation is given by:

281

$$\frac{da_i}{dt} = \alpha_\tau(T) + \alpha_s(S_i) + \alpha_E(E) \quad 1)$$

282

283 where a_i is irrigated area per capita, and i refers to the sub-region. In Equation 1, the
284 dynamics of a_i is governed by three growth rates, expressed by three constitutive
285 relationships: $\alpha_\tau(T)$ (function of technology, T), $\alpha_s(S)$ (function of water storage, S),
286 $\alpha_E(E)$ (function of community environmental awareness, E).

287

288 In this paper we consider technology, T , very broadly, and use it to embrace a whole
289 gamut of advances, such as mechanization, advanced irrigation practices (e.g., drip
290 irrigation), planting strategies to maximize water use, and plant breeding to increase crop
291 yield (see for example Hayami and Ruttan (1970) for a discussion on the two broad types
292 of agricultural technology: ‘mechanical’ and ‘biological and chemical’). All of these
293 contribute to higher a_i , and are reflected in $\alpha_\tau(T)$. Secondly, a_i is also governed by the
294 amount of water available for irrigation. Availability of water (e.g., storage in the
295 reservoir), provides confidence to farmers deciding to settle, invest and expand. Equation
296 1 captures this dependence in terms of constitutive relationship between the growth rate,
297 α_s , and reservoir storage (S) on the annual time scale. On the opposite side, increasing
298 awareness of environmental degradation may motivate some farmers to voluntarily
299 forego a part of their land during periods of drought for the sake of environmental
300 protection. The growth rate, α_E (less than zero), expressed as a function of environmental
301 awareness, E , is used to capture the negative feedback in response to environmental
302 degradation. Clearly, the dynamics of a_i is geared to the dynamics of reservoir storage, S ,
303 and environmental awareness, E . These dynamics are explicitly captured through
304 associated differential equations, which are described next. Technology, T , changes with
305 time too and here it is assumed to increase with time varying wealth, the details of which
306 are presented later.

307

308 **Population Equation**

309

310 The model simulations begin with an initially small population located in the downstream
 311 settlement only (denoted as 1, Figure 2), and zero populations in the middle stream and
 312 upstream settlements (denoted as 2 and 3, respectively). Subsequent change of population
 313 size can be due to three factors: natural growth (i.e., birth – death), migration (from
 314 outside), and internal relocation (up- or down-migration between settlements). For
 315 simplicity, the model assumes that migration to and from the outside is only to the
 316 downstream settlement. This assumption is based on results from Kandasamy *et al.*
 317 (2014), where this mechanism was observed in the early phase of settlement in the MRB.
 318 In addition, a model design with migration to and from the outside to the downstream,
 319 middle stream and upstream settlements did not yield better results and only increased
 320 model complexity. This means that the middle stream and upstream settlements populate
 321 or depopulate through internal relocation and subsequent internal growth. The governing
 322 equation for population dynamics for each of the settlements is given by:

323

$$\frac{dN_1}{dt} = N_1\{\psi_n + \psi_m(\varphi_1)\} + N_2\psi_{r_{21}} - N_1\psi_{r_{12}} \quad 2a)$$

$$\frac{dN_2}{dt} = N_2\psi_n + N_1\psi_{r_{12}} + N_3\psi_{r_{32}} - N_2\psi_{r_{23}} \quad 2b)$$

$$\frac{dN_3}{dt} = N_3\psi_n + N_2\psi_{r_{23}} - N_3\psi_{r_{32}} \quad 2c)$$

324

325 where ψ_n , ψ_m and ψ_r are the population growth rates: ψ_n is natural growth rate (assumed
 326 constant), ψ_m is growth rate through migration from outside, $\psi_{r_{ij}}$ is rate of growth or loss
 327 through internal relocation. In Equation 2a, $N_2\psi_{r_{21}}$ refers to growth through relocation
 328 from settlements 2 to 1, whereas the term $N_1\psi_{r_{12}}$ refers to loss through relocation from
 329 settlements 1 to 2.

330

331 The model assumes that people either move into an area or leave on the basis of a relative
 332 attractiveness level, defined as φ . In Equation 2 external migration rate, ψ_m , into
 333 settlement 1 is assumed to be nonlinear function of the level of attractiveness, φ_1 (see
 334 Table 3 for details for the associated (calibrated) constitutive relationship). The level of

335 attractiveness of any given region i is expressed in terms of the *per capita* irrigation
336 potential:

337

$$338 \quad \varphi_i = (a_i^{max} - a_i) \quad 3)$$

339

340 which is the difference between the potential (maximum possible) area available for
341 irrigation and the actual (present) area under irrigation, on a *per capita* basis. Broadly we
342 hypothesize that people migrate to the basin, and/or relocate within the basin, in order to
343 maximize their (*per capita*) income potential (see e.g. Fedotov *et al.*, 2008 for a similar
344 formulation). However, for simplicity and as a first step, we have assumed that irrigation
345 potential (Equation 3) can serve as a surrogate for the income potential. In reality,
346 however, income potential can also be impacted by water availability, the state of the
347 environment, and several other factors. There is therefore considerable room for
348 improvement of this formulation in the future, especially as more data become available
349 and our understanding of human motivations improves. The idea that people migrate to
350 maximize their economic profit is based on microeconomic fundamentals. The MRB is
351 an agriculture dominated area, where throughout the 20th century population change and
352 agricultural development occurred side by side (Kandasamy *et al.*, 2014). Therefore it is a
353 reasonable assumption that the migration of people is determined by irrigation potential
354 (economic gains) and environmental awareness (economic losses).

355

356 In Equation 2 relocation rate, $\psi_{r_{ij}}$, between two different settlements within the basin, i
357 and j , is assumed to be, to first order, a function of the difference in the levels of
358 attractiveness between the two. The difference in attractiveness, $(\varphi_j - \varphi_i)$, can be seen
359 as a gradient that drives the relocation. In this paper, in addition, we make a further
360 correction to reflect possible human desire to help mitigate the resulting environmental
361 degradation. The relocation rate, $\psi_{r_{ij}}$, is then governed by a combination of the
362 attractiveness gradient and environmental awareness, E . The resulting equation for $\psi_{r_{ij}}$ is
363 given by:

364

$$\psi_{rij} = r(\varphi_j - \varphi_i) + cE \quad 4)$$

365

366 where r and c are constants. Figure 3 conceptualizes the model formulation for the
 367 relocation of people: when $\psi_{rij} > 0$ the movement is from settlement i to j , when $\psi_{rij} < 0$
 368 the movement is from j to i . Equation 3 thus creates a relocation dynamics between the
 369 three downstream, middle stream and upstream settlements that emerges endogenously
 370 with the growth of irrigated areas, population size and environmental awareness.

371

372 The inclusion of the environmental awareness in Equation 4 is to accommodate a curb on
 373 the expansion of irrigated area and return part of the irrigated area back to nature. Such
 374 actions limit local consumption of water, and allows for more water to recharge the
 375 wetlands downstream. In this model, the inclusion of environmental awareness has the
 376 net effect of shifting people downstream. When the sign of cE is positive, and $\varphi_j - \varphi_i$ is
 377 downstream-directed, environmental awareness accelerates downstream relocation; and
 378 when the sign of cE is negative, and $\varphi_j - \varphi_i$ is upstream-directed, upstream relocation
 379 decelerates.

380

381 **Hydrology Equation**

382

383 The hydrology equation, essentially a water balance equation, tracks the dynamics of
 384 water stored within any one settlement ($i=1, 2, 3$) on a daily time step. The net inputs to a
 385 settlement are inflows at its upstream end (i.e., measured inflows at Wagga Wagga for
 386 the upstream settlement, or model simulated inter-settlement flows in the case of the
 387 middle stream and downstream settlements) plus the runoff generated within the
 388 settlement from rainfall. Net outputs are outflows/overflows to the settlement located
 389 downstream, and the amount of water extracted for irrigation. At the beginning of
 390 simulations (circa 1910), there is no reservoir storage. The daily water balance equation
 391 for settlement i is given by:

392

$$393 \quad \frac{dS_i}{dt} = Q_i^{in} + A_i^c \beta p_i - \max\{(\gamma_S(T) - (1 - \beta)p_i)N_i a_i, 0\} - Q_i^{out} \quad 5)$$

394

395 where S_i is net storage within the settlement, *including reservoir storage* (once it is
396 constructed), Q_i^{in} is inflow at the upstream end, and Q_i^{out} is outflow to the settlement at
397 the downstream end. The second term on the R.H.S (Right Hand Side) of Equation 5 is
398 the rate of runoff generated internal to the settlement, expressed as a product of the
399 “physical” catchment area A_i^c , average rainfall intensity p_i , and a runoff coefficient β ,
400 which is assumed to be constant here for simplicity. The third term is net water
401 extraction for irrigation, after accounting for rainfall. Here $N_i a_i$ is total irrigated area, and
402 $\gamma_S(T)$ is crop water demand per unit area, and their product is the net demand for water.
403 During rainfall events, since crops can directly access water from rainfall, water
404 extraction is the demand not met by the net amount of rainfall over the irrigated area.
405 When rainfall is more than enough to satisfy the irrigation demand, water extraction is set
406 to zero. Crop water demand per unit area, $\gamma_S(T)$, changes with time through technological
407 advances such as crop breeding. For this reason, $\gamma_S(T)$ is estimated as a function of
408 technology, T (see later for details).

409

410 Early in the simulations we assume that there are no reservoirs and temporary detention
411 storage in the river is the only storage in the system. Water is extracted directly from the
412 river, and during this early period excess water simply passes through to the downstream.
413 However, the model is conditioned such that on the basis of the trigger of a persistent
414 deficit in the water available over many years to meet irrigation demand, a reservoir is
415 introduced endogenously to mitigate that deficit. We define “water shortage days” (ω) as
416 the number of days in a year when the sum of storage in the reservoirs and river flow is
417 less than irrigation demand (e.g., during a period of drought). These days are monitored
418 over the years to quantify ‘water sufficiency’. The decision to construct a reservoir and
419 the timing of that construction are both linked to the number of “water shortage days”.
420 Reservoir construction is triggered when the mean “water shortage days”, ω , over five
421 years exceeds a specified drought threshold δ (days). Once the reservoir is constructed,
422 the threshold δ is doubled (but to a value not larger than 365 days), thereby modeling an
423 evolving tolerance for drought. The size of the reservoir Ω at each stage of construction
424 notionally follows user demand. We assume that Ω is linearly related to irrigation

425 demand, given by $\Omega = 10\gamma_S N_i a_i$. When river flow is not enough to satisfy the irrigation
426 water demand, reservoir storage (if already built) releases water to meet the unmet
427 demand. The amount of water released is the difference between water demand and river
428 flow. In the MRB, agriculture dominates, and therefore we neglect household water use.

429

430 **Ecology Equation**

431

432 In this paper, ecology refers to the functioning of the chain of riparian wetlands, which
433 are episodically recharged when river flow exceeds a prescribed threshold released from
434 the downstream settlement ($i = 1$). The wetlands are assumed to exist notionally only
435 and are located downstream of the downstream settlement (i.e., outside of the basin, for
436 example they may refer notionally to the Lowbidgee Wetlands, which is the largest
437 wetlands located within the MRB). The ecology governing equation is the water balance
438 equation of these wetlands, which receive water episodically through overflows of the
439 river, and then over a longer time lose the water through a combination of leakage and
440 evaporation. Both leakage and evaporative losses are assumed to be proportional to the
441 storage. This water balance equation is thus given by:

442

$$\frac{dW}{dt} = \max(0, Q_1^{out} - \mu) - kW \quad 6)$$

443

444 where W is the storage in the wetlands, Q_1^{out} is the river discharge reaching the wetlands
445 (outflow from the downstream section), μ is the recharge/overflow threshold above
446 which the wetland is recharged, and κ is a coefficient representing the combination of
447 evaporation and leakage loss.

448

449 **Environmental Awareness Equation**

450

451 The wetland storage simulated by the ecology equation (Equation 6) is used as a predictor
452 of ecosystem health. The state of ecosystem health is assumed to impact human behavior
453 with respect to irrigation area expansion and water extraction in a way that mitigates any

454 environmental degradation and thus helps to maintain or improve ecosystem health. In
455 the model such human feedbacks are channeled through a dynamic state variable called
456 environmental awareness, E .

457

458 It is assumed that environmental degradation takes place whenever wetland storage, W ,
459 falls below a threshold, W_d . It is only when this happens that environmental degradation
460 is recognized by the community, and the longer it persists, the longer the environmental
461 awareness, E , accumulates. On the other hand, whenever W is higher than W_d for the
462 entire year, then we allow the accumulated E to deplete. In other words, environmental
463 awareness, E , is akin to a memory bank that accumulates during times when the
464 environment degrades, and depletes during relatively healthier times.

465

466 Because of the episodic nature of these exceedances, we define n as the number of days
467 in a year during which W is below the threshold. Clearly n is connected to the wetland
468 storage dynamics (Equation 6), and therefore represents the coupling of environmental
469 awareness to the ecology equation. When n is positive, then E accumulates, whereas
470 when n is zero then E is allowed to deplete. The temporal dynamics of E is then given by
471 the following differential equation:

472

$$\frac{dE}{dt} = \varepsilon(n) \quad 7)$$

473

474 where $\varepsilon(n)$ is the rate of accumulation/depletion of environmental awareness. The
475 functional form of $\varepsilon(n)$ is calibrated so as to mimic the observed pendulum swing (the
476 calibrated expression for $\varepsilon(n)$ is presented in Table 3). In reality its exact formulation
477 will rely on ecological considerations, which is beyond the scope of this study. We also
478 highlight our assumption in this paper that environmental awareness is solely driven by
479 the ecological well-being, a variable that is local to the basin. Macro-scale variables, such
480 as regional or national politics and economy and climate, may play a role in determining
481 the dynamics of environmental awareness as indicated in the general framework
482 proposed by Elshafei *et al.* (2014), but have been ignored here.

483

484 **Model Coupling: Cross-System Feedbacks**

485

486 The socio-hydrologic model presented above is a coupled model that involves 5 sub-
487 systems represented by 5 ordinary differential equations and associated state variables.
488 The sub-systems are internally coupled, represented through several constitutive
489 relationships (see Table 3 for the expressions resulting from calibration). In the case of
490 irrigation area, population size and reservoir storage, the model is implemented in a
491 quasi-distributed way, dividing the study domain into 3 settlements. This brings about
492 additional couplings, involving the one-way exchanges of water (in the downstream
493 direction only), and the two-way exchanges of human populations. As already mentioned,
494 the ecologic and environmental awareness sub-systems are lumped systems, representing
495 a domain that is downstream of the study domain.

496

497 Figure 4 conceptualizes how the systems are coupled with each other, and the associated
498 feedback loops. The hydrology equation simulates the capacity of reservoir storage that is
499 available for irrigation. Increase of reservoir storage capacity contributes to an increase of
500 irrigated area per capita, a_i , in a given region, as reflected in the relationship $\alpha_S(S)$ in
501 Equation 1. The expansion of irrigated area has a self-magnifying effect: it increases
502 wealth, which is assumed to lead to the creation of a demand for and the ability to adopt
503 new or better technologies.

504

505 In this model, wealth is expressed in terms of the agricultural *per capita* Gross Basin
506 Product (GBP), P_{GB} , for the whole basin (combined value for all settlements). It is
507 defined as the product of crop price, f_p , crop yield per unit area, $\gamma_r(T)$, and the weighted
508 average of the irrigated area *per capita*, a_i obtained from Equation 1:

509

$$P_{GB} = \frac{\gamma_r(T) f_p \sum_{i=1}^M (a_i N_i)}{\sum_{i=1}^M N_i} \quad 8)$$

510

511 Since we have divided the basin into 3 sections, $M = 3$. T is the technology variable. The
 512 crop price, f_p , is an external input to the model, and the time series of f_p is obtained over
 513 the past 100 years for rice (taken here as the notional crop) from the World Bank (World
 514 Bank, 2013). Given the estimate of GBP (which is dynamically changing), technology is
 515 then expressed as a function of GBP (see for e.g. Eicher, 1995; Pande *et al.*, 2013). We
 516 prescribe a relationship between the two as follows:

517

$$T = [\lambda_1 + \lambda_2 \exp(-\eta P_{GB})]^{-1} \quad 9)$$

518

519 Note that the parameter values in Equation 9 are chosen as, $\lambda_1 = 0.1, \lambda_2 = 0.9, \eta = 0.07$,
 520 so that T is bounded between 1 and 10. Relative to this basin and relative to this time
 521 period, $T = 1$ represents a low technological level (e.g., primitive society, at an initial
 522 phase of a human settlement), and $T = 10$ represents the highest possible technological
 523 development. We note here that GBP in the above relationship is assumed to be impacted
 524 by past technological developments.

525

526 Technology, T , is thus an endogenous variable that broadly reflects productivity increase
 527 due to mechanization, efficient water distribution, planting, improved crops etc. In the
 528 model, T is assumed to contribute to three factors that affect agricultural and economic
 529 productivity: crop water demand per unit area, $\gamma_S(T)$; crop yield $\gamma_r(T)$, which is the
 530 amount of crop produced per unit irrigated area; and irrigated area per capita, a_i . In the
 531 case of $\gamma_S(T)$, a high value of T contributes to water savings, and reduces $\gamma_S(T)$. In the
 532 case of $\gamma_r(T)$, a high value of T increases crop yields, $\gamma_r(T)$. Together, improved
 533 technology enables more water to be saved per unit area and more crop to be produced
 534 per unit area, i.e., by reducing $\gamma_S(T)$ and increasing $\gamma_r(T)$. In addition, technology in the
 535 form of mechanization reduces human labor requirement, allowing for more land to be
 536 cultivated and managed *per capita*: in this way, $\alpha_r(T)$ increases, which in turn increases
 537 productivity and wealth. Taken together all of these feedbacks constitute a common
 538 *positive feedback loop* in the coupled socio-hydrologic system.

539

540 Productivity of the combined land, water and human resources, through wealth
541 generation and technological advances, contributes to their further exploitation. Over
542 time such intensification of production contributes to a progressive degradation of the
543 environment, which acts as a control or restraint on further growth. This *negative*
544 *feedback* is represented in the model in several ways.

545

546 Firstly, expansion of irrigated area leads to a reduction of flows released to the wetlands,
547 contributes to a reduction of storage in these wetlands, and in this way contributes to the
548 damage of the ecology of wetlands. Persistent damage, as measured by the number of
549 days of the year when W falls below the set threshold, sensitizes the population to
550 environmental damage. Thus ecological damage resulting from irrigation area expansion
551 feeds back to raise awareness in the local and wider community to slow or even reverse
552 the degradation and ultimately protect the environment. This is represented in Equation 1
553 in the form of a term, $\alpha_E(E)$, which represents a rate of reduction of irrigation area *per*
554 *capita* as a function of environmental awareness.

555

556 Secondly, for the basin as a whole, there is another facet to the exploitation of the land
557 and water resources. This is through increased population. Migration from outside and
558 relocation within has been assumed to be driven by “income potential”, represented here
559 by “irrigation potential”. As people settle in the downstream section and exhaust the area
560 available for irrigation, they migrate upstream, and open up new areas for irrigation, raise
561 demand for water, which then leads to construction of reservoirs. Limited area available
562 for irrigation constrains further growth. However, in addition, the upward expansion of
563 irrigation area, and subsequently the exploitation of water resources through construction
564 of more reservoirs upstream, reduces environmental flows downstream, sharply reducing
565 the recharge of wetlands. The resulting increase of environmental awareness is factored
566 in the model, helping to slow down the upward migration, and accelerating downward
567 movement of all relevant variables. Figure 4 captures the essence of both *positive* and
568 *negative* feedback loops that are captured in the model. Even if independently and
569 empirically derived, the organization of the coupled system closely resembles the generic
570 framework proposed by Elshafei *et al.* (2014).

571

572 **Initial and Boundary Conditions**

573

574 Figure 5 presents time series of measured discharge at Wagga Wagga and of world price
575 for rice over the past 100 years. These, and the average rainfall time series over the study
576 domain, are the only external drivers to the socio-hydrologic model. Upstream flow and
577 rainfall are clearly not impacted by human activity occurring within the MRB. Food price
578 is controlled by global food supply and demand dynamics and is outside the control of
579 the MRB (i.e., it is exogenous to MRB). All other dynamics are internally, or
580 endogenously, generated on the basis of the assumptions of the model and the assumed
581 constitutive relations. In this paper, we have chosen rice to serve as the surrogate for a
582 general food/crop price. Part of the reason is that rice was already introduced into the
583 MRB at the beginning of the study period, and constitutes over 50% of the irrigation
584 allocation (Gorman, 2013; Hafi *et al.*, 2005).

585

586 As initial conditions, it is assumed that the community begins to grow and expand from
587 the downstream end only and neither humans nor any organized agricultural activities
588 initially existed in the middle stream and upstream sections of the basin. Table 1 presents
589 the initial conditions for all state variables assumed in the model. A simple explicit
590 numerical scheme is used to solve the coupled set of differential equations. The model
591 uses variable time steps: the hydrology and ecology equations are solved on a daily time
592 step, whereas all other equations are solved with an annual time step. Table 2 presents the
593 definition of the parameter values used in the model and prescribed magnitudes in the
594 model. Note that the constitutive relations and their parameter values are calibrated and
595 the results are presented in Table 3. Kandasamy *et al.* (2014) illustrated the pendulum
596 swing in the Murrumbidgee in terms of variations of reservoir capacity, population size,
597 irrigation area and environmental flows, which are reproduced here in Figure 6a-d to
598 provide context. The aim of the model presented here is to capture broad features of these
599 trends (in space and time) and to gain deeper insights that might be generalized to other
600 places.

601

602 The model includes several constitutive relations that make it determinate. These include:
603 $\alpha_\tau(T)$, $\alpha_s(S_i)$, $\alpha_E(E)$, $\psi_m(\varphi)$ and $\varepsilon(n)$. Additionally, to complete the specification of the
604 problem we have to prescribe other relations such as those of $T(GBP)$, $\gamma_s(T)$ and $\gamma_r(T)$.
605 It is premature to prescribe these constitutive relations a priori. For the purpose of this
606 study these constitutive relations are “tuned” so that the model is able to mimic the
607 observed, emergent dynamics, as shown in Figure 6a-d. The data in Figure 6a-d was
608 taken from Kandasamy *et al.* (2014), based on (a) water storage development in the MRB
609 (sourced from NSW State Water Corporation), (b) population in the MRB (ABS, 2013a),
610 (c) irrigated area in the MRB (ABS, 2013b) and (d) irrigation flow utilization in the MRB
611 (DWR, 1989; ABS 2013b).

612

613 **Model sensitivity analysis**

614 The socio-hydrological modeling framework, though parsimonious, has numerous
615 parameters. While this allows flexibility in representing diverse socio-hydrological
616 behaviors, i.e. that it can generate several socio-hydrological realities, it may also lead to
617 equifinality in that it may generate similar socio-hydrological realities but with different
618 parameter values (Savenije, 2001). A sensitivity analysis of the model with respect to its
619 parameters is therefore important in order to reveal diverse realities that it can reveal, as
620 well as determine how prone it is to equifinality. The benefits of this analysis are three-
621 fold. First, we identify redundant, i.e. equifinal parameters. Second, it gives insight on
622 how parameters, fluxes and stocks are connected. Third, it allows us to explore the
623 alternate socio-hydrological realities that the presented modeling framework can
624 generate. To accomplish this we used a variance-based method, similar in spirit to Sobol’
625 (1993, 2001). Over the last years, various authors have used variance-based sensitivity
626 analysis to assess complex hydrologic or ecologic system models (e.g. Tang et al., 2007;
627 Rosero et al, 2009; Bois et al, 2008; Song et al., 2012). The variance-based index that we
628 use to assess parameter sensitivity of model outcomes, S_i , is computed as:

$$S_i = \frac{V_i}{V(Y)}$$

629 where V_i is the variance of model outcome statistic Y (for e.g. mean squared error in
630 simulating the best fitting population time series) when the i^{th} parameter is varied and

631 $V(Y)$ is the sum of variances V_i over all the parameters. We here note that $V(Y)$ is the sum
632 taken over parameters one at a time and not over all possible combinations of parameters.

633

634 All parameters are varied within a given range, which can be seen in Table 4. Every
635 parameter is varied (uniformly sampled from the corresponding parameter range) one at
636 the time, yielding corresponding modeled time series for outcome variables: population,
637 irrigated area, storage, wetland storage and environmental awareness. These are
638 compared with the best fitting model outcome to determine the root mean squared error
639 (RMSE), yielding a RMSE per outcome variable for all samples of the parameter i . The
640 variance of the RMSEs, V_i , corresponding to the samples of parameter i is then
641 calculated. The variances of these RMSEs over the parameters sampled are then summed
642 to obtain the following equation for the sensitivity of a model outcome to the i^{th}
643 parameter,

$$S_i = \frac{V_i}{\sum_{i=1}^d V_i}$$

644 where i is the tested parameter, $d (= 15)$ is the total number of parameters ($i = 1, \dots, d$), V_i is
645 the variance of RMSEs corresponding to parameter i , and S_i is the sensitivity index for
646 the i^{th} parameter. The results of the model are used to explore sensitivity of model
647 outcomes to parametric perturbations and the ability of the presented model to simulate
648 diverse socio-hydrological realities.

649

650 **3 Results and Discussion**

651

652 The results of model implementation to the Murrumbidgee Basin are presented in four
653 parts: (i) the resulting model-predicted temporal (and spatial) dynamics of the state
654 variables and fluxes, (ii) outcomes of the constitutive relations obtained after matching
655 the observed dynamics, (iii) presentation of the dynamics of other internal variables to
656 help provide insights into the co-evolutionary dynamics and (iv) the sensitivity and
657 robustness of the model.

658

659 **3.1. Temporal and spatial dynamics of the state variables and fluxes**

660

661 Figure 6e presents the time variations of reservoir capacity, population size, irrigation
662 area, and water extraction for irrigation over the 100 year period to mirror the
663 corresponding observed trends shown in Figure 6a-d. Figure 6e also shows the upstream
664 migration of reservoir capacity. In both Figures 6e-h and 7, we divide the study period
665 into the four major eras identified by Kandasamy *et al.* (2014). Figure 7 presents the
666 calibrated constitutive relations. The functional forms of these constitutive relations are
667 presented in Table 3. The results demonstrate that the model is able to mimic in a
668 “general” way the temporal trends in the observed dynamics of water resources, area
669 under irrigation, population size, including the “pendulum swing”.

670

671 However, by itself this is not claimed to be a unique result of the model, given that these
672 are calibrated results. The complexity of the model and the many degrees of freedom
673 available to it, can lead to simulation of patterns that are different from the observed
674 pendulum swing. While high complexity is desirable to simulate a rich class of emergent
675 patterns, such models when calibrated, especially for sparsely gauged basins (in terms
676 either of socio-economic or hydrological data), may not reliably predict the dynamics
677 driven by future yet unseen exogenous forcing. See for example Sivapalan *et al.*, (2003),
678 Jakeman and Letcher (2003), Fenicia *et al.*, (2008), Pande *et al.* (2012), Pande (2013),
679 Arkesteijn and Pande (2013) for extensive analyses of the relationships between model
680 complexity, model structure deficiency, prediction uncertainty. Furthermore, the
681 differences in the shapes of the curves between observations and predictions, especially
682 in the case of irrigation area, points to model improvements that can still be made: for
683 example, the assumption that attractiveness level is a function of irrigation potential may
684 have to be improved with the hindsight of additional data. In this way these modelling
685 efforts can also give guidance and focus to future data collection efforts and analyses.

686

687 **3.2. Outcomes of the constituent relations**

688

689 Regardless of how well the model is able to reproduce the observed dynamics, we are
690 more interested in answering the following questions. How did the observed dynamics

691 unfold? What is a plausible explanation for the observed dynamics? What insights can be
692 gained through the implementation of the model? However we acknowledge that, given
693 the complexity of the model and the associated equifinality issues, what we can learn
694 from the calibrated model is just one possible explanation, one of several.

695

696 Figures 8 to 10 provide possible answers to these questions through recourse to the
697 simulated dynamics of several internal variables, which may provide insights into how
698 the observed hydrologic and human process dynamics emerged through the human-water
699 interactions and feedbacks. Exploration of the causes of the observed behavior must
700 begin with the recognition that the only external drivers are: (i) climate, although in this
701 case this is replaced by the water inflows from the upstream catchment area, as measured
702 at Wagga Wagga (which acts as the surrogate to climate), and (ii) the time series of world
703 rice prices. Apart from these, the entire dynamics is endogenous or internally generated,
704 and emerged in response to these external drivers.

705

706 The figures illustrate the complex feedbacks that the model incorporates. Figure 8 is a
707 demonstration of positive feedback loop mediated by human innovation, i.e. technology,
708 while Figure 10 is a negative feedback loop that is mediated by human awareness of the
709 environment. Figure 9 demonstrates the adaptation of human population, through
710 migration, to such feedbacks through migration. Therefore, human migration, in a sense,
711 facilitates the swing between the positive and negative feedbacks.

712

713 The results in Figure 6 showed that the total irrigation area steadily increased until the
714 turnaround that happened around 1980. This corresponds with the emerging appearance
715 of environmental degradation, partly due to agricultural activities (Kandasamy *et al.*,
716 2014). Figure 8 expands upon the modeled dynamics. Irrigated area per capita, which
717 constitutes one of two major inputs for agricultural production (i.e., land and water),
718 contributes to wealth generation. Higher gross basin production per capita implies higher
719 income for households in the community, which through investment in education and
720 training fuels human innovation. Newer agricultural technologies are either invented or
721 adopted that increase crop yields and crop water demand per capita. Humans thus

722 enhance their capacity to irrigate more land per capita through innovation in all three
723 sections of the MRB. This in turn feeds back to higher agricultural production per capita,
724 fueling the positive feedback even further (Figure 8).

725

726 **3.3. Co-evolutionary dynamics**

727

728 The next question is, how did the turnaround happen? In spite of technological
729 innovation, the attractiveness of a settlement reduces with increasing area being irrigated
730 per capita. This influences the pattern of human migration both from outside and from
731 within different sections of the basin (Figure 9). Given that initially the upstream areas
732 were not inhabited, humans first exploited the potential of downstream areas before
733 migrating upstream. Increased migration over time eventually makes upstream areas less
734 attractive as well. The reduction in irrigation potential due to population growth also
735 reflects excessive exploitation of the basin as a whole resulting in, for example, lower
736 environmental flow. The latter, also described by Kandasamy *et al.* (2014) is one of the
737 direct reasons for environmental degradation. Subsequently, humans attempt to balance
738 their urge to maximize (technology mediated) agricultural income and minimize
739 environmental impacts of such activities. They do so by gradually migrating back to
740 downstream sections as they become more aware of environmental degradation. As a
741 result, the total population in the two upstream sections reduces while the population in
742 the most downstream section increases at an even higher rate. Consequently, the
743 attractiveness of the two upstream sections begins to pick up towards the end of 2010
744 while the attractiveness of the most downstream section does not recover (although it
745 stabilizes).

746

747 Figure 10 documents the modeled dynamics of environmental awareness in greater detail.
748 The migration from downstream section to the middle and upstream sections results in
749 water extraction in the two upstream sections that first increases until 1970s and then
750 declines. The water extraction in the most downstream section never declines due to the
751 ensuing migration pattern as demonstrated in Figure 9. As a result, outflow as a fraction
752 of inflow declines until the 1970s. This declining outflow influences the wetland storage,

753 causing it to severely fall below the critical threshold around 1970. This appears to be a
754 historical moment as it strongly sensitizes the population to environmental degradation
755 due to their production activities and begins to influence the decision of humans where to
756 migrate. Migration to upstream sections drops sharply. Instead they decide to migrate
757 back to the downstream section in an attempt to restore ecosystem services, in a manner
758 that balances nature's demand with their demand to maximize individual livelihood. This
759 feeds back into water extraction patterns, which are now strongly influenced by
760 environmental awareness. As individuals become more aware of their environment, more
761 migrate from upstream sections to the downstream sections in an attempt to restore
762 ecosystem services. By around 2010, the community is extremely sensitive to
763 environmental degradation. This was also concluded by Kandasamy *et al.* (2014), where
764 it was found that in 2007 the era of remediation and environmental restoration started.

765

766 These results, once they are organized in this way, point to the presence of *two competing*
767 *drivers* that are behind the pendulum swing, as shown in Figure 11a. The first one
768 involves a *positive feedback* loop related to the economic system: in this loop the main
769 resources of water, land and humans are combined to produce wealth (in the form of
770 agricultural crop). The wealth leads to advances in technology, which contributes to the
771 attractiveness of the area for expansion of agriculture, which attracts people, and the
772 cycle continues in this way. Liu *et al.* (2014) have explained this growth in terms of the
773 concept of the *human productive force*, illustrating it through the co-evolution of humans
774 and water in the Tarim Basin in Western China over the past 2000 years. The positive
775 feedback loop dominated the Murrumbidgee for the first 80 years.

776

777 The second driver, part of the *negative feedback* loop, reflects nature's reaction to the
778 exploitation of water and land. As more and more water is extracted from the river, and
779 more and more land is put to irrigated agriculture, both the riverine and terrestrial
780 environments begin to degrade, and after some time, they begin to impact the farmers
781 either directly (through reduced productivity of the land, cost of the environmental
782 degradation) and indirectly through increased environmental awareness (both locally and
783 globally, through environmental lobbies and through government intervention). In the

784 case of the Murrumbidgee, this negative feedback became exacerbated due to a persistent
785 severe drought that happened in the 2000s, forcing the hand of humans, as if nature's
786 restorative forces are demanding action from the community.

787

788 Consequently, we argue that the “pendulum swing” phenomenon is the result of the self-
789 organization of human-water system, which we claim is a result of balancing productive
790 forces that appeal to individual preferences for wealth and the restorative forces that aim
791 to preserve the natural environment. On the production side, the goal is to utilize water
792 for enterprise and profit and the community's economic well-being. On the restorative
793 side, the goal is to conserve water to satisfy “nature's demand” (e.g., biodiversity,
794 wetland ecology). If nature's demand is not met, extreme events such as droughts have
795 the ability to magnify the effects, then requiring human intervention.

796

797 Either way, the competition between water for humans and water for the environment is
798 still principally mediated by humans, acting for themselves and acting for the
799 environment. As indicated in Figure 11a, this is played out in the arenas of technology
800 change and environmental awareness, both facets of human enterprise and endeavor. The
801 pendulum swing resulting from the competition between the productive and the
802 restorative forces is consistent with the Taiji-Tire model outlined in the companion paper
803 by Liu *et al.* (2014), shown in Figure 11b, except that the particular features observed in
804 the Murrumbidgee are a reflection of the particular climatic and socio-economic and
805 politico-legal set up of the region.

806

807 **3.4. Model sensitivity and robustness**

808

809 We have performed a sensitivity analysis in order to assess alternate realities that the
810 socio-hydrologic model can generate and to identify sensitive parameters of the model.
811 Table 4 shows the 15 parameters of the model that are analyzed and their assumed
812 realistic ranges. Figure 12 shows the variation in one outcome, variable, namely
813 population, as a result of the variation of parameters one at a time. Each subfigure shows
814 the variation in the simulated population when one of the 15 parameters is varied within

815 the ranges prescribed in Table 4. It shows that not all parameters have a significant
816 influence on the model outcome. The most sensitive parameters are natural growth rate
817 ψ_n and maximum effective irrigated area $A_{I,max}$. It is not just the timing and the
818 magnitude of the population time series that is affected when parameters are varied. It
819 appears that the model is able to simulate 3 different modes of a socio-hydrologic system,
820 i.e. continued growth, growth followed by decline and no growth, under different
821 parametric perturbations. In most cases, the parameter selections lead to outcomes that
822 are relatively close to the best fit with reality, i.e. growth followed by a decline (Figure
823 12, thick line). However, perturbations with several parameters (e.g. high natural growth
824 rate ψ_n , low maximum effective irrigated area $A_{I,max}$ or high wetland leakage rate κ) lead
825 to time series that resemble continued growth. On the other hand, perturbation with some
826 other parameters (e.g. high maximum effective irrigated area $A_{I,max}$) lead to low
827 population change along with no development in the basin.

828

829 Figure 13 shows the sensitivity index of all system model outputs (Population, Irrigated
830 area, Storage, Wetland storage and Environmental awareness) to parametric variations. It
831 shows that Wetland storage W and Environmental awareness E are sensitive to only a few
832 parameters. This is to be expected since only a few of the model equations are connected
833 to W and E . The parameters that have the largest influence are the wetland leakage rate,
834 the wetland recharge threshold and the wetland danger threshold. Population N , irrigated
835 area A and Storage S are sensitive to more parameters. The population outcome is highly
836 sensitive to maximum effective irrigated and the natural population rate. These
837 parameters limit the growth potential of the population. When this is increased or
838 decreased, it significantly affects the irrigation potential, the growth and the speed of
839 saturation of the basin. For example, with a larger natural population growth rate, it is
840 likely that the carrying capacity of the system will be reached sooner. Finally, Figure 14
841 presents the three different modes of the various model outcomes that the model can
842 converge to under parametric perturbations. One of the modes is the optimal and most
843 realistic of the outcomes, which is similar to Figure 6. The other mode is one of apparent
844 unbounded growth. When the natural population growth is high, the population and the
845 irrigated area start to grow exponentially. As this development makes the society less

846 resilient to droughts, the storage is increased as well. However, the modeled time frame is
847 too short to investigate whether this will be followed by a dispersal of the system. The
848 third mode is that of no growth. This happens when the maximum effective irrigated area
849 is low and very little potential for agricultural development exists. The incentive for
850 people to migrate and further develop the MRB is then low. Figure 14 shows how the 3
851 modes of Population, Irrigated area and Storage are highly inter-connected. For all three,
852 the modes occur for similar parameter selections. The modes for wetland storage occur
853 when the wetland recharge threshold μ are high or low. A higher μ requires higher river
854 discharge before flooding occurs. The opposite happens when μ is low. The
855 environmental awareness is most strongly affected by the Wetland danger threshold W_d .

856

857 The sensitivity analysis shows that the model results are (in some cases strongly) affected
858 by parameter selection. This means that the modeling framework may provide equifinal
859 representations of a socio-hydrological reality. The value of field data in such cases
860 cannot be over-emphasized. Another interesting finding of the sensitivity analysis is the
861 discovery of 3 system modes that the model can replicate. This means that the framework
862 allows the flexibility to model diverse socio-hydrological realities. This highlights how
863 socio-hydrologic modeling might be used to simulate other coupled human-water
864 systems.

865

866 The development of the model presented in this paper, including the performed
867 sensitivity analysis, shows the potential of using socio-hydrologic modeling to explain
868 observed dynamics in human-water coupled systems. Our model is fundamentally sound
869 conceptually, and is in line with other socio-hydrologic models (e.g. Di Baldassarre,
870 2013b; Srinivasan, 2013; Elshafei *et al.* 2014; Lui et al., 2014).

871

872 **4. Conclusions**

873

874 This paper presents a socio-hydrologic modeling framework that has contributed new
875 insights into the drivers of the co-evolution in the Murrumbidgee River Basin. We use a
876 simple coupled model that attempted to mimic human-water system. A series of

877 simplifying but plausible assumptions were made (e.g., productivity, growth, migration,
878 water use, ecosystem health, environmental awareness) to configure the model to be able
879 to mimic human-water interactions at a generic level. Clearly such a parsimonious but
880 rudimentary model cannot match the *fine* reality in the Murrumbidgee, which is far more
881 complex. Nonetheless, the model has sufficient degrees of freedom and is mathematically
882 complex. It is possibly because of this that the model development and implementation
883 brought out *key* elements that control the dynamics and organizing principles that may
884 help frame human-water dynamics not only in the Murrumbidgee but in other similar
885 river basins. We therefore encourage the use of our presented approach to other river
886 basins to be able to eventually arrive at generic socio-hydrologic concepts.

887

888 The model had two external drivers one climate related and the other socio-economic.
889 The rest of the dynamics was endogenously generated in response to the external drivers
890 and the chosen internal model parameterizations. In spite of the details and the specificity
891 of the model to the Murrumbidgee, one aspect stood out. The model results demonstrated
892 that the emergent dynamics, i.e., pendulum swing, was a result of two internal forces. The
893 first one has to do with the economy, which Liu *et al.* (2014) called “human productive
894 force”, which contributed to the growth in exploitation of land, water and human
895 resources, with technology evolution playing an important role. The second one had to do
896 with the environment, which we call here a “environmental restorative force”. The
897 exploitation of land and water resources led to environmental degradation, which
898 eventually began to act as a constraint, through the intervention of humans responding to
899 the growth of community environmental awareness. It is the balance of these productive
900 (exploitative) and restorative (environmental) forces that has contributed to the emergent
901 dynamics, as shown in in Figure 11a. The model built along these lines, along with the
902 results of model simulations, conforms to the Taiji-Tire Model enunciated by Liu *et al.*
903 (2014) based on a historical socio-hydrologic analysis of the Tarim Basin in Western
904 China, and summarized in Figure 11b. It also has many similarities to a more generic
905 formulation proposed by Elshafei *et al.* (2014), wherein human “demand” for water
906 resources and human “sensitivity” for the environment trade off to determine the (enviro-
907 centric or anthro-centric) “behavioral response” of humans to water use practice.

908

909 The paper modeled two keys to the operation and success of a coupled socio-hydrological
910 system. The first was technology, which was the key to increased basin production
911 through exploitation of the land, water and human resources. The second was
912 environmental awareness, which restricted basin production in order to restore the
913 functioning of ecosystem services to certain extent. Both technology mediated demand
914 for water and human sensitivity for their environment were modeled in broad terms. Any
915 further advance of socio-hydrologic modeling would therefore require considerable
916 research to quantify them in acceptable ways for the purposes of modeling. The other two
917 key factors were external: climate (as reflected in the water inflows) and external socio-
918 economic conditions (as reflected in the world food prices). Therefore the specificity of
919 any socio-hydrologic system, and the differences between several different systems, may
920 be said to arise from the climatic and socio-economic externalities, and the socio-
921 economic and political milieus that govern the evolution of technology and
922 environmental awareness in each of these places.

923

924 The sensitivity study with the model showed that the model is sensitive to perturbations
925 of certain parameter values. This revealed interesting sensitivities of model outcomes to
926 selected parameters and shed light on how the socio-hydrologic model might be used and
927 improved. Our results showed that the mode of a socio-hydrological system functioning
928 (realistic, unbounded growth or no growth) strongly depends on the selection of certain
929 parameter values, e.g. the natural population growth rate, maximum effective irrigated
930 area, wetland recharge rate and the wetland recharge threshold. For the sake of simplicity
931 we considered these values as static, but one can argue that these might also vary in time
932 and space. These parameters were the main factors that restricted or boosted system
933 development. It would therefore be interesting to confirm these findings with other socio-
934 hydrologic modeling studies. The sensitivity study also revealed the insensitivity of
935 model outcomes to other parameters and hence revealed the possibility of equifinal
936 models that are equally capable of representing observed socio-hydrological patterns.
937 Thus the sensitivity analysis revealed some important implications for robust socio-
938 hydrological model identification and parameter selection.

939

940 We used a simplified Sobol' method for our sensitivity analysis. It did not take into
941 account the sensitivity of model outcomes to perturbations of all possible parameter
942 combinations. A detailed sensitivity analysis may be required to better understand the
943 system dynamics if it is sensitive to perturbations of parameter combinations as well. We
944 would also like to emphasize on the need of studying the stability of socio-hydrologic
945 models. As these models consist of coupled nonlinear differential equations, further
946 studying of the stability and sensitivity might shed additional light on how socio-
947 hydrologic models might be applied to different area. This is left to future research.
948 Nonetheless our sensitivity analysis revealed the capacity of the model to represent 3
949 dominant modes of behavior under the same socio-hydro-climatic forcing.

950

951 A natural extension of the analysis would be to explore system dynamics under different
952 socio-hydro-climatic forcings, and initial and boundary conditions. However, the
953 parameters would be kept fixed in this case, for example, fixed at the parameter values
954 found reasonable to represent the socio-hydrological dynamics of the MRB. Such an
955 analysis would explore various co-evolutionary trajectories initiated by different
956 conditions under different forcings in the co-evolutionary space of population, growth,
957 migration, water use, ecosystem health and environmental awareness. Depending on
958 socio-hydrological characteristics, different trajectories might be identified by parts of the
959 co-evolutionary space that these trajectories take the system to in the long run. Such an
960 extended analysis might even reveal socio-hydrological characteristics that result in
961 chaotic system dynamics, where co-evolutionary trajectories that are initially close to
962 each other lead to diverse socio-hydrological outcomes in the long-run. A richer set of
963 dominant modes might then be revealed, each depending on the type of forcings, initial
964 and boundary conditions and socio-hydrological characteristics. This is exciting because
965 the presented socio-hydrologic modeling framework can then be used to replicate and
966 understand alternate socio-hydrological realities. However, this is left for future research.

967

968 In conclusion, this paper has advanced the state of the art of socio-hydrological modeling
969 by making a case for a more general modeling framework that may be transferrable to

970 other coupled human water systems. It used constitutive relations that may also be
971 explicitly derived based on individual decision making (see for example Lyon and Pande,
972 2004). For example, it modeled human migration patterns based on an individual's
973 tendency to maximize economic gains. It models technological innovation and adoption
974 as a function of aggregate production at basin scale based on the assumption that
975 technology and wealth are intrinsic to system dynamics (see for example Romer, 1990;
976 Eicher, 1996 on endogenous technological change). The model also incorporated
977 changing values and norms of a society by introducing environmental awareness as
978 another co-evolutionary variable of system dynamics. As a consequence, the model saw
979 the coevolution of human-water system as a competition between 'productive' and
980 'restorative' forces that emerge from the ensuing dynamics.

981

982 Finally, the modeling framework presented here is the first spatially explicit socio-
983 hydrological model that has the capacity to replicate observed patterns of population
984 migration and growth, technological adoption and aggregate production at basin scale.
985 We thus conjecture that the models of this type are capable of mimicking dominant
986 controls on the trajectory of co-evolution of *diverse* coupled human-water systems since
987 they can incorporate such layers of complexity. However, the model presented in this
988 paper focused exclusively on surface water utilization for agriculture and food production.
989 The situation may be different in groundwater dependent ecosystems or in regions where
990 rain-fed agriculture dominates, which may present different contexts within which to
991 develop socio-hydrologic models. Application of models such as these, suitably adapted
992 to these different contexts, may help bring out fundamental differences in the emergent
993 dynamics that may result. In this paper we show how socio-hydrology modeling can be
994 used as a framework to study the co-evolutionary dynamics of complex coupled human-
995 water systems. We hypothesize that this approach, when applied to other systems, can
996 contribute to the development of generic models that can be applied more universally.
997 This is the long-term goal of our research.

998

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1014

1015 **5. References**

- 1016 ABC, Australian Broadcasting Commission: Angry crowd burns copy of Murray-Darling
1017 report. [http://www.abc.net.au/news/2010-10-13/angry-crowd-burns-copy-of-](http://www.abc.net.au/news/2010-10-13/angry-crowd-burns-copy-of-murray-darling-report/2296638)
1018 [murray-darling-report/2296638](http://www.abc.net.au/news/2010-10-13/angry-crowd-burns-copy-of-murray-darling-report/2296638) , (last access: Feb 2014), 2014.
- 1019 ABS: Australian Yearbook, Australian Bureau of Statistics, available at:
1020 <http://www.abs.gov.au/AUSSTATS/abs@.nsf> (last access: May 2013), 2013a
- 1021 ABS: Australian Bureau of Statistics, available at: <http://www.abs.gov.au/> (last access:
1022 May 2013), 2013b.
- 1023 Arkesteijn, L. and S. Pande: On hydrological model complexity, its geometrical
1024 interpretations and prediction uncertainty, *Water Resour. Res.*, 49, 7048–7063,
1025 doi:10.1002/wrcr.20529, 2013.
- 1026 Bois, B., Pieri, C. Van Leeuwen, L. Wald, F. Huard, J.-P. Gaudillere and E. Saur: Using
1027 remotely sensed solar radiation data for reference evapotranspiration estimation at a
1028 daily time step, *Agric.Forest Meteorol.*, 148(4), 619-630, 2008.
- 1029 Chan, Karen, A. Saltelli, and S. Tarantola: Sensitivity analysis of model output: variance-
1030 based methods make the difference, *Proceedings of the 29th conference on Winter*
1031 *simulation*, IEEE Computer Society, 1997.
- 1032 Chen, H. and M. Li: Environmental tax policy, habit formation and nonlinear dynamics,
1033 *Nonlinear Anal.-Real.*, 12, 246–253, 2011.
- 1034 Crutzen, P. J. and E. F. Stoemer: The Anthropocene. *Global Change Newsletter*, 41, 17-
1035 18, 2000.

- 1036 Cuypers, J. G. M. and O. Rademaker: An analysis of Forrester's World Dynamics Model,
1037 *Automatica*, 10, 195–201, 1974.
- 1038 Davies, E. G. R., and S. P. Simonovic: Global water resources modeling with an
1039 integrated model of the social-economic-environmental system. *Adv. in Water*
1040 *Resour.*, 34(6), 684-700, 2011.
- 1041 Di Baldassarre, G., M. Kooy, J. S. Kemerink, and L. Brandimarte: Towards
1042 understanding the dynamic behaviour of floodplains as human-water systems.
1043 *Hydrol. Earth Syst. Sci.*, 17, 3235-3244, 2013a.
- 1044 Di Baldassarre, G., A. Viglione, G. Carr, L. Kuil, J. L. Salinas, and G. Blöschl: Socio-
1045 hydrology: conceptualising human-flood interactions. *Hydrol. Earth Syst.*
1046 *Sci.*, 17, 3295-3303, 2013b.
- 1047 DWR: Water distribution operations in irrigation areas and districts of NSW, New South
1048 Wales Department of Water Resources, Gutteridge, Haskins & Davey, Sydney,
1049 1989.
- 1050 Eicher, T. S.: Interaction between endogenous human capital and technological change,
1051 *Rev. Econ. Stud.*, 63, 127–144, 1996.
- 1052 Elshafei, Y., M. Sivapalan, M. Tonts, and M.R. Hipsey: A prototype framework for
1053 models of socio-hydrology: identification of key feedback loops and
1054 parameterisation approach, *Hydrol. Earth Syst. Sci.*, 18, 2141-2166,
1055 doi:10.5194/hess-18-2141-2014, 2014.
- 1056 Falkenmark, M. and M. Lannerstad: Consumptive water use to feed humanity - curing a
1057 blind spot. *Hydrol. and Earth Sys. Sci.*, 9(1-2), 15-28, 2005.
- 1058 Fedotov S., D. Moss and D. Campos: Stochastic model for population migration and the
1059 growth of human settlements during the Neolithic transition. *Phys. Rev. E*, 78,
1060 026107, 2008.
- 1061 Fenicia, F., H. H. G. Savenije, P. Matgen and L. Pfister: Understanding catchment
1062 behavior through stepwise model concept improvement. *Water Resour. Res.*, 44,
1063 W01402, doi: 10.1029/2006WR005563., 2008.
- 1064 Forrester, J. W.: *World Dynamics*, Wright-Allen, Cambridge, Massachusetts, 1971.
- 1065 Gleick, P. H. and M. Palaniappan: Peak water limits to freshwater withdrawal and use.
1066 *Proc. Nat. Acad. of Sci.*, 107(25), 11155-11162, 2010.
- 1067 Gorman, E.: Growing rice on the Murrumbidgee River: cultures, politics, and practices of
1068 food production and water use, 1900 to 2012, *J. Austral. Studies*, 37 (1) 96-115,
1069 2013.
- 1070 Grafton, R. Q., J. Pittock, R. Davis, J. Williams, G. Fu, M. Warburton, B. Udall, R.
1071 McKenzie, X. Yu, N. Che, D. Connell, Q. Jiang, T. Kompas, A. Lynch, R. Norris,
1072 H. Possingham and J. Quiggin: Global insights into water resources, climate change
1073 and governance. *Nature Climate Change*, 3, 1-7, doi: 10.1038/ NCLIMATE1746,
1074 2012.
- 1075 Greif, A. and D. A. Laitin: A theory of endogenous institutional change, *Amer. Polit. Sci.*
1076 *Rev.*, 633-652. doi:10.1017/S0003055404041395, 2004.

- 1077 Hafi, A., S. Beare, A. Heaney, and S. Page: Water Options for Environmental Flows,
 1078 ABARE eReport 05.12, prepared for the Natural Resource Management Division,
 1079 Australian Government Department of Agriculture, Fisheries and Forestry,
 1080 Canberra, November, 2005.
- 1081 Hayami, Y. and V. W. Ruttan: Factor prices and technical change in agricultural
 1082 development: The United States and Japan, 1880-1960. *J. Polit. Econ.* , 78(5), 1115-
 1083 1141, 1970.
- 1084 Jakeman, A. J. and R. A. Letcher: Integrated assessment and modelling: features,
 1085 principles and examples for catchment management. *Env. Model. & Softw.*, 18,
 1086 491–501, 2003.
- 1087 Kallis, G.: When is it coevolution? *Ecol. Econ.*, 62, 1–6, 2007.
- 1088 Kallis, G.: Coevolution in water resource development: The vicious cycle of water supply
 1089 and demand in Athens, Greece. *Ecol. Econ.*, 69, 796-809, 2010.
- 1090 Kandasamy, J., Sountharajah, D., Sivabalan, P., Chanan, A., Vigneswaran, S., and
 1091 Sivapalan, M.: Socio-hydrologic drivers of the pendulum swing between
 1092 agricultural development and environmental health: a case study from
 1093 Murrumbidgee River basin, Australia, *Hydrol. Earth Syst. Sci.*, 18, 1027-1041,
 1094 doi:10.5194/hess-18-1027-2014, 2014.
- 1095 Kelly, R. A. A. J., Jakeman, O. Barreteau, M. E. Borsuk, S. ElSawah, S. H. Hamilton, H.
 1096 J. Henriksen, S. Kuikka, H. R. Maier, A. E. Rizzoli, H. van Delden and A. A.
 1097 Voinov: Selecting among five common modelling approaches for integrated
 1098 environmental assessment and management. *Env. Model. & Softw.*, 47 , 159-181,
 1099 2013.
- 1100 Kumar, P.: Typology of hydrologic predictability, *Water Resour. Res.*, 47, W00H05,
 1101 doi:10.1029/2010WR009769, 2011.
- 1102 Liu, Y., Tian, F., Hu, H., and Sivapalan, M.: Socio-hydrologic perspectives of the co-
 1103 evolution of humans and water in the Tarim River basin, Western China: the Taiji-
 1104 Tire model, *Hydrol. Earth Syst. Sci.*, 18, 1289-1303, doi:10.5194/hess-18-1289-
 1105 2014, 2014.
- 1106 Lyon, K., and S. Pande: The costate variable in a stochastic renewable resource model.
 1107 *Nat. Resour. Model.*, 19(1), 45-66, 2006.
- 1108 Maneta, M.P., M. O. Torres, W. W. Wallender, S. Vosti, R. Howitt, L. Rodrigues, L. H.
 1109 Bassoi, and S. Panday: A spatially distributed hydroeconomic model to assess the
 1110 effects of drought on land use, farm profits, and agricultural employment. *Water*
 1111 *Resour. Res.*, 45, doi: 10.1029/2008WR007534, 2009.
- 1112 Ostrom, E.: A general framework for analyzing sustainability of social-ecological
 1113 systems. *Science*, 325, 419-422, 2009.
- 1114 Pande, S.: Quantile hydrologic model selection and model structure deficiency
 1115 assessment 1: Theory, *Water Resour. Res.*, 49, 5631–5657, doi:10.1002/
 1116 wrcr.20411, 2013.

- 1117 Pande, S., B. van den Boom, H. H. G. Savenije, and A. K. Gosain (2011). Water
 1118 valuation at basin scale with application to western India, *Ecol. Econ.*, 70, 2416–
 1119 2428, doi:10.1016/j.ecolecon.2011.07.025.
- 1120 Pande, S., L. A. Bastidas, S. Bhulai and M. McKee: Parameter dependent convergence
 1121 bounds and complexity measure for a class of conceptual hydrological models, *J.*
 1122 *Hydroinform.*, 14(2), 443–463, 2012.
- 1123 Pande, S. and Ertsen, M.: Endogenous change: on cooperation and water availability in
 1124 two ancient societies, *Hydrol. Earth Syst. Sci.*, 18, 1745-1760, doi:10.5194/hess-18-
 1125 1745-2014, 2014.
- 1126 Pande, S., M. Ertsen and M. Sivapalan: Endogenous technological and population change
 1127 under increasing water scarcity. *Hydrol. Earth Syst. Sci.*, 18, 3239–3258,
 1128 doi:10.5194/hess-18-3239-2014, 2014.
- 1129 Pulido-Velazquez, M., J. Andreu and A. Sahuquillo: Economic optimization of
 1130 conjunctive of surface and groundwater at the basin scale. *J. Water Resour. Plan.*
 1131 *Manage.*, 132(6), 454-467, 2006.
- 1132 Röckström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, III, E. Lambin, T. M.
 1133 Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T.
 1134 Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U.
 1135 Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B.
 1136 Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley.: Planetary
 1137 boundaries: Exploring the safe operating space for humanity. *Ecology and Society*,
 1138 14(2): 32, available at: <http://www.ecologyandsociety.org/vol14/iss2/art32/>, 2009.
- 1139 Roderick, M. L.: Introduction to special section on water resources in the Murray-Darling
 1140 Basin: Past, present, and future. *Water Resour. Res.*, 47, W00G01, doi:
 1141 10.1029/2011WR010991, 2011.
- 1142 Romer, P.: Endogenous technological change, Part 2: The problem of development: a
 1143 conference of the Institute for the Study of Free Enterprise Systems (October 1990),
 1144 *J. Polit. Econ.*, 98, S71–S102, 1990.
- 1145 Rosero, E., Z. L. Yang, T. Wagener, L. E. Gulden, S. Yatheendradas and G. Y. Niu:
 1146 Quantifying parameter sensitivity, interaction, and transferability in hydrologically
 1147 enhanced versions of the Noah land surface model over transition zones during the
 1148 warm season. *J. Geophys. Res.: Atmospheres* (1984–2012), 115(D3), 2010.
- 1149 Saltelli, A.: Making best use of model evaluations to compute sensitivity
 1150 indices. *Computer Physics Communications*, 145(2), 280-297, 2002.
- 1151 Saltelli, A., M. Ratto, S. Tarantola, and F. Campolongo: Sensitivity analysis practices:
 1152 Strategies for model-based inference. *Reliability Engineering & System*
 1153 *Safety*, 91(10), 1109-1125, 2006.
- 1154 Savenije, H.H.G.: Equifinality, a blessing in disguise?, *Hydrol. Process.*, 15(14), 2835-
 1155 2838, 2001.
- 1156 Savenije, H.H.G., A.Y. Hoekstra and P. van der Zaag: Evolving water science in the
 1157 Anthropocene. *Hydrol. Earth Syst. Sci.*, 18, 319-332, 2014.

- 1158 Sivapalan, M.: Predictions under Change: Water, Earth and Biota in the Anthropocene.
 1159 White Paper produced for NSF, available at: [http://cwaces.geog.uiuc.edu/](http://cwaces.geog.uiuc.edu/synthesis/reports/index.html)
 1160 [synthesis/reports/index.html](http://cwaces.geog.uiuc.edu/synthesis/reports/index.html), 2011
- 1161 Sivapalan, M., L. Zhang, R. Vertessy, R. and G. Blöschl: Downward approach to
 1162 hydrological prediction. *Hydrol. Process.*, 17: 2099. doi: 10.1002/hyp.1426, 2003.
- 1163 Sivapalan, M., H. H. G. Savenije and G. Blöschl: Socio-hydrology: A new science of
 1164 people and water. *Hydrol. Process.*, 26, 1270–1276, doi: 10.1002/hyp.8426, 2012.
- 1165 Sivapalan, M., M. Konar, V. Srinivasan, A. Chhatre, A. Wutich, C. A. Scott, J. L.
 1166 Wescoat and I. Rodriguez-Iturbe: Socio-hydrology: Use-inspired water
 1167 sustainability science for the Anthropocene. *Earth's Future*, 2, 225-230,
 1168 doi:10.1002/2013EF000164, 2014.
- 1169 Srinivasan, V.: Coevolution of water security in a developing city. *Hydrol. Earth Syst.*
 1170 *Sci. Discuss.*, 10, 13265-13291, 2013.
- 1171 Sobol', I. M.: Sensitivity analysis for nonlinear mathematical models, *Math. Modell.*
 1172 *Comput. Exp.*, 1, 407 – 414, 1993.
- 1173 Sobol', I. M.: Global sensitivity indices for nonlinear mathematical models and their
 1174 Monte Carlo estimates, *Mathematics and Computers in Simulation*, 55, (1-3), 271-
 1175 280, 2001.
- 1176 Song, X., B. A. Bryan, K. I. Paul and G. Zhao: Variance-based sensitivity analysis of a
 1177 forest growth model, *Ecol. Modell.*, 247, 135-143, 2012.
- 1178 Tang, Y., P. Reed, T. Wagener, and K. Van Werkhoven: Comparing sensitivity analysis
 1179 methods to advance lumped watershed model identification and evaluation, *Hydrol.*
 1180 *Earth Syst. Sci.* , 11(2), 793-817, 2007.
- 1181 Thompson, S. E., M. Sivapalan, C. J. Harman, V. Srinivasan, M. R. Hipsey, P. Reed,
 1182 A. Montanari, and G. Blöschl: Developing predictive insight into changing water
 1183 systems: Use-inspired hydrologic science for the Anthropocene. *Hydrol. Earth Syst.*
 1184 *Sci.*, 17, 5013–5039, doi:10.5194/hess-17-5013-2013, 2013.
- 1185 Turner, G. M.: A Comparison of the Limits to Growth with Thirty Years of Reality,
 1186 Socio-Economics and the Environment, in: Discussion (SEED) Working Paper
 1187 Series 2008-09,CSIRO Sustainable Ecosystems, Canberra, Australia, 2008.
- 1188 UNEP, United Nations Environmental Program: State-and-Trends of the Environment:
 1189 1987–2007, in Fourth Global Environment Outlook: Environment for Development
 1190 Assessment Report, Progress Press, Malta, ISBN 978-92-807-2872-9, 2007.
- 1191 Vitousek, P. M., J. D. Aber, R. W. Howarth, G. E. Likens, P. A. Matson, D. W.
 1192 Schindler, W. H. Schlesinger, W. H. and D. G. Tilman: Human alteration of the
 1193 global nitrogen cycle: Sources and consequences. *Ecol. Appl.*, 7(3): 737-750, 1997.
- 1194 Vörösmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers: Global water resources:
 1195 Vulnerability from climate change and population growth, *Science*, 289, 284–288,
 1196 doi:10.1126/science.289.5477.284, 2000.
- 1197 Vörösmarty, C. J., P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green,
 1198 S. Glidden, S. E. Bunn, C. A. Sullivan, C. Reidy Liermann and P. M. Davies:
 1199 Global threats to human water security and river biodiversity, *Nature*, 467, 555-561,
 1200 2010.
- 1201 Wagener, T., M. Sivapalan, P. A. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P.
 1202 Kumar, P. S. C. Rao, N. B. Basu, and J. S. Wilson: The future of hydrology: An

1203 evolving science for a changing world, *Water Resour. Res.*, 46, W05301,
1204 doi:10.1029/2009WR008906, 2010.

1205 World Bank: Global Economic Monitor (GEM) Commodities:
1206 <http://database.worldbank.org>, (last access: July 2013), 2013.

1207 Zalasiewicz, J., M. Williams, W. Steffen and P. Crutzen: The new world of the
1208 Anthropocene. *Env. Sci. Tech.*, 44(7), 2228-2231, 2010.

1209 Zehe, E. and M. Sivapalan: Threshold behavior in hydrological systems as (human) geo-
1210 ecosystems: manifestations, controls and implications. *Hydrol. Earth Syst. Sci.*,
1211 13(7), 1273-1297, 2009.

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1254 Tire model representation of the dynamics operating within the Murrumbidgee River
1255 Basin (Taiji-Tire model is concept borrowed from Liu *et al.* 2014).

1256 **Figure 12:** Modeled time series of total population for different values of the tested
1257 parameters. All subplots correspond to one tested parameter, the separate lines represent
1258 model outcome for a given parameter.

1259 **Figure 13:** Sensitivity index S_i for all parameters, indicating the sensitivity of population
1260 P , irrigated area A , storage S , wetland storage W and environmental awareness E to the
1261 parameter selection.

1262 **Figure 14:** Three model modes for population, irrigated area, water storage, wetland
1263 storage and environmental awareness: realistic (solid), increasing (dashed) and declining
1264 (dash-dot).

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1269 **Table 1:** Model initial condition setup

Model initial condition (t=0)				
Variables	Unit	Downstream settlement	Middle Stream settlement	Upstream settlement
S	[m ³]	0	0	0
N	[capita]	5000	0	0
a_i	[km ² /capita]	0.03	0	0
E	[-]	0	0	0
W	[m ³]	5000	-	-

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1271 **Table 2.** Definitions of the parameters of the coupled human-water system model and the
 1272 chosen magnitudes of parameter values.

Variables	Unit	Description	Eq.	Domain	Value
c	[day ⁻¹]	Environmental awareness memory correction coefficient	(18)	Population	0.5
β	[-]	Runoff coefficient	(4)	Hydrology	0,01
A^c	[km ²]	Physical catchment area	(4)	Hydrology	20.000
γ_s	[m ³ day ⁻¹ km ⁻²]	Crop water demand	(4)	Irrigation	10.000
T	[-]	Technology	(8)	Internal	-
γ_r	[ton km ⁻²]	Crop yield per unit area	(5)	Internal	-
δ	[day]	Drought threshold	-	-	50
μ	[m ³ day ⁻¹]	Wetland recharge threshold	(5)	Ecology	10 ⁸
W_d	[m ³]	Wetland danger threshold	-	Environmental awareness	300
n	[day]	Days of environmental degradation	(6)	Internal	-
κ	[day ⁻¹]	Wetland leakage rate	(5)	Ecology	0,001
ψ_n	[day ⁻¹]	Natural population growth rate	(2)	Population	0,006
ψ_m	[day ⁻¹]	External migration rate	(2)	Population	-
ψ_r	[day ⁻¹]	Internal relocation rate	(2)	Population	-
A_{max}	[km ²]	Effective irrigated area	-	-	2.000
ζ	[-]	Environmental awareness dissipation rate	-	-	0.005
φ_i	[km ² capita ⁻¹]	Attractiveness of settlement i	(3)	Population	-
ε	[day ⁻¹]	Rate of change of environmental awareness	(7)	Environmental awareness	-
r	[cap km ⁻² day ⁻¹]	Attractiveness coefficient	(4)	Population	1
Q	[m ³ day ⁻¹]	Discharge	(5)	Hydrology	-
f_p	[\$ ton ⁻¹]	Product of crop price	(7)	-	-

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Table 3. Calibrated constitutive relations needed to completed model specification

Domain	Calibration constitutive relationship
Technology	$T = [0.1 + 0.9e^{-0.07P_{GB}}]^{-1}$
Irrigation	$\alpha_S(S) = 0.42 \times 10^{-8}S$
Irrigation	$\alpha_T(T) = 0.06 - 0.0732e^{-0.2T}$
Irrigation	$\alpha_E(E) = 0.03[e^{-E} - 1]$
Irrigation	$\gamma_S(T) = 8000e^{-0.4T} + 4500$
Irrigation	$\gamma_r(T) = [0.75 + 0.833e^{-0.75T-0.75}]^{-1}$
Population	$\psi_m(\phi_i) = 0.145 - 0.4205 [1 + \exp(6.35 \psi_i + 0.635)]^{-1}$
Environmental Awareness	$\varepsilon(n) = \begin{cases} 0.0019\{e^{0.0085n} - 1\}; & n > 0 \\ -\zeta; & n = 0 \end{cases}$

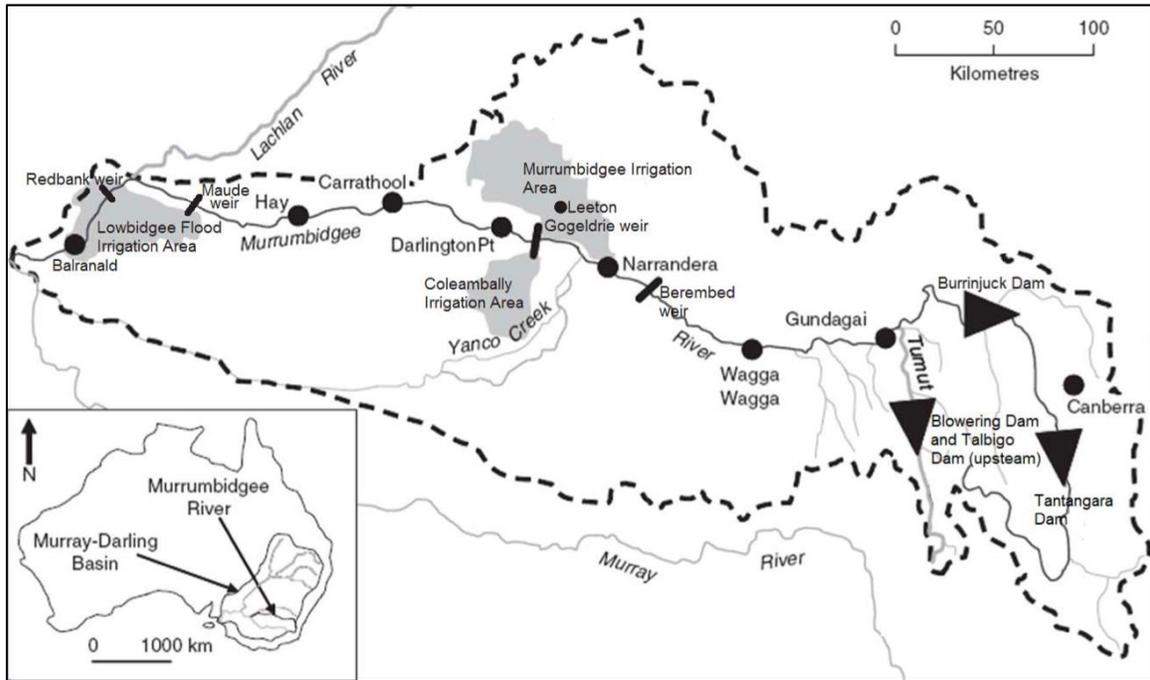
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1278 **Table 4:** Parameters tested during the sensitivity analysis, including the minimum and
 1279 maximum values of the tested parameter range.
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Variables	Description	Value	Min	Max
c	Environmental awareness memory correction coefficient	0.5	0	1
β	Runoff coefficient	0.01	0	1
A^c	Physical catchment area	20000	0	40000
δ_1	Drought threshold	50	1	500
δ_2	Drought threshold	50	1	500
δ_3	Drought threshold	50	1	500
μ	Wetland recharge treshold	10^8	10^6	10^{10}
W_d	Wetland danger treshold	0.03	0	0.1
κ	Wetland leakage rate	0.001	0.001	0.05
ψ_n	Natural population growth rate	0.006	1	10000
$A_{1,max}$	Max. effective irrigated area	2000	1	10000
$A_{2,max}$	Max. effective irrigated area	2000	1	10000
$A_{3,max}$	Max. effective irrigated area	2000	1	0.2
ζ	Environmental awareness dissipation rate	0.005	0	1
r	Attractiveness coefficient	1	0.001	0.2

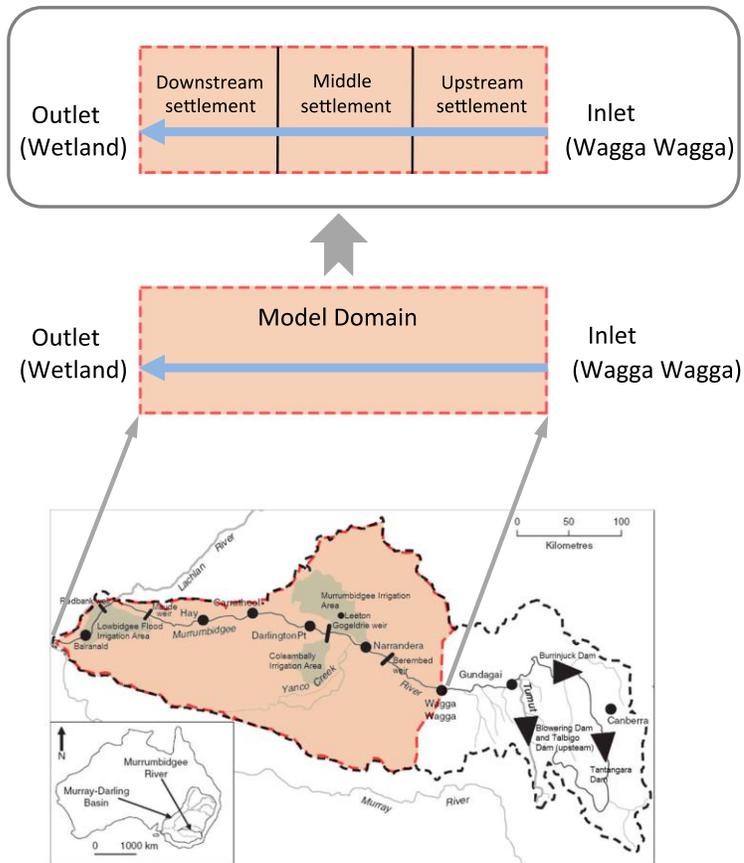
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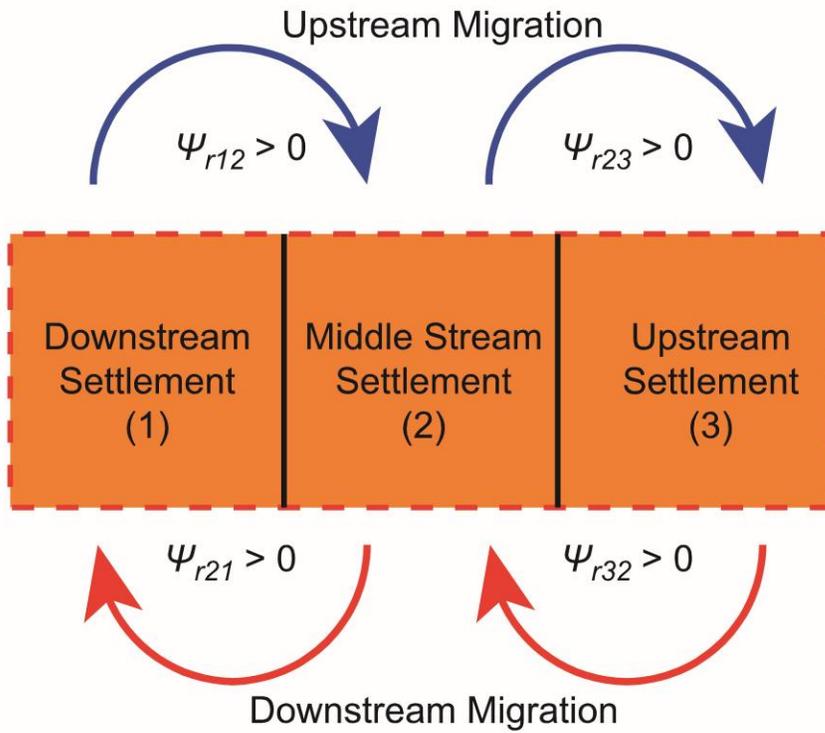
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1289 **Figure 1:** Location of the Murrumbidgee Basin within the Murray-Darling River Basin
1290 (Kandasamy *et al.*, 2014)



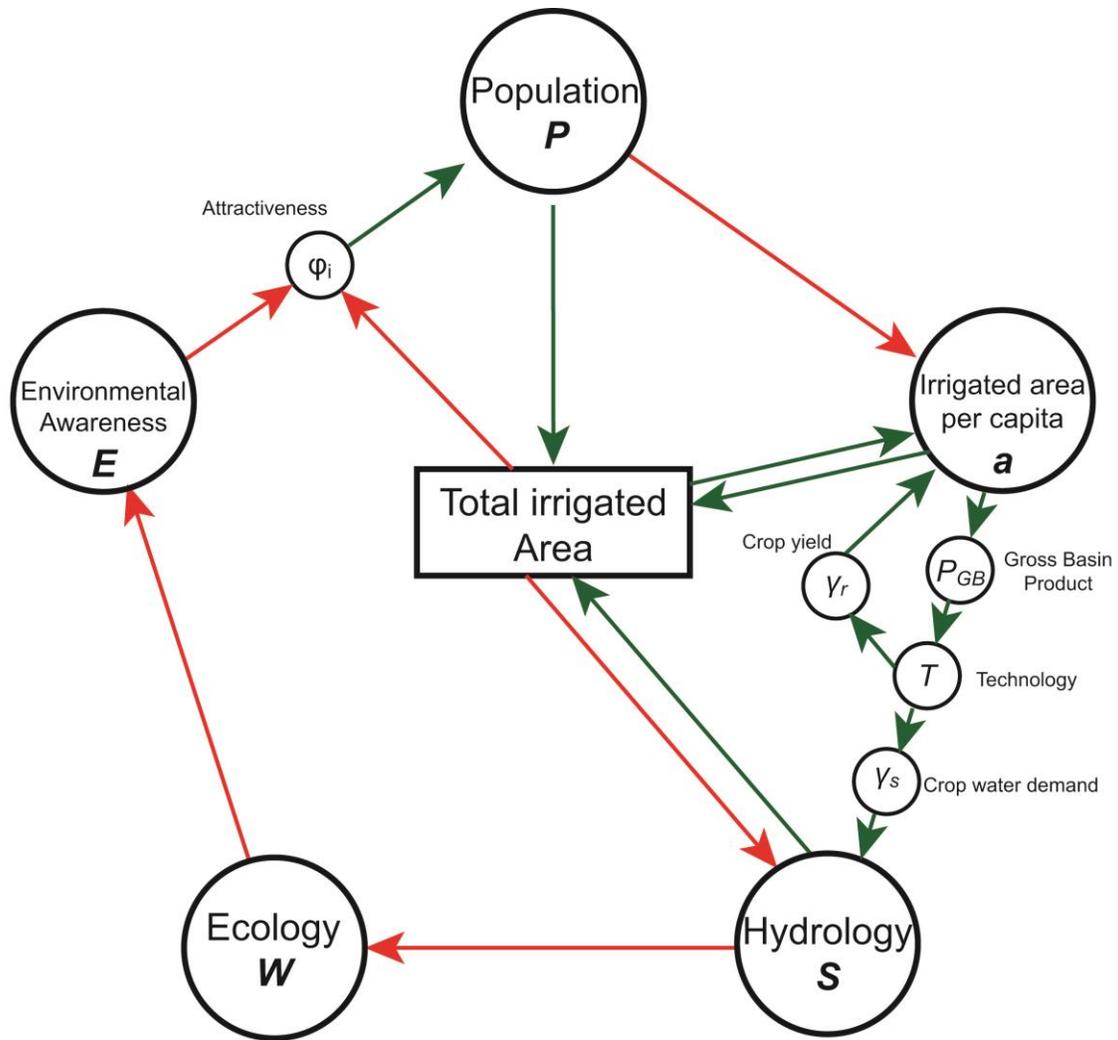
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Figure 2: Model domain and the discretization into three settlements (downstream, middle stream and upstream).



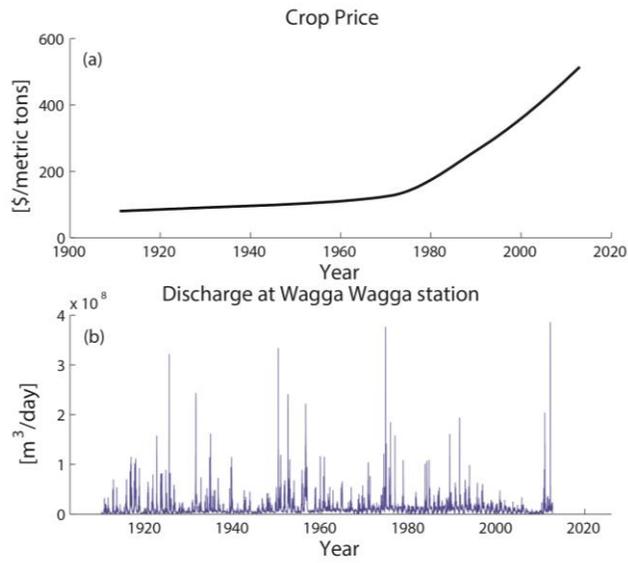
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1296 **Figure 3:** Schematic diagram describing the framework adopted in the model for internal
 1297 relocation of humans between the three settlements (See Equations 2-4).



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1299 **Figure 4:** Conceptual framework coupling the five subsystems (Hydrology, Population,
 1300 Irrigation, Ecology and Environmental Awareness) and the cross-system feedbacks.
 1301 Green: positive feedback; Red: negative feedback.



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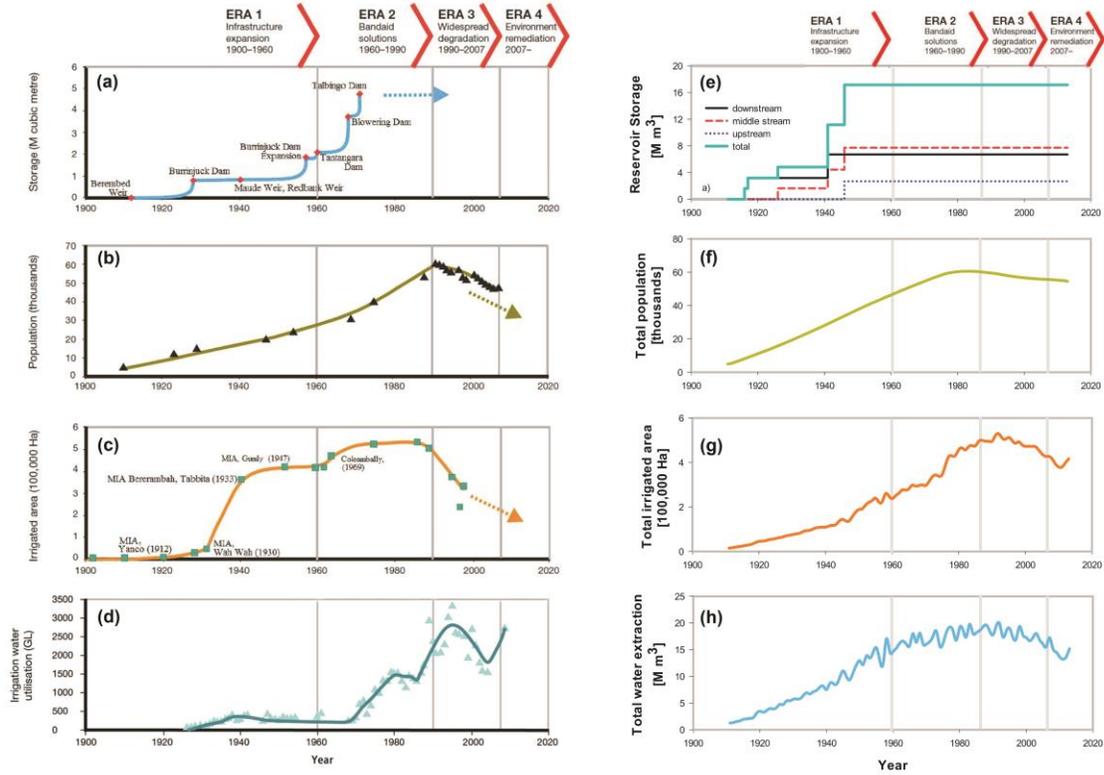
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Figure 5: External drivers of the socio-hydrologic system (a) world food (rice) prices

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(taken from the World Bank), and (b) measured discharge at Wagga Wagga.

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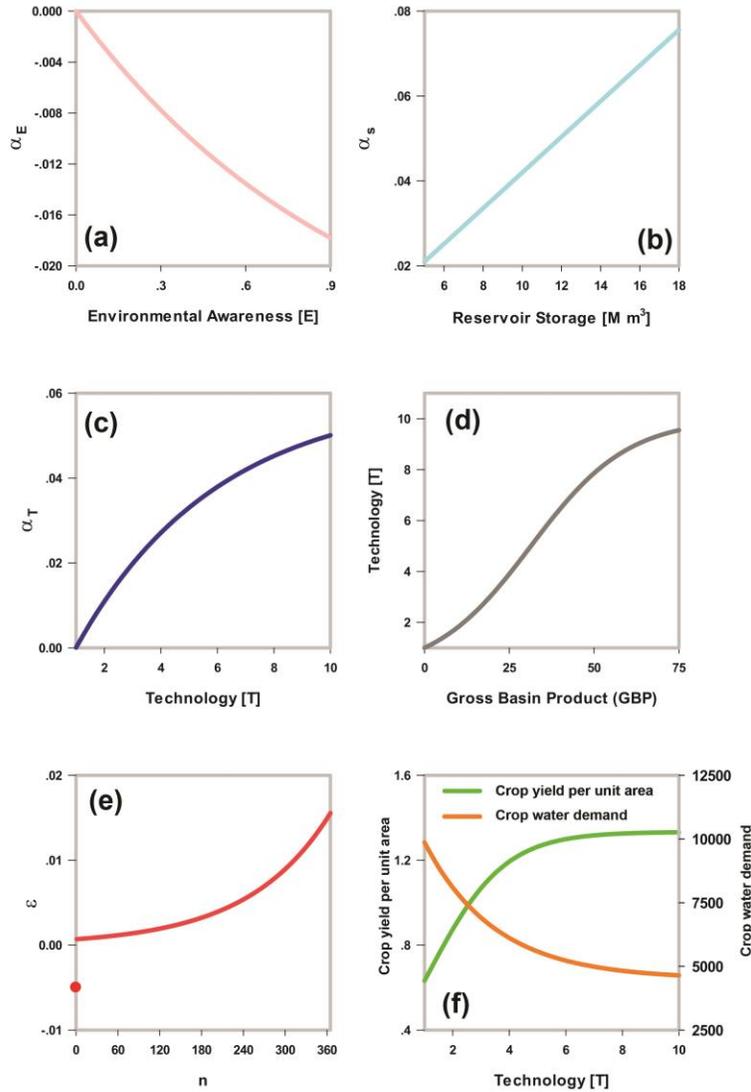


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1307 **Figure 6:** Observed (based on Kandasamy *et al.*, 2014) and modeled Pendulum Swing in
 1308 the Murrumbidgee Basin. Observed times series of (a) reservoir storage, (b)
 1309 total population within basin, (c) total irrigated area, and (d) irrigation water use. Modeled
 1310 time series of (e) expansion of reservoir storage capacity, (f) total human population, (g)
 1311 total irrigated area, and (h) irrigated water extraction, over the study period.

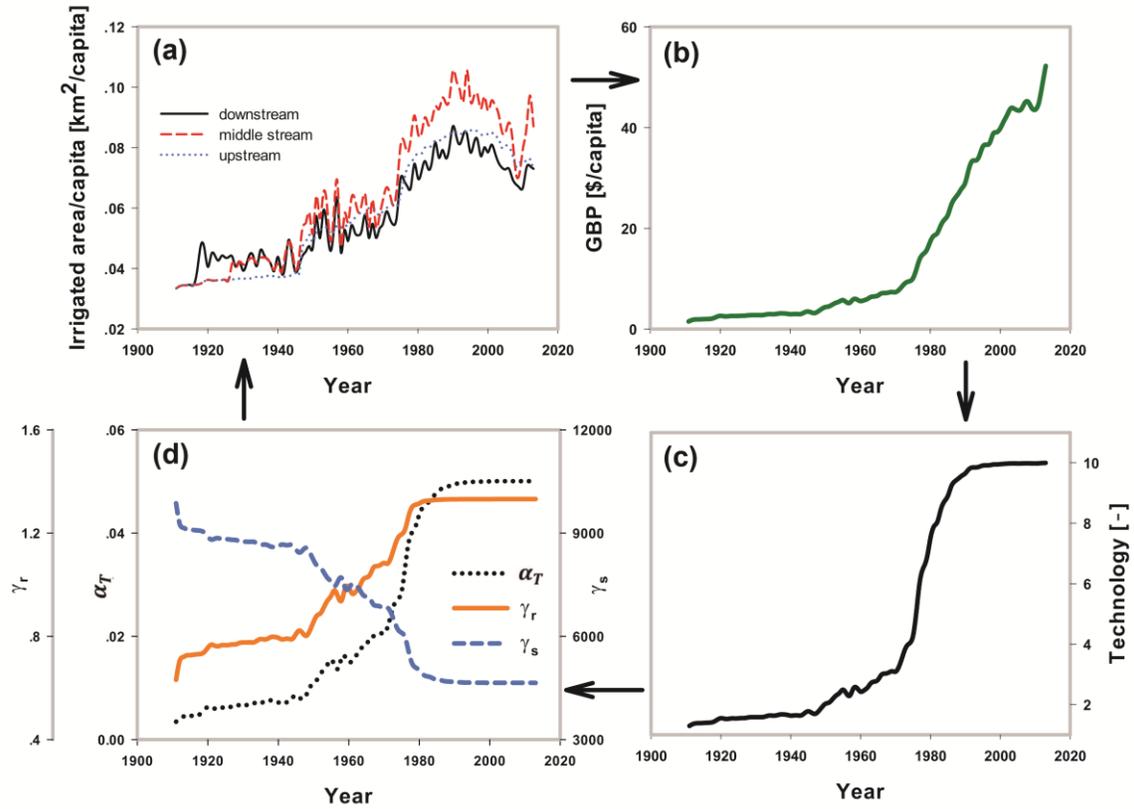
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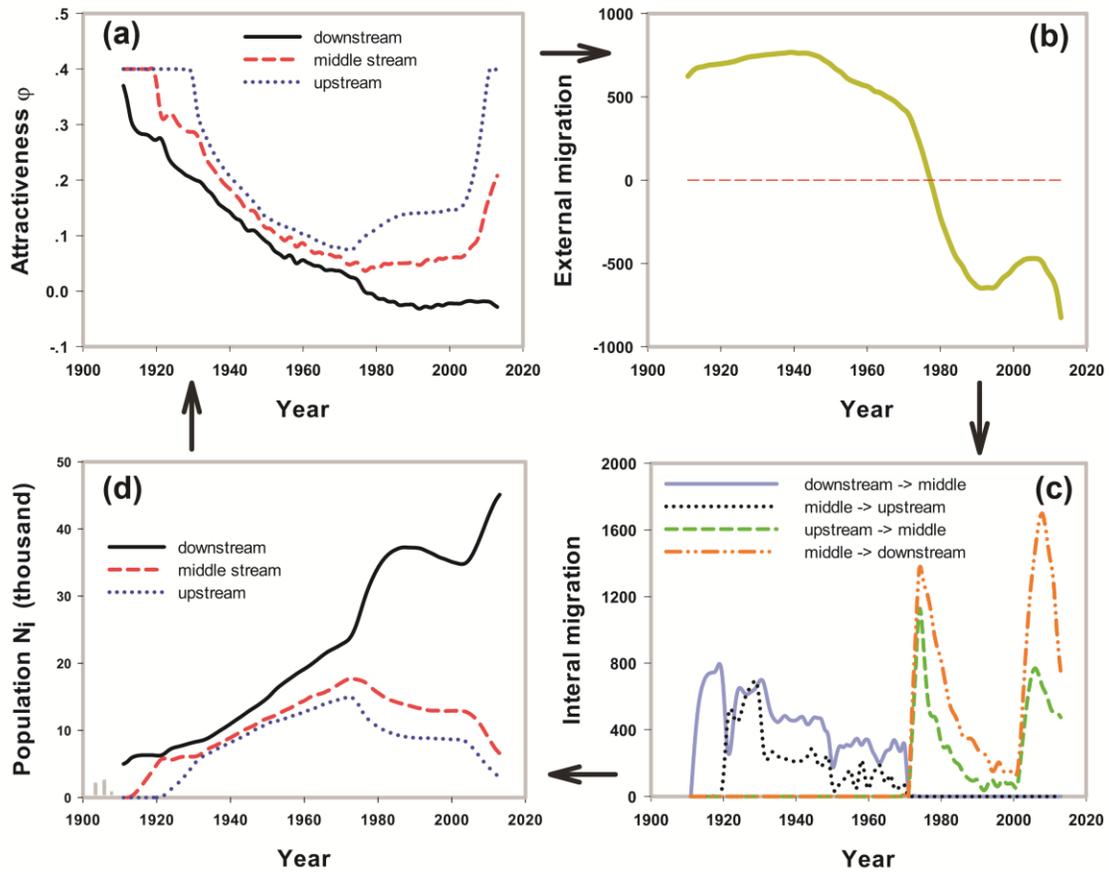
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1315 **Figure 7:** Calibrated constitutive relationships: a) environmental awareness E vs.
 1316 population growth rate α_E ; b) reservoir storage S vs. population growth rate α_S ; c)
 1317 technology T vs. population growth rate α_T ; d) Gross Basin Product vs. technology T ; e)
 1318 water shortage days n vs. rate of change of environmental awareness ϵ (red dot
 1319 represents the forgetting rate); f) technology T vs. crop water demand γ_S and crop yield
 1320 γ_r (see Table 2 for more details).



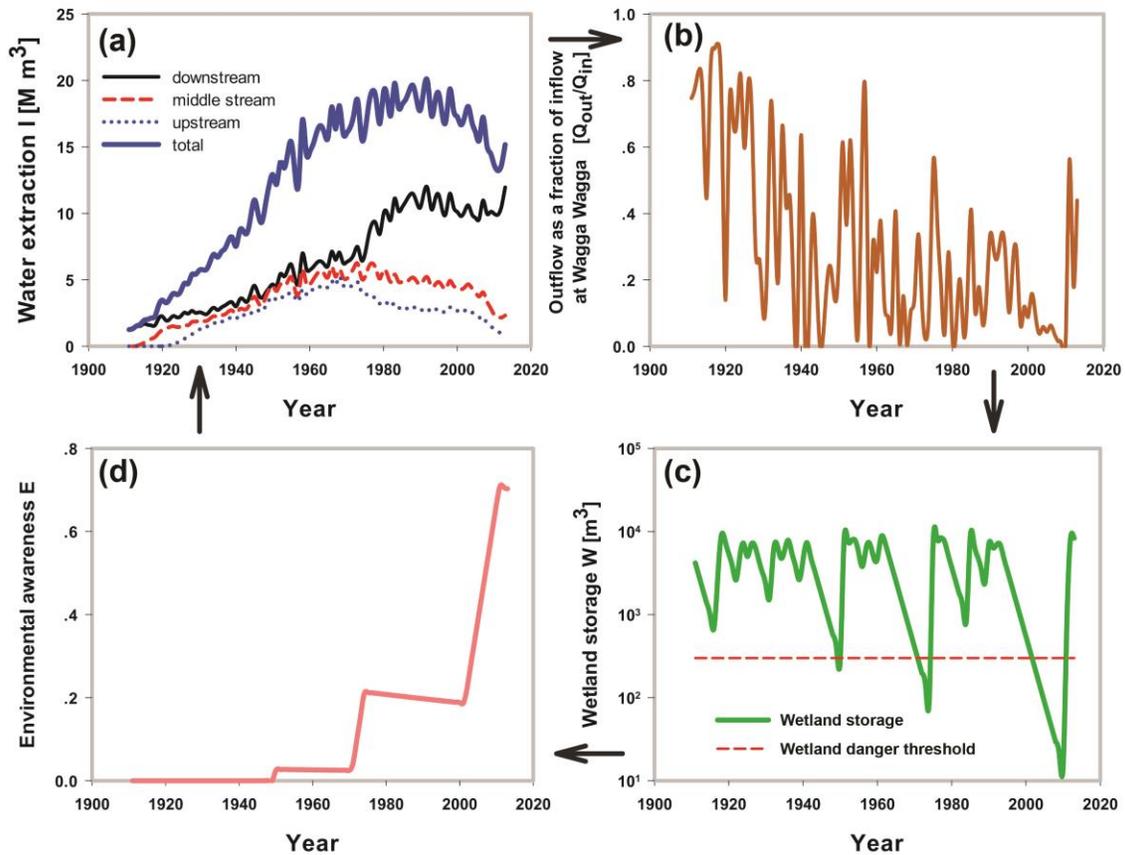
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1322 **Figure 8:** Time variation of socio-economics: a) irrigated area per capita for each of the
 1323 three settlements; b) Gross Basin Product in \$/capita; c) crop yield γ_r , crop water
 1324 demand γ_s and the technology factor α_T ; and d) technology T.



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1326 **Figure 9:** Time variation of population dynamics: a) attractiveness factor for each of the
 1327 three settlements; b) rate of external migration; c) rates of internal relocation between the
 1328 three settlements; and d) size of population in the three settlements.

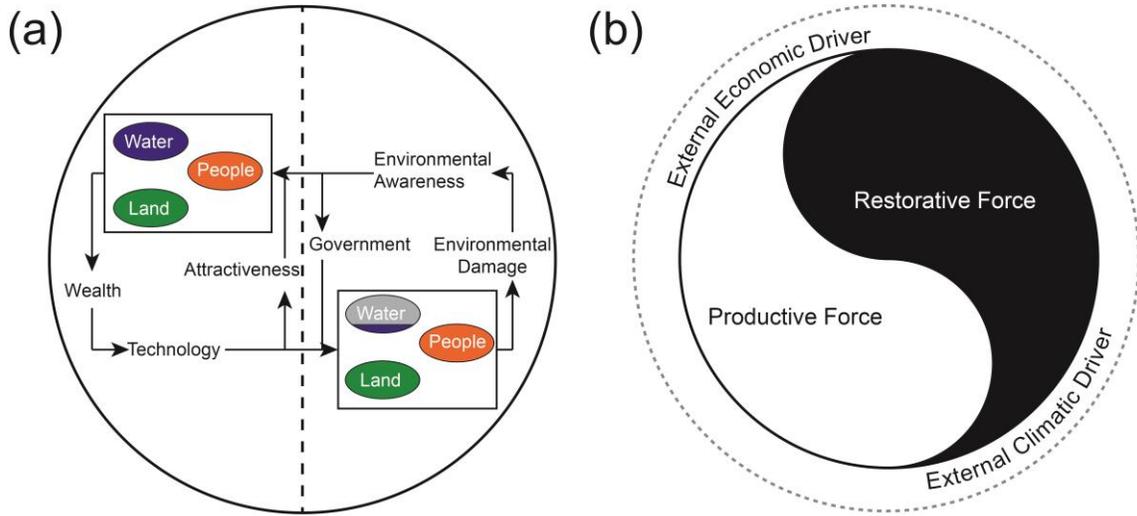


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1330 **Figure 10:** Time variation ecology-environmental awareness: a) rates of water extraction
 1331 in the three settlement and total rate of water extraction; b) environmental (out)flow to
 1332 downstream wetlands as a ratio of inflow at Wagga Wagga; c) wetland storage and
 1333 wetland danger threshold; and d) environmental awareness.

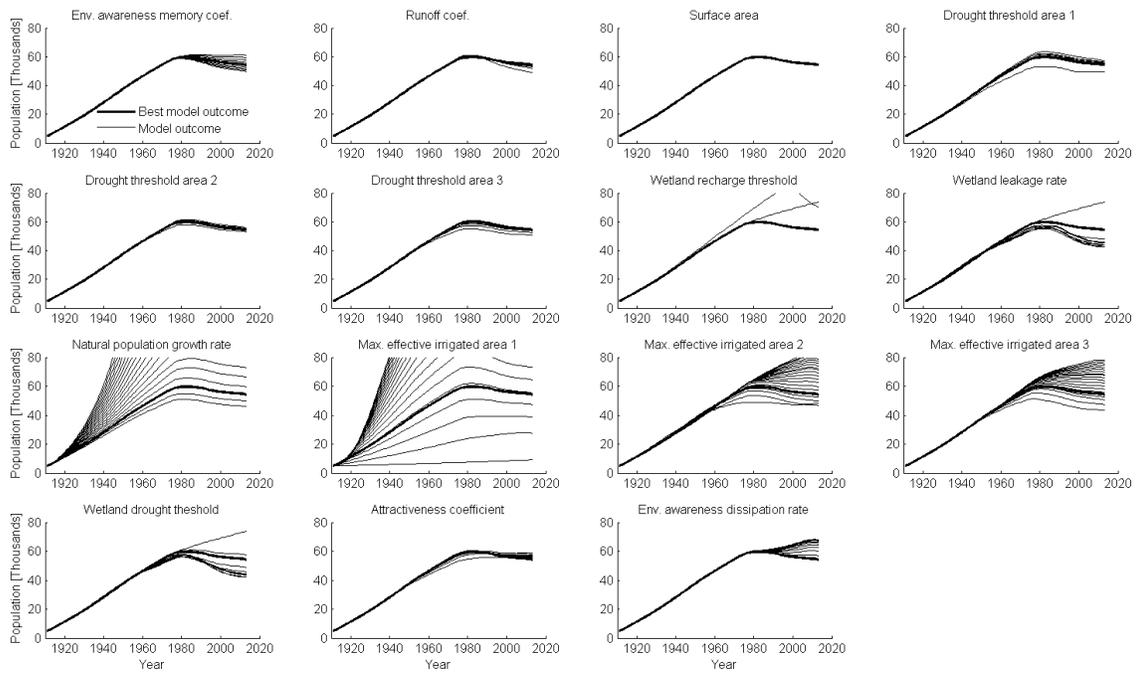
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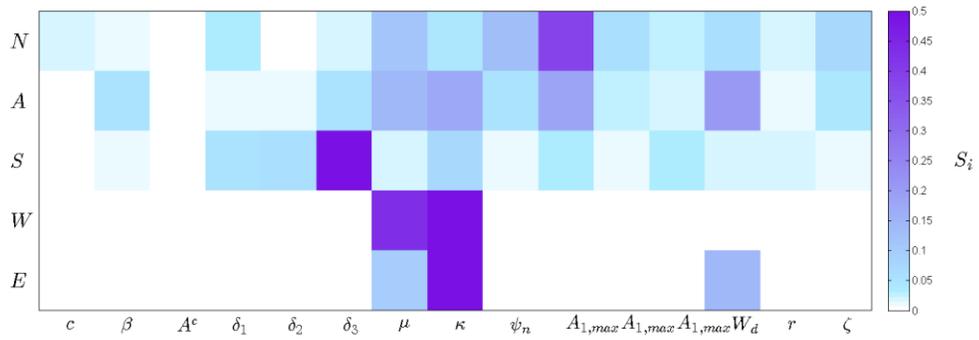
Figure 11: a) positive and negative feedback loops that are built into the model; b) Taiji-Tire model representation of the dynamics operating within the Murrumbidgee River Basin (Taiji-Tire model is concept borrowed from Liu *et al.* 2014).



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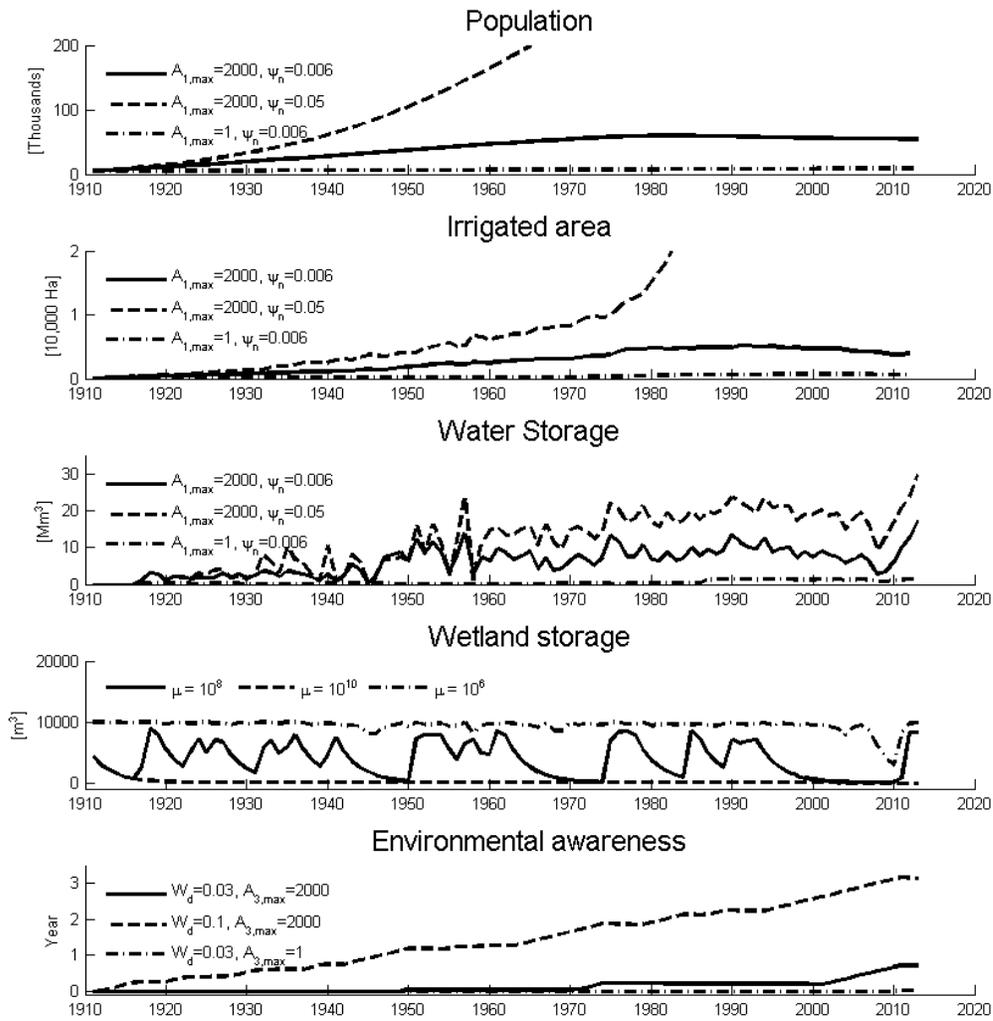
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