



Endogenous technological and population change under increasing water scarcity

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Abstract. Ancient civilizations may have dispersed or collapsed under extreme dry conditions. There are indications that the same may hold for modern societies. However, hydroclimatic change cannot be the sole predictor of the fate of contemporary societies in water-scarce regions. This paper focuses on technological change as a factor that may ameliorate the effects of increasing water scarcity and as such counter the effects of hydroclimatic changes. We study the role of technological change on the dynamics of coupled human–water systems, and model technological change as an endogenous process that depends on many factors intrinsic to coupled human–water dynamics. We do not treat technology as an exogenous random sequence of events, but assume that it results from societal actions.

While the proposed model is a rather simple model of a coupled human–water system, it is shown to be capable of replicating patterns of technological, population, production and consumption per capita changes. The model demonstrates that technological change may indeed ameliorate the effects of increasing water scarcity, but typically it does so only to a certain extent. In general we find that endogenous technology change under increasing water scarcity helps to delay the peak of population size before it inevitably starts to decline. We also analyze the case when water remains constant over time and find that co-evolutionary trajectories can never grow at a constant rate; rather the rate itself grows with time. Thus our model does not predict a co-evolutionary trajectory of a socio-hydrological system where technological innovation harmoniously provides for a growing population. It allows either for an explosion or an eventual dispersal of population. The latter occurs only under increasing water

scarcity. As a result, we draw the conclusion that declining consumption per capita despite technological advancement and increase in aggregate production may serve as a useful predictor of upcoming decline in contemporary societies in water-scarce basins.

1 Introduction

The question of how climatic change affects societies has grown in importance in recent years and is expected to gain ever-increasing attention in years to come. In an attempt to offer a way to explore the question, Pande and Ertsen (2014) recently proposed a theory of endogenous change in the context of basin-scale socio-hydrology under increasing water scarcity conditions. The authors suggested that an exogenous (external to the system) change in hydro-climatology can lead to endogenous changes in cooperative structures such as socio-political organization and trade (see also Pande and McKee, 2007). They also showed that this may bring about other endogenous changes such as in demography, and may thus lead to a (virtuous or vicious) cycle of future changes in cooperative structures and demography.

Van der Zaag (2013), in a commentary on the original discussion paper (Pande and Ertsen, 2014), criticized the proposed theory by suggesting that it ignored the dynamics underlying the changes, for example the role of technological change in shaping human societies. Van der Zaag (2013), in our interpretation, suggested that without any consideration for (technological) change, the theory proposed an outcome that is hydro-climatologically deterministic. As explained in

Pande and Ertsen (2014), such determinism is not suggested by the concept of endogenous change. However, studying processes of technological change within society would shed light on why change happens, as is also argued by Ertsen et al. (2014). Indeed, technology may play a key role in the departure of a society's evolution from one predicted by hydro-climatic determinism. See for example van Emmerik et al. (2014), who inferred that technological change may have played a similar role in the socio-hydrology of the Murrumbidgee Basin, Australia.

The historical development of water resources within the Murrumbidgee Basin in Australia over the past century (as given in Kandasamy et al., 2014) shows that the basin witnessed a rapid rise in population amid increasing concerns of salinity and declining ecosystem services. It was able to sustain the growth in population and agricultural production by first increasing reservoir capacities and then through investments in infrastructure and technologies to control soil salinity and algal blooms, such as drip irrigation systems, barges and an upgrade of sewage treatment plants. Yet it was unable to curb the eventual decline in population and domestic production that began around 1990. The sustained decline in water available for the environment, and hence its ultimate degradation, led to the rise of the notion of the environmental consumer in the basin by 2007 (Kandasamy et al., 2014). The system reached the stage whereby inhabitants of the Murrumbidgee Basin were no longer solely driven by consumption from the income that agriculture generated if it was at the cost of environmental degradation. They reached the point where they were, collectively, willing to give up consumption for improved environment quality and higher environmental flows. Interestingly, the long-term socio-hydrologic dynamics observed within the Murrumbidgee are not unique, one-off events. In fact, as Elshafei et al. (2014) demonstrate, similar dynamics have also been recorded within the Lake Toolibin catchment in Western Australia.

Such a change in the values and norms of individuals within the basin resulted in a different dynamic between agricultural production and environment quality (Chen and Li, 2011). The changing values and norms, via changes in the dynamics of human consumption and environment quality fed back to changes in the delivery of ecosystem services. Nonetheless, this led to a continued decline in population and rice production within the basin. Overall, the rise and fall of population and crop production led to the spatio-temporal pendulum swing in the area under irrigation within the basin. What is observed in the Murrumbidgee River basin is an intrinsic part of the dynamics of coupled human–water systems, as studied within the socio-hydrologic framework proposed by Sivapalan et al. (2014). Notably, van Emmerik et al. (2014) modeled technology as a function of gross basin product when modeling the socio-hydrology of the Murrumbidgee Basin, in spirit similar to the endogenous growth theory proposed within this framework.

Technological development is conditioned by factors such as earlier innovations, human resource development, market demand and the structure of a water economy (Van de Poel, 1998, 2003; Ertsen, 2010). Let us perceive technological development in context of Sewell's and Giddens' concept of societal structure (Sewell, 2005; Giddens, 1979, 1984). A societal structure can be understood as rules and resources, which emerge from the evolutionary dynamics of human agencies within society (Latour, 2005). One may then suggest that humans construct technologies through social interactions in a similar manner as they construct society. In the context of a coupled human–water system, this would mean that technology emerges from the intrinsic dynamics of the system. That is, humans reproduce existing water-related technologies by applying and changing them. In its evolution, this path-dependency is a symptom of an endogenous process of technological change (Jaffe et al., 2003; Lyon and Pande, 2005; Pande and McKee, 2007). Such continuity necessarily excludes the case that technology develops like some external force, with a will of its own, without any possibility for humans to influence its course (Burlingame, 1961; Bijker, 1995; Wright, 1997).

No technological innovation may surmount the physical limit of water resource availability (Smart, 2005). Technological change may, however, buffer the response of a system to change. Technological innovation or adoption can compensate for the effect of increasing population and reducing water resource availability on human well-being (Aghion and Howitt, 1997). Technological innovation is almost a necessity if “timeless” growth is desired, which is when a society is sustained forever (Sachs and McArthur, 2002).

We argue in this paper that in some cases technological change may delay a society's response to change under increasing water scarcity, which may give an impression that it is on top of change. In order to demonstrate and defend this claim, we propose a simple model of endogenous technological change, along the lines of Romer (1990) and Eicher (1996), but framed within the context of socio-hydrology and change (Montanari et al., 2013). The model shows the evolution of a society under increasing water scarcity by endogenous feedbacks between population growth and technological change. The nature of feedbacks (whether positive or negative) are not externally imposed by a modeler but are determined by the intrinsic dynamics of the system. Our model, though simple, is general enough to emulate a variety of feedbacks between population growth and technological change, depending on how a society is conceptualized (parameterized) in the model. All the cases that are considered assume that the water resources available at any time are entirely consumed by the production activity that the society engages in. The change in water resources is assumed to be exogenous to mimic hydro-climatic change.

The model is used to generate valuable insights into the dynamics of coupled human–water systems. For example, the amount that is available to humans to consume per capita

consistently declines over time before a decline in population and production is witnessed. This is also corroborated by data from the Murrumbidgee Basin as well as output from a limits to growth model. The data from the basin indeed shows that income per capita, calculated in terms of rice produced, consistently declined prior to the drop in population and rice production around 1990 (Kandasamy et al., 2014). Meanwhile, the limits to growth model (Hayes, 2012) can be considered as another conceptualization of the coupled human–water system, which also suggests that food available per capita first declines for some time before other co-evolutionary variables such as population and industry decline.

The supporting evidence provided by the Murrumbidgee data and by the outputs of an independent non-linear dynamics model (called the limits to growth model) suggest that declining consumption per capita can be a useful predictor of upcoming decline (or dispersal) of a technology-mediated socio-hydrological system. That is, the population within a coupled system ultimately disperses if consumption per capita has been declining for some time, even when the population has access to technology. Whether this is always the case requires us to demonstrate that the amount available to consume per capita for humans always grows in cases when coupled human–water systems do not disperse. The second part of the paper demonstrates this through a targeted sensitivity analysis of the model. This analysis supports our argument that model outputs are robust and that declining consumption per capita is a credible predictor of dispersal of socio-hydrological systems under increasing water scarcity, such as the Murrumbidgee Basin.

Nonetheless, the model is limited in several aspects, especially since it is a simplistic conceptualization of the coupled human–water system. Several limitations of the model, such as its conceptualization of technology, population change and water use, are raised towards the end of the paper and their bearing on model results are discussed. But first, we begin with a discussion on the motivation and assumptions behind the socio-hydrological model based on endogenous technology and population growth that is introduced in this paper.

2 Towards modeling endogenous growth

2.1 Endogenous growth theory

The endogenous growth theory proposes that economic growth cannot be sustained in the long run without technological growth. One basic premise of such a theory is that capital depreciates in value over time. Consider water as the (natural) capital used in agricultural production for example. Often agricultural production leads to negative outcomes for the environment, such as environmental pollution that leads to depreciation in the value of water for agricultural production. Production technology is required to grow in order to compensate or offset such negative consequences

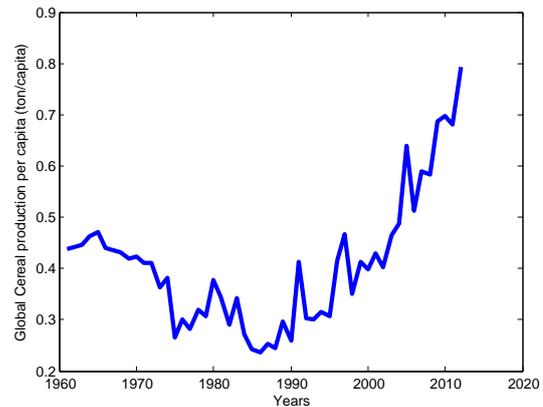


Figure 1. Global cereal production per capita (ton/capita) obtained by dividing global cereal production by global population (data source: <http://faostat.fao.org/>). Note that the population has been growing over the same time frame.

of agricultural production. This especially holds in the case when the population grows at a certain rate and production has to grow at a sufficient pace to sustain the growing population.

The relevance of the concept of technological growth is shown by the data on global cereal production per capita. Figure 1 for example demonstrates that global cereal production per capita first declined and then rose sharply over the past 50 years (this is in contrast to Funk and Brown, 2009; here FAO data on world total population is used). Global cereal production not only kept pace with population over the years, but its rate even exceeded the population growth rate. Clearly, this could not have been possible without consistent progress in production technology. However, how technology grows is not yet given in these data.

A technological change that is external to the dynamics of production and growth can also sustain such growing production per capita. But the persistent differences in the observed rate of production growth per capita (or in aggregate production) across countries or across basins can only be explained by assuming that technology change is driven by decisions made by actors within a production system, as has been argued for the differences in rates of overall production across countries (Hayami and Ruttan, 1970; Aghion and Howitt, 1997). That is, technological change emerges from the inherent dynamics of the systems, possibly as a result of investments made in bringing about technological change (Kaldor, 1957; Arrow, 1962; Nordhaus, 1969; Shell, 1973).

In order to model behavior that emerges from the dynamics of coupled human–water systems, we consider humans in the system as composed of two generations that overlap. “Overlapping generations” models have a rich history of modeling economic systems that span multiple generations (Oded, 1992; Diamond, 1965; Imrohroglu et al., 1999). Often they are used in different contexts, for example water

quality and economic growth (Chen and Li, 2011). In particular, these models are useful in modeling how agents save and how investments (coming from those savings) in technology are made (Eicher, 1996). It is for this reason that we use an overlapping generations model to understand technological change that emerges from the intrinsic dynamics of a socio-hydrological system. In such models, population growth is either considered zero or constant. Our model makes population growth “endogenous”, in other words, it is determined by the internal dynamics of the system.

2.2 Endogenous technological change model

As mentioned, we consider an overlapping generation model with two generations. This is a simple conceptualization of a society that is assumed to be composed of two generations that overlap each other as they evolve in time. Each generation lives for two time periods, thus young individuals of one generation always overlap with old individuals of the other generation. Each generation grows at a certain rate (based on the population growth model described in Sect. 3.3), with a rate of growth that depends on consumption per capita (i.e., the amount of food that is available to individuals to consume per capita). The individuals in a society produce one composite good (that conceptualizes the entire spectrum of goods and services that a population lives from) that is water intensive and requires both unskilled and skilled labor as the other two inputs. The technology scales this production linearly (Romer, 1990; Eicher, 1996). The technology is such that one unit of additional skilled labor produces more of the composite good than one unit of unskilled labor. This conceptualizes that skilled labor is more productive than unskilled workers (as one would expect by definition).

Within each generation the newborns at any time are born without any endowment, that is, they are born penniless and have to work to earn a living. They have to choose between either becoming a researcher who invests her time in innovation to advance current technology or becoming an unskilled worker and start to earn a living. They use this living to consume and save. The unskilled are assumed to retire in the next time period and live on the savings (that may appreciate or depreciate in value based on the intrinsic dynamics of the system) that they made in the previous time step. The researchers in the next time period becomes skilled workers, earning a higher wage than unskilled workers in that time period. Since the researchers do not yet make a living in the first time step, they have to live on a loan against their future earnings that they would make as skilled workers. The loan is provided by the savings of unskilled workers in that time period. It is assumed that only the unskilled workers reproduce. Both the skilled and unskilled workers die penniless. See for example Eicher (1996) for a similar conceptualization.

3 Building the model equations

The model is composed of three main components: production, individual livelihood maximization, and population dynamics. These components are then coupled to estimate the predictive equations of the socio-hydrologic model under certain conservation of mass-type equilibrium conditions.

3.1 Production of composite goods and technological change

We assume a Cobb–Douglas production function that produces y_t amount of the good for a given amount of available water X_t , unskilled workers U_t , and skilled workers E_t .

$$y_t = f(X_t, U_t, E_t; v_t) = v_t X_t^\alpha U_t^\beta E_t^{1-\alpha-\beta}.$$

Here, v_t represents the current technology that scales up the amount of production linearly (see for example Romer, 1990 and Eicher, 1996), $0 < \alpha < 1$ and $0 < \beta < 1$ are the parameters such that $\alpha < \beta < 1 - \alpha - \beta$. We emphasize that water availability here holistically represents the productive supply of water. It encompasses the effects of both water quality and quantity. The supply of water may effectively be reduced due to lower water quality, for example salinity that may lower plant water uptake, thereby affecting crop production.

Technological change, in a particular time period, is brought about by researchers, S_t , but also depends on the current state of technology. If each researcher consumes c_t^U , the technological innovation is thought of as a random process that is proportional to the total consumption of the researchers $c_t^S S_t$, thereby measuring total energy available for innovation. The expected change in technology per unit current technology, $\frac{v_{t+1} - v_t}{v_t}$, is then given by

$$\frac{v_{t+1} - v_t}{v_t} = \gamma c_t^S S_t.$$

Here, $0 \leq \gamma \leq 1$ represents the success rate with which a unit of energy available for innovation results in a technological advancement. It therefore represents how efficiently available energy gets converted into technological advancement. It further bounds a change in technology in a particular time period.

3.2 Livelihood (utility) maximization

We assume all the individuals in a society have identical preference structures between the present and future consumption of the composite commodity. The choices of an individual born at time t are driven by their tendency to maximize their livelihood (utility) function of consumption at time t and $t + 1$. However, they are limited by the income that they generate through their participation in the production activity of the society.

For a researcher, who consumes c_t^S at time t but becomes a skilled worker at time $t + 1$ and consumes c_{t+1}^E , choice

of $\{c_t^S, c_{t+1}^E\}$ is determined by the following maximization problem:

$$W^S = \max_{\{c_t^S, c_{t+1}^E, b_t\}} \ln c_t^S + \beta_0 \ln c_{t+1}^E,$$

such that

$$c_t^S = b_t$$

$$c_{t+1}^E = w_{t+1}^E - b_t(1 + r_t).$$

Here, b_t is the amount that the researcher at time t plans to borrow to support herself, only to return it once she participates as a skilled worker in the production activity in the next time period, earning an income of w_{t+1}^E as a result. The amount that she has to return, i.e., $b_t(1 + r_t)$, may be larger or smaller than the amount that she borrowed (determined by the rate of return r_t) and depends on the availability of the funds and propensity of agents to save. The parameter β_0 (> 0) represents how she weighs her future consumption relative to present consumption. This parameter is equal to $\frac{\theta}{1-\theta}$, where $0 < \theta \leq 1$ is an individual's propensity to save. Thus the larger the β_0 , the larger the propensity to save.

The researcher, for given skilled labor income in the next time period (w_{t+1}^E) and the current rate of return r_t plans her consumption over her lifetime such that her livelihood function is maximized.

Similarly, for an unskilled worker, who consumes c_t^U and saves m_t at time t but does not work at time $t + 1$ when she consumes c_{t+1}^U from what she saved at time t , choice of $\{c_t^U, c_{t+1}^U\}$ is determined by the following maximization problem:

$$W^U = \max_{\{c_t^U, c_{t+1}^U, m_t\}} \ln c_t^U + \beta_0 \ln c_{t+1}^U,$$

such that

$$c_t^U = w_t^U - m_t$$

$$c_{t+1}^U = m_t(1 + r_t).$$

Here, w_t^U is the income that the unskilled worker earns at time t . At $t + 1$, she reproduces and provides an offspring for the next generation starting at time $t + 2$.

3.3 Population dynamics

The population of a generation at time t , Ω_t , grows at a rate of r_t^Ω . The unskilled workers at time t have the role of reproducing at time $t + 1$ when they do not work and live off their savings made at time t . Thus, it is assumed that the rate of population growth may reduce or even become negative if consumption per capita of unskilled worker reduces. This is to reflect the tendency of population outmigration or decline when livelihood of individuals deteriorates. We model the rate of population growth to become negative once unskilled worker's consumption, c_t^U , falls below a certain threshold, \underline{c}^U .

$$\Omega_{t+1} = \Omega_t(1 + r_t^\Omega),$$

where,

$$r_t^\Omega = \begin{cases} \bar{r}^\Omega > 0 & \text{if } c_t^U > \underline{c}^U \\ \underline{r}^\Omega < 0 & \text{if } c_t^U \leq \underline{c}^U \end{cases}.$$

This conceptualization is similar to the dominant mode analysis of Cuypers and Rademaker (1974) of the World2 model of Forrester (1971). Cuypers and Rademaker (1974) found that the complex set of coupled equations of the World2 model can be simplified to a hierarchical system where the population dynamics is driven by natural resource availability and capital investment. Consumption per capita represents the joint effect of water resource availability and food production on population growth rate.

3.4 Equilibrium conditions

The partitioning of total population at any time t , $\Omega_t = S_t + U_t$, into S_t and U_t is determined by assuming that an individual at time t is indifferent to choosing between contributing to production activity as an unskilled worker, or investing herself in advancing current production technology. It is therefore assumed that the utility maximized by being a researcher is the same as the utility maximized by being an unskilled worker over a lifetime, that is

$$W^S = W^U.$$

The rate of return on savings m_t or the cost of borrowing b_t is r_t and it is determined by the balance between total demand for borrowing $S_t b_t$ and the total supply of funds that is the sum of total amount of savings, $U_t m_t$ and surplus Q_t generated by the production activity. The surplus Q_t that is generated by the production activity is the produce left after paying for the labor of unskilled workers, $w_t^U U_t$, and skilled workers, $w_t^E E_t$. By pooling the surplus into the total supply of funds, we assume that gains from production activity and gains in efficiency by advancing technology feed back to advance technology in the future even more. Higher surpluses lower the costs of borrowing, hence they encourage higher participation of researchers in technological advancement. The total borrowing $S_t b_t$ of researchers is balanced by total savings $U_t m_t$ of unskilled workers and surplus Q_t ,

$$S_t b_t - U_t m_t = Q_t.$$

Here $Q_t = y_t - w_t^U U_t - w_t^E E_t$.

The wages that workers are paid are at their marginal productivity. Thus

$$w_t^U = \frac{\partial f(X_t, U_t, E_t; v_t)}{\partial U_t} \text{ and } w_t^E = \frac{\partial f(X_t, U_t, E_t; v_t)}{\partial E_t}.$$

We here note that workers earn a living at the rate of their marginal productivity, $w_t^U U_t = \beta y_t$ and $w_t^E E_t = (1 - \alpha - \beta) y_t$. The surplus generated is the implicit value of water or the contribution of water in total

production, i.e., $Q_t = w_t^X X_t = \alpha y_t$. Here w_t^X represents the marginal productivity of water. This has an interesting bearing on the discourse of scale of cooperation and technological change that Pande and Ertsen (2014) proposed. Larger surpluses per unit additional water are generated when water is relatively scarce. Thus an extension of the scale of cooperation under water-scarce conditions, which results in an increase in total availability of water, generates more surplus per unit additional water than when conditions are not as scarce. This may in turn reduce the cost of borrowing and hence spark more innovation per unit additional water in the case when water is scarcer. We may thus find a positive correlation between technological innovation and rise to maturity of a society under water-scarce conditions. This argument is closely related to Romer (1990), who suggested that larger integration of markets, for example through trade, can result in larger surpluses. Imagine integration, through trade, of smaller socio-hydrological systems into larger systems. Note that the larger integration of markets is equivalent to increasing the scale of cooperation, for example between basins or regions, through trade. This in turn can fuel further technological innovation because of new synergies that are built by the expansion of scales. Here we assume that technological innovation merely boosts the production level. We ignore innovations that are biased towards saving the limiting factor (Hayami and Ruttan, 1970), which in the context of the paper is water. Hence we will not be able to model innovations that may be triggered by increasing water scarcity conditions unless the scarcity conditions first trigger an increase in the scale of cooperation between basins or regions.

In the analysis below, we do not consider an increasing scale of cooperation, for example through the integration of smaller socio-hydrological systems into a larger one, with increasing scarcity conditions. Therefore we observe slowing rates of innovation, even under heightened scarcity conditions, in certain cases that we examine below.

Finally, a researcher at time t becomes a skilled worker at time $t + 1$, i.e., $S_t = E_{t+1}$.

3.5 Model equations

A set of model equations for labor diversification, wages, rate of return, production and surplus generated, technological change and consumption per capita are obtained based on livelihood maximization, technological advancement, production activity and the above equilibrium conditions.

The diversification of labor, that is, the ratio of individuals who choose to be unskilled workers and those who choose to be researchers in order to become skilled workers in the next time step, is a constant. The diversification depends on how critical water is to the production activity and on an individual's propensity to save.

$$\frac{U_t}{S_t} = \delta = \frac{1}{\beta_0 \left(1 + \frac{\alpha}{\theta\beta}\right)}.$$

Since the sum of the unskilled workers and researchers define the population of the generation starting at time t , i.e., $S_t + U_t = \Omega_t$, the number of unskilled workers and researchers at any time t can be obtained as

$$S_t = \frac{\Omega_t}{1 + \delta},$$

$$U_t = \delta \frac{\Omega_t}{1 + \delta}.$$

Since the income earned by individuals is at their marginal productivities, the wage rates for unskilled and skilled workers are given by

$$w_t^U = \beta v_t X_t^\alpha U_t^{\beta-1} E_t^{1-\alpha-\beta},$$

$$w_t^E = (1 - \alpha - \beta) v_t X_t^\alpha U_t^{\beta-1} E_t^{-\alpha-\beta}.$$

The surplus Q_t that is generated at time t is given by

$$Q_t = \alpha f(X_t, U_t, E_t; v_t).$$

The savings made by the unskilled workers, m_t , and the borrowing of the researchers, b_t , are given by

$$m_t = \theta w_t^U,$$

$$b_t = \theta \frac{w_{t+1}^E}{\beta_0 (1 + r_t)},$$

where the rate of return on savings, r_t , is given by

$$r_t = \frac{\theta w_{t+1}^E}{\beta_0 (1 + r_t)}.$$

The consumption per capita of unskilled and skilled workers can now be given as

$$c_t^U = w_t^U - \theta w_t^U,$$

$$c_t^S = \theta \frac{w_{t+1}^E}{\beta_0 (1 + r_t)}.$$

Meanwhile the consumption of the same individuals at time $t + 1$ is given by

$$c_{t+1}^U = m_t (1 + r_t),$$

$$c_{t+1}^E = w_{t+1}^E - b_t (1 + r_t).$$

Finally the endogenous technology change equation is given by

$$v_{t+1} = v_t \left[1 + \gamma S_t \left(\theta \delta w_t^U + Q_t / S_t \right) \right].$$

Note that the rate of technological change is never negative, in other words, technology never deteriorates but rather builds upon previously generated technology, in addition to other factors. The rate of change is endogenous because it depends on factors that are endogenously determined in the evolution of a society. It is proportional to a random variable γ that determines the rate of success of (implicit) investment in technological advancement. The investment is the sum of the wage of an unskilled worker forgone by a researcher (since she decides to work on advancing technology, she lives on a debt and forgoes the income that she could have earned had she rather worked as an unskilled worker) and the surplus generated by the production activity.

4 Results

4.1 Model parameters

For our simulations we assume that (renewable) water resource availability X_t declines exponentially over time at the rate of 2% ($k = -0.02$), i.e., $X_{t+1} = (1 + k)X_t = 0.98X_t$. We consider that a system reaches a physical limit once X_t falls below 1% of $X_{t=0}$ and the evolution of the society abruptly stops. We also assume that γ is gamma distributed, with a mean of $\bar{\gamma} > 0$, to represent sparks of innovation. Thus, we assume that a positive surplus is not sufficient to spark an innovation, thereby allowing certain additional factors that are exogenous to the system to determine the rate of success.

We assume $\alpha = 0.3 < \beta = 0.35$. The coefficient β_0 that measures the patience of an individual in terms of her present to future consumption is assumed to be 0.99. We therefore model a society with individuals who prefer, though marginally, to consume a unit at present rather than relegating it to the future. We assume the positive and negative population growth rates, \bar{r}^Ω and \underline{r}^Ω are 0.01 and -0.02 , respectively, which suggests that population increases at a rate of 1% and once the consumption per capita of an unskilled worker crosses a certain threshold, \underline{c}^U , it falls to -2% , representing decline due to outmigration or higher death rate than birth rate. We assume that this critical threshold is η ($0 < \eta < 1$) fraction of the consumption per capita that unskilled workers witnessed under water abundance, i.e., $\underline{c}^U = \eta c_{t=0}^U$. Thus varying sensitivity (resilience) of populations to the critical threshold is modeled. We consider $\eta = 0.1$, unless otherwise stated. Finally, we initialize the model with an initial technological level, $v_{t=0} = 0.02$, initial population level $\Omega_{t=0} = 1$ and initial water resource $X_{t=0} = 1$. The model can be scaled up by appropriately setting $X_{t=0} \Omega_{t=0} v_{t=0}$ and k .

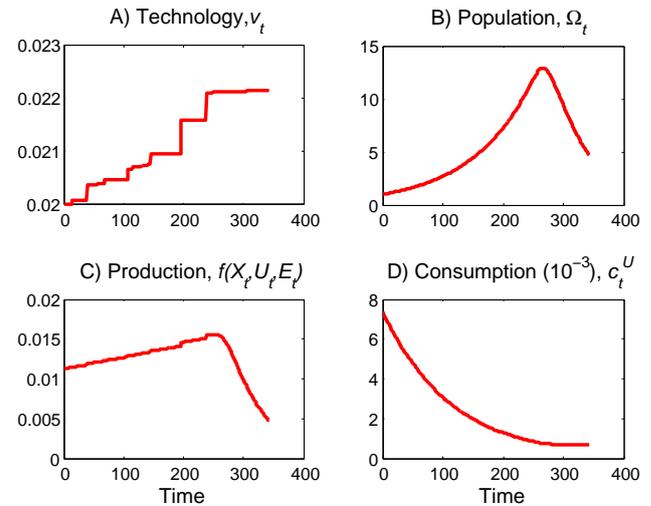


Figure 2. The co-evolution of technology, population, production and consumption per capita under a modest rate of success ($\gamma = 0.10$). The population growth rate threshold $\eta = 0.10$. Randomness in technological rates of success is assumed to be gamma, distributed with mean $\bar{\gamma}$ and variance $100\bar{\gamma}^2$.

4.2 Population decline (or dispersal) under technological advancement

Consider the case of a resilient society in the sense that its population growth rate is only affected once its consumption per capita falls below 10% of the initial level (at $t = 0$), i.e., $\eta = 0.10$. Let the long-run rate of success in technological innovation be $\bar{\gamma} = 0.10$. We assume that the randomness in the rate of technological success is represented by a gamma distribution with a mean $\bar{\gamma}$ and a standard deviation of $100\bar{\gamma}^2$.

The technology of the society advances throughout the period until said society reaches its physical limit, around 350 time units (Fig. 2a). Even though technology advances throughout, it does not allow the individuals in the society to escape the physical limit. Clearly, the technological advancement is not sufficient to support an ever-increasing population (Fig. 2b). The population initially increases under technological advancement, which leads to an initial increase in production, even though water scarcity is increasing (Fig. 2c). However, the increase in production, both due to technological advancement and the increasing population that contributes skilled and unskilled workers, is not sufficient to support a comfortable level of consumption per capita of an increasing population (Fig. 2d). Note that the consumption per capita of researchers and unskilled workers is the same for all t . This leads to a persistent decrease in consumption per capita over time.

The ever-decreasing consumption per capita and moderate rate of success in technological advancement finally catches up with an increasing population growth. Since technological

advancement does not just depend on its rate of success but also “endogenously” on consumption per capita, persistently decreasing consumption per capita feeds back into the human capacity (or capital) to innovate and reduce the rate of technological change. While the technology still advances, it advances at a slower rate over time.

Once the population peaks and starts to decline, lower availability of workers reinforces the feedbacks of increasing scarcity and decreasing per capita consumption (equivalent to attrition of human capital) on the rate of technological advancement and aggregate production. The reduction in the rate of technological advancement is now sharper, and technological advancement can no longer stop the fall in aggregate production. While declining population negatively feeds back to reduce the rate of decline in per capita consumption, the society soon reaches its physical limit of water availability.

The decline (or dispersal) of the society is triggered long before it reaches its physical limit. While reducing water resources availability has a role, its decline is not determined by it. This is because the decline does not happen when the water resource reduces to 0, which is around 350 time units. The decline in population and production well before 350 time units points to a tradeoff between increasing water scarcity and technological progress that attempts to compensate for the effect of increasing water scarcity. Thus the decline in population and production, even when mediated by technology, is not trivial. The dispersal is trivial if it occurs when water resource availability reduces to 0.

The reason behind the non-trivial dispersal is the rate of success in technological innovation (as represented by $\bar{\gamma}$) that is not sufficiently high. The individuals in a society cannot escape the dispersal since they cannot innovate sufficiently fast, which in turn affects their future capacity to innovate (measured in terms of consumption per capita). The society witnesses a persistent decline in consumption per capita in spite of technological advancement and increasing production (until around 270 time units). This prolonged reduction in human capacity to innovate finally triggers a decline around 270 time units. Perhaps that is what happened in the Murrumbidgee Basin around 1990. The early and mid-20th century saw technological innovation that was able to offset the negative consequences of population growth within the basin. However, towards 1990 it could no longer keep up with population growth, leading to eventual dispersal of the population within the basin.

The conclusion that a society cannot escape a decline if they cannot innovate sufficiently fast appears to be intuitive. It may as well apply when the reduction in water resource availability is not exogenous but induced by human activities and when the definition of water resource availability is broad enough to encompass the effect of quantity, quality and variability on water use. The effect may even be stronger since the rate of decline would then depend on the rate of increase in production. Finally a decline of water resource

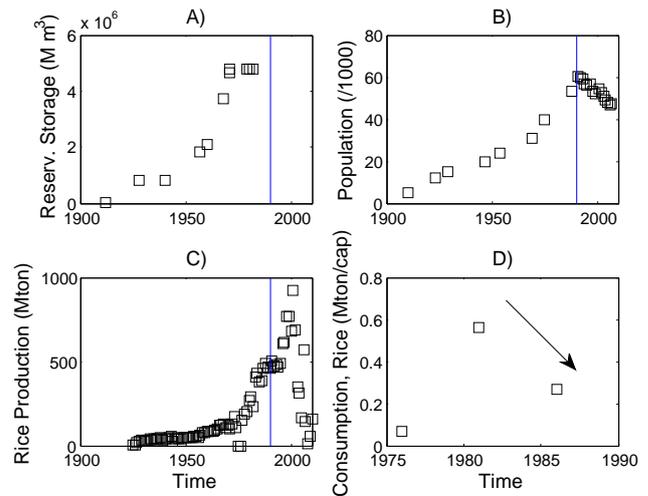


Figure 3. (a)–(c) Historic reservoir capacity, population and rice production in Murrumbidgee River basin, Australia (Kandasamy et al., 2014). The vertical lines indicate the year 1990. (d) Imputed Agricultural Income per unit labor, in units of mton/capita. Based on New South Wales censuses 1976, 1981, 1986. See the Appendix on how the values are imputed and converted into rice amounts. A decline in consumption per capita for a decade before 1990 (the year of eventual decline in Murrumbidgee population) is evident.

availability to 0 may be deemed inevitable under an increasing population since human tissue is mostly made of water. A growing population will reduce water available for production since it will use up water to build body mass, effectively removing an increasing amount of water from the water cycle. However given the timescale involved, it may not be realistic to suggest that water resource availability eventually declines to 0.

These results suggest that a society need not immediately decline once water scarcity starts to increase. A certain population level may contribute to technological advancement and an initial increase in production through individual contribution to innovation and production. This in turn may initially support an increasing population even under increasing scarcity.

Consider Fig. 3, which displays the time series of reservoir storage capacity, population and rice production for the Murrumbidgee Basin (Kandasamy et al., 2014) and a proxy for consumption per capita for New South Wales in Australia (see Appendix for an explanation). The basin witnessed a population decline in the 1990s amid ecological and salinity concerns stemming from the early 1960s (Kandasamy et al., 2014). The basin witnessed declining water availability under our definition for nearly 4 decades. If the reservoir storage capacity (Fig. 3a) that scaled up production by smoothing the intra-annual supply of water can be considered a proxy for technology, the similarity of its pattern with Fig. 2a is clear. The patterns of population and production are also similar (compare Figs. 2b, c and 3b, c). The consumption per

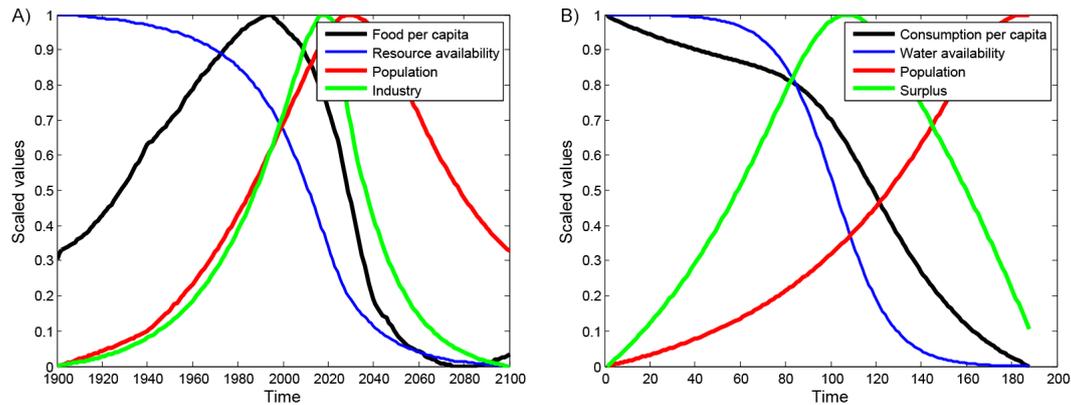


Figure 4. (a) World3 model output for business-as-usual scenario (Hayes, 2012). (b) Output of the endogenous technological change model presented here. All the variables in both the figures have been scaled between 0 and 1 by subtracting the minimum and dividing by the range. Variables “food per capita”, “resource availability” and “industry” in (a) are equivalent to “consumption per capita”, “water availability” and “surplus” in (b).

capita (Fig. 3d; from census) shows a declining trend in the decade before the eventual decline of population in the Murrumbidgee Basin in the early 1990s. It therefore appears that declining consumption per capita under declining water resource availability, even in presence of technological change, may be a credible predictor of upcoming population decline. Surely, the Murrumbidgee Basin had ample opportunity to access and adopt smart water saving and purification technologies. Yet, it was unable to stem the eventual population decline. This example therefore serves as a counterargument to the suggestion that technological advancement is sufficient for societies to be on top of physical constraints imposed by nature.

Consumption per capita as a credible predictor of eventual decline is further supported by the outputs of the “Limits to Growth World3” model (Hayes, 2012). In contrast to endogenous growth models, limits to growth models (Forrester, 1971) are complex models including high dimensional system dynamics; they represent the dynamics of a coupled human–environmental system through a system of coupled differential equations that propose relationships between the variables. In endogenous growth models the relationships between the variables themselves emerge from the inherent dynamics. Yet this difference between the limits to growth and endogenous growth models is subtle. A simplification of limits to growth model by Cuypers and Rademaker (1974) in the context of a coupled human–water system is a case in point. Here, water resource and investment in agricultural production “drives” population growth (through prescribed functional relationships). Population growth, in tandem with water resource availability and production, in turn affects water resource quality and production. Note that these relationships are prescribed a priori in the limits to growth model. A similar hierarchy and rationale of relationships can also be

obtained from an endogenous technological and population growth model of a coupled human–water system.

Figure 4 demonstrates the major variables for a comparison between limits to growth and the endogenous growth models presented in this paper. Figure 4a suggests that the declining natural resource availability and increasing pollution output may represent declining water resource availability in the context of this paper. The outputs suggest that population and production (industry) initially increase despite declining resource availability and increasing pollution. However, the eventual decline in population and production is preceded by a persistent decline in consumption per capita (food per capita) for over 50 years. Similar patterns are replicated by the model of endogenous technological change in Fig. 4b. Note here that an *S*-shaped function is used to represent declining water resource availability (unlike the exponential decline that has been used elsewhere in the paper) in order to reproduce a similar shaped decline in natural resource availability produced by the World3 model (in Fig. 4a).

4.3 Role of the rate of success in innovation on the nature of population change

While the model is currently unable to replicate the bell-shaped patterns of consumption per capita that appear both in Figs. 3 and 4a due to its parsimonious nature, the connection between its persistent decline and eventual population decline is evident in both the models. One may ascribe the cause behind the decline in population to the resilience of population growth to consumption per capita. Figure 5b shows that the decline begins earlier when it is assumed that population growth becomes negative when consumption per capita falls below 25% of initial consumption per capita, i.e., $\eta = 0.25$ than when it is assumed that $\eta = 0.10$. For the remainder of the paper, we let $\gamma = \bar{\gamma}$, in other words, we do not allow any randomness in the rate of success in

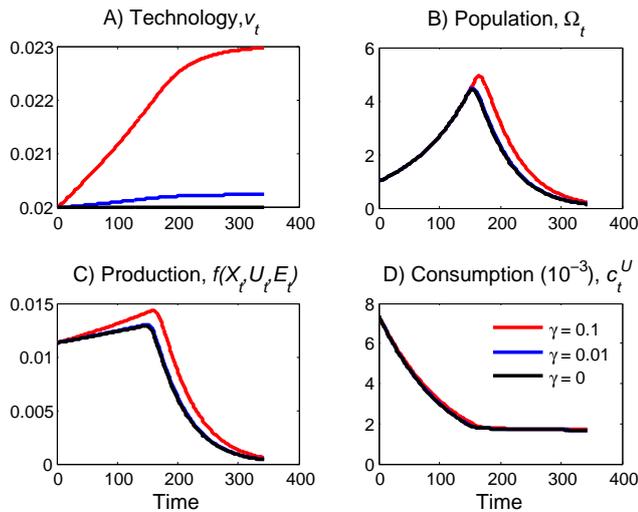


Figure 5. The co-evolution of technology, population, production and consumption per capita under a modest rate of success ($\gamma = 0.10, 0.01$) and no technological change ($\gamma = 0.00$). The population growth rate threshold $\eta = 0.25$. No randomness in the technological rate of success is assumed, i.e., $\gamma = \bar{\gamma}$.

technological innovation (γ) for a given long-run mean ($\bar{\gamma}$), and investigate the effect of the rate of technological innovation on the timing of societal decline. All initial conditions are assumed to be the same as in Sect. 4.1.

Figure 5a demonstrates the evolution of endogenous technological change for three rates of success: modest ($\gamma = 0.10$), low ($\gamma = 0.01$) and zero ($\gamma = 0.00$). The last case represents the case of no technological change. Figure 5b demonstrates that an increase in the rate of success delays the peak of population growth. Nonetheless, the population eventually declines for the cases considered here. The population evolution also closely follows a gradual increase and then fall in production (even under no technological change) in Fig. 5c. The consumption per capita appears not to be too different across the 3 cases.

As a whole, Fig. 5 illustrates that societies may disperse when the rate of success of technological innovation is not sufficiently high. In these cases, technological change may at best delay the advent of decline but may not allow individuals in a society to escape from it.

However, it appears that individuals in society may escape an eventual decline if the rate of success in technological innovation is sufficiently high. Note that technological change is a function of human capital (represented in terms of total consumption of the researchers) and the rate of success. Furthermore, the production is a function of technological level, water resource availability and availability of skilled and unskilled workers. While increasing population and water scarcity put downside pressure on aggregate production, increasing population and technological levels attempt to pull up aggregate production as well. Thus sufficiently fast

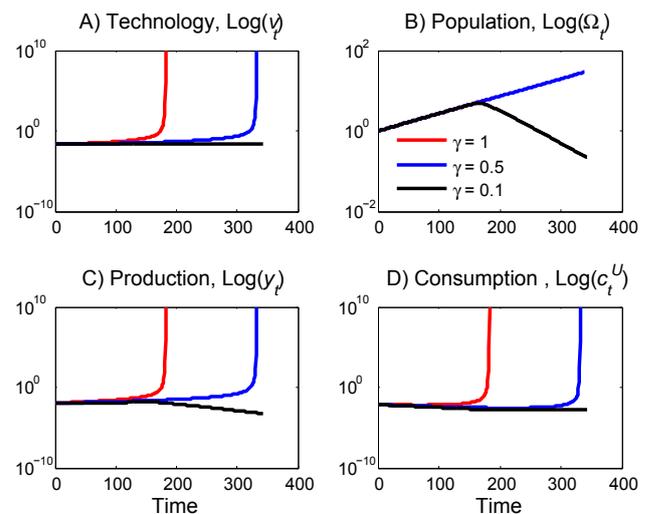


Figure 6. Technological singularity: the co-evolution of technology, population, production and consumption per capita under high rates of success ($\gamma = 0.50, 1.00$) and modest rates of success ($\gamma = 0.10$). The population growth rate threshold $\eta = 0.25$. No randomness in technological rate of success is assumed, i.e., $\gamma = \bar{\gamma}$.

increments in technological levels may overcome the downside pressure on production to the extent that consumption per capita ultimately begins to rise, positively reinforcing technological advancement. A virtuous cycle ensues, allowing individuals in a society to “escape” water scarcity.

This is illustrated by Fig. 6, which demonstrates the effect of the rate of technological success on population growth. For $\gamma = 0.5$ and $\gamma = 1.0$, the technological level explodes (a “technological singularity” is reached) before the society reaches the physical limit. The level of technology at this singularity is infinite, implying that the society can sustain an infinite population irrespective of water resource availability. Figure 6b shows that for $\gamma = 0.5$ the population explodes to infinity around the time when the physical limit of water resource availability is reached, while for $\gamma = 1.0$ it explodes to infinity around 190 time units. In both the cases, the consumption per capita initially declines slightly but recovers at later time steps. The consumption per capita recovers before the society reaches its singularity and this rise (at a rate faster than exponential) in consumption per capita accelerates its approach to singularity.

The implausibility of the notions of singularity and escape from the ultimate resource constraint may suggest the implausibility of rates of success such as 0.5 and 1.0. Nonetheless, the model of endogenous technological and population change allows for it.

Unlike the cases when the rates of success (γ) are high, population and technology are not always positively correlated, even under technological advancement (Fig. 7a, b). The population first rises and then falls with increasing technological advancement. The maximum population that is

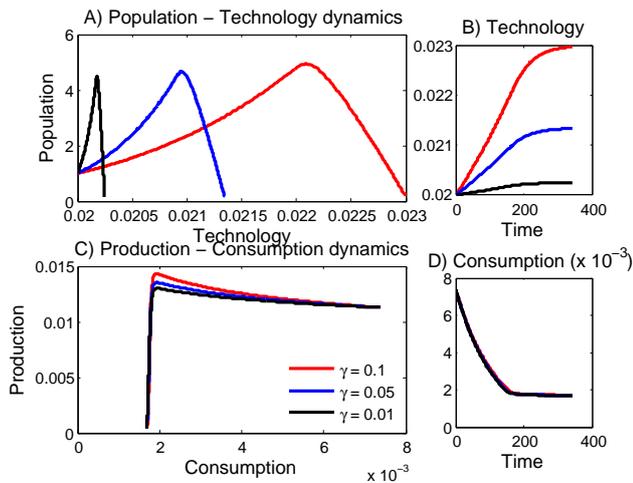


Figure 7. Population–technology and production–consumption dynamics: the relationship itself evolves over time and varies for different rate of success, $\gamma = \{0.1, 0.05, 0.01\}$ considered. Note that consumption per capita declines even when aggregate production rises before its eventual decline. The population growth rate threshold is $\eta = 0.25$. No randomness in the technological rate of success is assumed, i.e., $\gamma = \bar{\gamma}$.

achieved increases with increasing γ . However, the rise to a maximum and fall thereafter with increasing technology are steeper for lower values of γ . Even for a given rate of success, γ , the fall in population with increasing technology is steeper than the rise. These observations illustrate the complex feedbacks between population growth and technological change that this model implements. These complex feedbacks are communicated through variables such as aggregate production and consumption. Figure 7c and d demonstrate that consumption per capita is first negatively correlated with production, followed by a positive correlation once population reaches its maximum. After a mild rise to a maximum, aggregate production sharply drops per unit reduction in consumption once the population peaks for each of the three rates of success. These results demonstrate that the model is capable of imputing a relationship between variables of interest that may change over time.

Figure 7a suggested that the population peak occurs before the technology stabilizes. However, both the peak population and “mature” (asymptotic) technological level, v^* , increase with increasing γ . Figure 8a shows that the change in v^* with γ is super-exponential. A technological singularity is achieved for a critical rate of success γ_c around 0.49, suggesting that unlimited population growth is possible for $\gamma \geq \gamma_c$. Thus societies may escape from the physical limit posed by water scarcity at high rates of technological success.

Figure 8b shows that technology continues to advance, though at slow rates, for low to medium rates of success ($\gamma < \gamma_c$) until the time when the physical limit of water availability is reached. The population peaks before it hits the

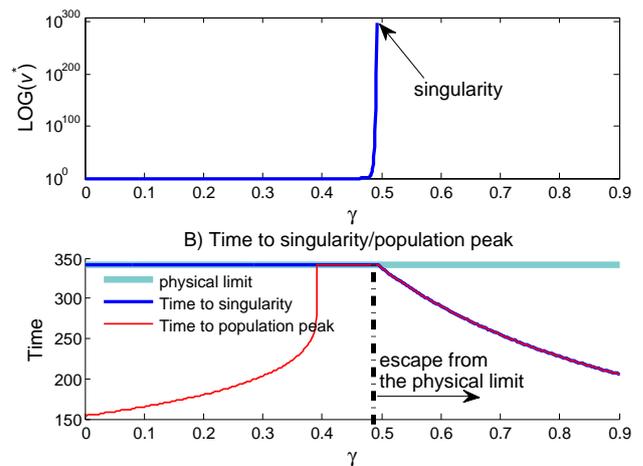


Figure 8. (a) The asymptotic technological level is super-exponential in the rate of success. (b) The escape of society from the physical limit beyond the critical rate of success γ_c , when technological singularity appears. Note that for $\gamma < \gamma_c$, the population decline appears before the physical limit of water resource availability is reached, while for $\gamma \geq \gamma_c$, population explodes to infinity (hence its peak) at the same time when technological singularity appears.

physical limit. Thus societies decline before its individuals witness the physical limit of water resource availability. However, for $\gamma \geq \gamma_c$, societies witness technological singularity. The populations explode to infinity before the time of the physical limit and, at the same time, when its individuals witness technological singularity. The time to singularity decreases with increasing rates of success, γ , when $\gamma \geq \gamma_c$. Hence the time to population peak coincidentally decreases with increasing rates of success, γ , when $\gamma \geq \gamma_c$.

All the above cases suggest that the trajectories of the socio-hydrological system either co-evolve to 0 or to infinity at a rate faster than an exponential rate (so-called super-exponential rate). Is it not possible that technology advances in harmony with the demands of a growing population and that they co-evolve at a constant rate? Are socio-hydrological systems that grow at a stable rate possible within the realm of the model? The above cases also provided evidence that consistently declining consumption per capita may be a credible predictor of population dispersal under increasing water scarcity conditions. Is it then that consumption per capita decline only in systems where the population ultimately declines or can it happen in other cases as well?

We now perform and analyze a targeted sensitivity analysis in order to demonstrate that declining consumption per capita is a robust predictor of an eventual dispersal of population under increasing water scarcity. The targeted sensitivity analysis is performed for cases when water availability remains constant in order to demonstrate that the rate of growth of production and population is neither constant nor negative.

Hence declining consumption per capita is a symptom only of socio-hydrological systems that eventually disperse.

4.4 Is growth-stabilized trajectory possible?

A growth-stabilized trajectory is a case where the aggregate production grows at a constant growth rate. If we represent aggregate production $f(X_t, U_t, E_t; v_t)$ at time t by f_t , then for a growth stabilization trajectory it is required that $\frac{f_{t+1}}{f_t} = 1 + d$. Here d is a (constant) rate of stabilized growth that does not depend on time.

We now demonstrate through a targeted sensitivity analysis that a growth stabilization trajectory is not possible unless (i) the effectiveness of investment on technological change is zero (i.e., $\gamma = 0$ or no technological change occurs) or (ii) water resource availability declines at a “unique” rate. Further, we show that the growth rate is never negative unless water resource availability declines. Both these are important conditions that are needed to demonstrate that declining consumption per capita is a symptom only of technology-mediated socio-hydrological systems that eventually disperse under increasing water scarcity.

First we note that

$$f_t = v_t X_t^\alpha U_t^\beta E_t^{1-\alpha-\beta}.$$

We first consider the case of no declining water resource availability, i.e., $k = 0$. Then

$$\frac{f_{t+1}}{f_t} = \frac{v_{t+1}}{v_t} \left(\frac{U_{t+1}}{U_t}\right)^\beta \left(\frac{E_{t+1}}{E_t}\right)^{1-\alpha-\beta}. \tag{1}$$

The model equations suggest that skilled workers at time $t + 1$ are researchers at time t , or $E_{t+1} = S_t$. Further, according to the model equations, the number of unskilled workers and researchers at time t are proportional to the overall population of the system, i.e., $U_t \propto \Omega_t$ and $S_t \propto \Omega_t$. Substituting these relationships in Eq. (1) we obtain

$$\frac{f_{t+1}}{f_t} = \frac{v_{t+1}}{v_t} \left(\frac{\Omega_{t+1}}{\Omega_t}\right)^\beta \left(\frac{\Omega_t}{\Omega_{t-1}}\right)^{1-\alpha-\beta}. \tag{2}$$

Again, from the derived model equations, we note that population growth is endogenous in the sense that, depending on a consumption per capita threshold c^U , it either grows at a certain rate (when consumption per capita is above this threshold) or declines (when consumption per capita is below this threshold) at a certain rate. The threshold therefore represents the resilience of the population to livelihood that is possible within the basin. At one extreme, if $c^U = 0$, the society is extremely resilient and is able to grow even if no livelihood is possible within the basin. Another extreme is the case when $c^U = c_{t=0}^U$, which is a case of a society that is extremely vulnerable.

For now, we assume that the population grows at a certain constant rate \tilde{r}^Ω . We later show through simulations for $c^U = 0.99 c_{t=0}^U$ (i.e., $\eta = 0.99$) and $c^U = 0.01 c_{t=0}^U$

(i.e., $\eta = 0.01$) that the conclusions we draw with constant \tilde{r}^Ω remain the same (that a stabilized growth trajectory is beyond the realm constructed by the model).

Thus from Eq. (3) we have

$$\begin{aligned} \frac{f_{t+1}}{f_t} &= \frac{v_{t+1}}{v_t} (1 + \tilde{r}^\Omega)^\beta (1 + \tilde{r}^\Omega)^{1-\alpha-\beta} \\ &= \frac{v_{t+1}}{v_t} (1 + \tilde{r}^\Omega)^{1-\alpha}. \end{aligned} \tag{3}$$

However, as we can see from Eq. (4), even if the population grows at a constant rate, the growth rate of aggregate production depends on the growth rate of technology. We now show that unless $\gamma = 0$, the technology does not grow at a constant rate.

We note from the model equations that

$$\begin{aligned} \frac{v_{t+1}}{v_t} &= \left[1 + \gamma S_t (\theta \delta w_t^U + Q_t/S_t)\right] \\ &= \left[1 + \gamma \frac{S_t}{U_t} (\theta \delta U_t w_t^U + Q_t)\right]. \end{aligned} \tag{4}$$

Further, the model equations (in Sect. 3.5) suggest that the ratio of researchers to unskilled workers at any time is constant, given by $\frac{S_t}{U_t} = 1/\delta$.

We now note the following two equations from the model equations that we obtained in Sect. 3.5. The first equation suggests that the wage rate of an unskilled worker multiplied by the number of unskilled workers is proportional to aggregate production. The second equation suggests that the surplus that is generated by the society at any time t , Q_t , is proportional to aggregate production. In both the cases the constant of proportionality are corresponding factors of production. Hence

$$\begin{aligned} U_t w_t^U &= U_t \beta v_t X_t^\alpha U_t^{\beta-1} E_t^{1-\alpha-\beta} = \beta v_t X_t^\alpha U_t^\beta E_t^{1-\alpha-\beta} = \beta f_t. \\ Q_t &= \alpha f_t. \end{aligned}$$

If we now substitute these equations in Eq. (4), we obtain

$$\frac{v_{t+1}}{v_t} = [1 + \gamma(\theta\beta + \alpha) f_t]. \tag{5}$$

Finally, if we substitute Eq. (6) in Eq. (4) we obtain a more simplified form for growth of aggregate production

$$\begin{aligned} \frac{f_{t+1}}{f_t} &= [1 + \gamma(\theta\beta + \alpha) f_t] (1 + \tilde{r}^\Omega)^{1-\alpha} \\ &\propto [1 + \gamma(\theta\beta + \alpha) f_t]. \end{aligned} \tag{6}$$

Equation (7) demonstrates that the only way the model simulates a stabilized growth trajectory would be when $\gamma = 0$ (i.e., the effectiveness of investment on technological innovation is 0), especially since the parameters θ, β, α are required to be greater than 0. If $\gamma > 0$, the growth rate is not a constant since it then depends on f_t itself.

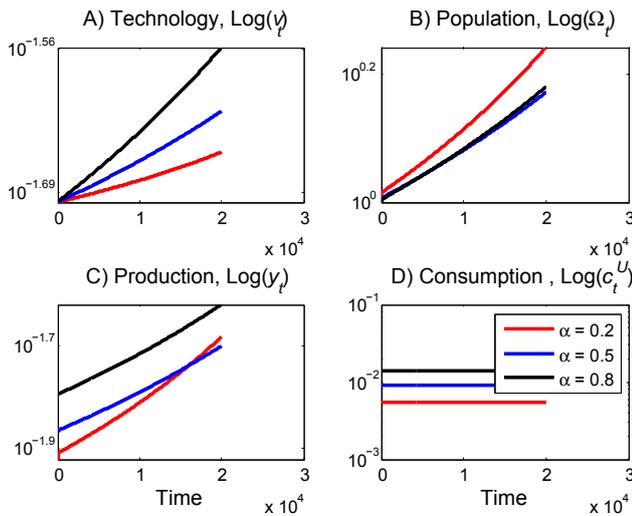


Figure 9. Case of a vulnerable society and highly productive skilled labor. Assumptions: $\eta = 0.99$ to represent a highly vulnerable society, low effectiveness of investment on technological change ($\gamma = 1 E - 3$), the ratio of factors of production of skilled to unskilled worker, $\frac{1-\alpha-\beta}{\beta} = 2$ and constant availability of water resources (i.e., $k = 0$).

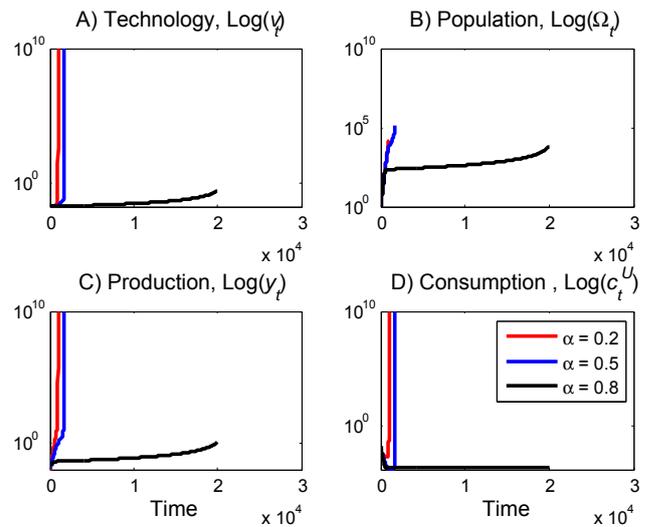


Figure 10. Case of a resilient society with highly productive skilled labor. Assumptions: $\eta = 0.01$ to represent a highly vulnerable society, low effectiveness of investment on technological change ($\gamma = 1 E - 3$), $\frac{1-\alpha-\beta}{\beta} = 2$ and constant availability of water resources (i.e., $k = 0$).

To be exact, if we solve for d_t in $\frac{f_{t+1}}{f_t} = 1 + d_t$, we obtain

$$d_t = [1 + \gamma(\theta\beta + \alpha) f_t] (1 + \tilde{r}^\Omega)^{1-\alpha} - 1. \quad (7)$$

Clearly, d_t is not a constant and varies over time. It is evident from the above that as the magnitude of γ increases, d_t is a stronger non-constant. Thus we perform a targeted sensitivity analysis on c_t^U as previously suggested for a low value of γ ($= 1 E - 3$) and show that even in the case of weak effectiveness of investment on technological change (i.e., low value of γ), d_t is not a constant.

4.4.1 Case 1

Vulnerable society and highly productive skilled labor. We assume $\eta = 0.99$ to represent a highly vulnerable society. We also assume low effectiveness of investment on technological change ($\gamma = 1 E - 3$). Since skilled is more productive than unskilled worker, we assume the ratio of their factors of production (the parameters associated with skilled and unskilled labor in the production function), $\frac{1-\alpha-\beta}{\beta} > 1$. Here we consider a case that $\frac{1-\alpha-\beta}{\beta} = 2$. This would mean that for one unit of output produced by the society, the contribution of skilled labor is twice the contribution of unskilled labor. Hence we call this case a highly productive skilled labor case because there is a large difference between the (per unit output) contribution of skilled labor to that of unskilled labor. Finally, we assume constant availability of water resources (i.e., $k = 0$).

Figure 9 plots four dominant variables of the coupled dynamics (technology, population, production, consumption per capita).

For a stabilized growth trajectory we would expect the plot for production to be linear on a log scale. None of the three productive cases for water show a linear trend, though it appears to be linear for the case for $\alpha = 0.8$. The population trajectories are also not linear in time for any α , hence the population trajectories are not growth stabilized either. Consumption per capita appears to co-evolve at a near-zero rate. Again the trajectories of technology appear to grow linearly in a log scale for $\alpha = 0.8$, possibly due to near-stabilized production growth. Thus, even in the case of weak effectiveness of investment on technological change ($\gamma = 1 E - 3$, which is considerably less than 1), we do not see stabilized growth for any scenario of factor of production. This becomes evident when the time limit for simulations is increased from 20 000, as in the present case, to $2 E + 5$ (figure not shown). Singularity (i.e., spiked trajectory) in the growth in all four dominant variables is observed. This holds for the following three cases as well.

4.4.2 Case 2

Resilient society with a highly productive skilled labor. We assume $\eta = 0.01$ to represent a resilient society. We also assume low effectiveness of investment on technological change ($\gamma = 1 E - 3$). We again consider the case that $\frac{1-\alpha-\beta}{\beta} = 2$ and assume constant availability of water resources (i.e., $k = 0$).

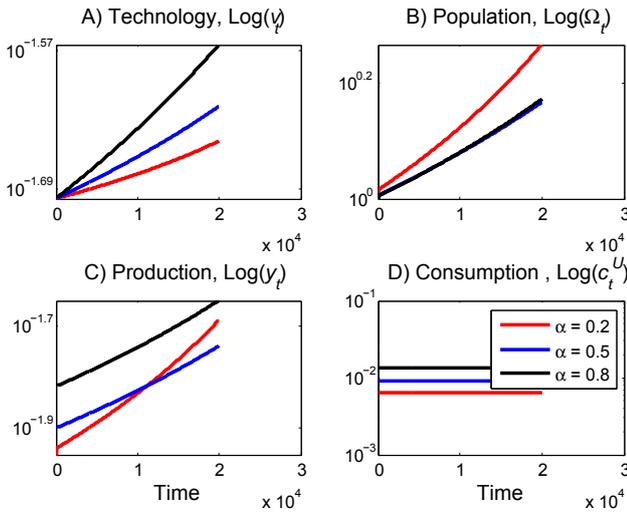


Figure 11. Case of a vulnerable society with marginally productive skilled labor. Assumptions: $\eta = 0.99$ to represent a highly vulnerable society, low effectiveness of investment on technological change ($\gamma = 1 E - 3$), $\frac{1-\alpha-\beta}{\beta} = \frac{0.35}{0.3}$ to represent a skilled labor force that is marginally productive over unskilled labor and constant availability of water resources (i.e., $k = 0$).

Figure 10 present the results. As expected, a resilient society sees “singularity” in the trajectories (spiky) of all four dominant variables for small to medium factors of production of water ($\alpha = 0.2$ and $\alpha = 0.5$ resp.). In none of the cases is the growth of any of the variables stable. For the non-singular trajectory case of $\alpha = 0.8$, which is when the factor of production of labor is small compared to that of water, none of the variables’ trajectories is linear. This indicates that even here the growth is not stable.

4.4.3 Case 3

Vulnerable society with marginally productive skilled labor. We assume $\eta = 0.99$ to represent a highly vulnerable society. We also assume low effectiveness of investment on technological change ($\gamma = 1 E - 3$). We consider a case in which $\frac{1-\alpha-\beta}{\beta} = \frac{0.35}{0.3}$ to represent a skilled labor force that is marginally productive over unskilled labor. Finally, we assume constant availability of water resources (i.e., $k = 0$).

We witness a pattern similar to case 1 in Fig. 11. It appears that the factor of production of skilled labor relative to unskilled labor does not have much influence over the trajectories of dominant variables. Rather, it depends on the resilience of a society to available livelihood and hence population growth.

4.4.4 Case 4

Resilient society with a marginally productive skilled labor. We assume $\eta = 0.01$ to represent a resilient society. We also assume low effectiveness of investment on

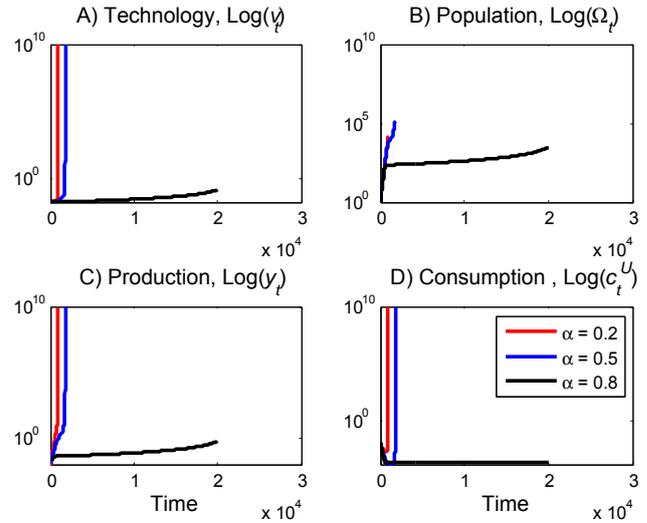


Figure 12. Case of a resilient society with marginally productive skilled labor. Assumptions: $\eta = 0.01$ to represent a highly vulnerable society, low effectiveness of investment on technological change ($\gamma = 1 E - 3$), $\frac{1-\alpha-\beta}{\beta} = \frac{0.35}{0.3}$ and constant availability of water resources (i.e., $k = 0$).

technological change ($\gamma = 1 E - 3$). We again consider the case that $\frac{1-\alpha-\beta}{\beta} = \frac{0.35}{0.3}$ and assume constant availability of water resources (i.e., $k = 0$).

Again, we witness the same pattern as for case 2 in Fig. 12. Nonetheless, in none of the cases do we find stabilized growth, though for large η it appears that a near-stable growth path is realized. This was also concluded from Eq. (8). All four cases were simulated for low effectiveness of investment on technological change (for a low value of γ). A higher value of γ would only introduce a stronger non-constant growth rate as Eq. (8) (and additional sensitivity analysis not shown here) demonstrates.

The above analytical result and targeted sensitivity analysis together demonstrate that for constant water resource availability, a growth-stabilized trajectory is only possible for the case when $\gamma = 0$. However, this case then represents a socio-hydrological system that is not exposed to technological innovation.

It may not be the only case when a growth-stabilized trajectory of dominant a variable is realized. We assumed $k = 0$ to ignore the case of declining water availability. For a negative $k > -1$, reducing water resource availability compensates non-stabilized growth. We assumed this reduction to be external to the system. It is, however, possible to incorporate a negative consequence of growth on water resource availability (that encapsulated both quality and quantity) that may result in a constitutive relationship between growth and water resource availability. The growth may then stabilize if the constitutive relationship is such that it exactly compensates

for the effect of population and technology (time-varying) growth.

To be exact, as we defined earlier, let $\frac{X_{t+1}}{X_t} = (1 + k_t)$ represent how water resource availability varies in time. Then Eq. (8) under varying water resource availability can be reformulated as

$$d_t = [1 + \gamma(\theta\beta + \alpha)f_t](1 + \tilde{r}^\Omega)^{1-\alpha} (1 + k_t)^\alpha - 1. \quad (8)$$

Then for d_t to be constant in time for a growth-stabilized trajectory, say d , it would require that water resource availability varies in correspondence with f_t to preserve a constant d given by

$$1 + d = [1 + \gamma(\theta\beta + \alpha)f_t](1 + \tilde{r}^\Omega)^{1-\alpha} (1 + k_t)^\alpha.$$

Whether this would be a realistic constitutive relationship is beyond the scope of the paper. It might be possible but a feedback relationship between growth and water resource availability would often be determined by relationships independent of a growth-stabilized trajectory.

Nonetheless, declining water resource availability is a necessary condition (within the realm of the model) for population to decline (or disperse), even when newer technologies are innovated to combat reducing water resource availability.

We also note from the above sensitivity analysis that the consumption per capita persistently did not decline in any of the cases studied. Yet from the analysis in Sect. 4.3 that was under reducing water availability, we observed that consumption per capita persistently declined in cases of population dispersals. This indicates that it would be sufficient to observe a persistent decline in consumption per capita to predict an eventual population decline. Such a conclusion is also intuitive. The endogenous population growth depends on consumption per capita in the model. If the latter falls below the critical threshold on consumption per capita (\underline{c}^U), the population growth turns negative. Negative population growth in turn reduces aggregate production since the population supplies labor for the production activity. This feeds back to consumption per capita since lower aggregate production reduces the wages which the population spends to consume. Thus a vicious circle of declining population and consumption per capita ensues.

5 Discussion

The paper has presented an overlapping-generations model of endogenous technological change and population growth under decreasing water availability. The overlapping generation model parsimoniously represented an economy where only one good is produced and consumed by four different types of agents: young researchers, young unskilled workers, retired (unskilled) workers and skilled workers. Balances of the goods produced and the payments were maintained.

The technological change was either induced or adopted based on the total consumption of young researchers who

subsisted on loans provided by unskilled workers and the surplus maintained by the society.

Multiple feedbacks between population, production, consumption and innovation were modeled. The strengths of these feedbacks were endogenously determined; hence, they may vary over time. Population growth was determined by consumption per capita realized by the various agents. Population, depending on how it endogenously splits into four different types of agents, contributed to production activities and implicitly determined consumption per capita. Consumption per capita depended on how much income an agent made, which in turn endogenously depended on the production technology, the labor participation and the level of specialization. Production depended on available technology, available resources and the specialization of the labor force (between skilled and unskilled workers).

In order to sustain a growing population, the production from technological advancement must surpass the consumptive demands of a growing population. It must counter the downward pull of decreasing water resource availability (though population growth also increases production at a constant level of other inputs). Unfortunately water availability decreases over time. The only way to avoid this physical limit is a state of singularity wherein technology is so infinitely superior that a physical limit no longer applies. In more realistic, non-singular cases, technological advancement can at best delay the effect of declining water availability on consumption per capita and hence on eventual population decline. In all these realistic cases, it therefore appears that persistent decline in consumption per capita, in spite of increasing production and technological change, is a credible predictor of eventual population decline.

A targeted sensitivity analysis was performed in order to test the robustness of the conclusion that a persistent decline in consumption per capita is a credible predictor of population dispersal in a socio-hydrological system. It was shown that production and population of a socio-hydrological system grow at a non-constant rate when water resource availability is constant. The growth rate in fact itself grows at a positive rate. Consequently consumption per capita grows. The targeted sensitivity analysis thus suggested that persistent decline in consumption per capita is a symptom only of a technology-mediated socio-hydrological system that eventually disperses.

Needless to say, technological advancement is not necessarily sufficient to allow societies to be limitlessly on top of nature – it is likely to be implausible. This mechanism of limits to technological advancement was hypothesized to be the case for the ancient Indus Valley civilization by Pande and Ertsen (2014) and for the contemporary case of the Murrumbidgee Basin by Kandasamy et al. (2014). The Indus Valley civilization rose to maturity despite decreasing water resource availability and advances in technology such as sophisticated water management systems. Yet it eventually dispersed. The Murrumbidgee Basin also witnessed a rise in

population and agricultural production amid increasing concerns of water quality. The population also eventually declined in the 1990s and continued its decline despite heavy investments in improving water management and changes in values and norms of individuals with respect to their use of water. Similar dynamics were also observed within the Lake Toolibin catchment in Western Australia (Elshafei et al., 2014). Our approach explains the rise and dispersal of societies observed in these different cases, although we do not claim that it can explain the development processes in and of these societies in full detail. We do not claim that our model is a unique or sole representation of the reality of these societies, but that it may be one possible representation of the underlying socio-hydrologic dynamics. Alternative explanations may be possible and are of course welcome.

6 Final remarks

The presented model is still limited in several aspects, which we discuss in the following. Only one type of technological change is considered that scales up production level (Jaffe et al., 2003). We therefore have ignored technological innovations that may be biased towards saving water (Hayami and Ruttan, 1970). Other types of inputs such as land or other resources have not been considered. Stratification in the society is simplistic and only one type of good is considered. Net population growth rate depends only on consumption per capita. Important aspects such as environmental quality and taxation to support technological innovation have been ignored (Chen and Li, 2011). We have also ignored the possibility of substitution between diverse sources of water due to the parsimonious nature of the model.

In principle, we do not see a decline in population as catastrophic. The decline may be a story of comparative advantage. The threshold on consumption per capita conceptualizes the notion of comparative advantage (though in a limited manner). It is implicitly assumed that there are always places outside the basin that allow for larger consumption per capita than this threshold. We therefore do not equate population to the success of a society. Since our model associates success of a society with aggregate production (which is equivalent to gross domestic product at basin scale), we can model positive population growth even under declining aggregate production (see for example Fig. 4b).

To allow for a response to population change, we have considered a very simple endogenous migration conceptualization by having a step change in the population growth rate as a function of consumption per capita. Nevertheless, our model does not sufficiently account for endogenous migration in the face of declining consumption per capita. This limitation is partly due to the need to preserve a parsimonious construct of society within the model. For example, to introduce the effect of increasing aggregate production on fertility rates and hence on population growth may require the

modeling of leisure (free time) alongside labor (time spent on work), which may further complicate the model.

We assumed that water available is used up for production since its supply would always be binding in water-scarce regions. Thus, the model at present does not allow agents to choose the amount of water. The model can, however, be extended further to allow for this, and may yield additional interesting dynamics. Additional complexity to the model may be introduced by allowing agents to choose between various sources of water supply (in addition to the amount that is used from each such supply). We also assumed, except during the sensitivity analysis, that water resource availability declines exponentially (at a rate close to 1) due to factors external to the system. The reducing water availability conditions around 4200 BP in the Indus Valley and elsewhere serves as one such example of externally imposed reducing water resource availability (Pande and Ertsen, 2014). However, the model can be made more realistic by implementing a feedback between production activity and water resource availability (reducing water quality).

While we provided a targeted sensitivity analysis for selected parameters in order to assess the possibility of a stabilized growth trajectory, the specification of the remaining parameters of the model was based on values generally reported in literature. For example, the parameter β_0 that measures the patience of an individual in terms of her choice to consume at present or save and consume the same unit sometime in the future is commonly assumed to be close to 1 but less than 1. Thus, we model individuals who are slightly impatient and like to consume at present, if given an opportunity, rather than patiently wait to consume the same at a later date. Our sensitivity analysis (which we did not show) on this parameter, however, suggests that patterns of dominant variables do not change with β_0 .

We defined a closed economy through our parsimonious overlapping generations model. An economy within a basin is probably never closed since it is exposed to food prices, trade and human migration, amongst other things (van Emmerik et al., 2014). However, such external effects can be introduced with the modeling framework presented here. For example, trade can be introduced in the livelihood maximization problem by bringing in the effect of trade and external (international) food prices on the wages of the agents.

Finally, the objective of the model was to understand possible mechanisms behind a particular socio-hydrological pattern observed in societies such as Lake Toolibin, Murrumbidgee and the Indus Valley. The pattern was that of the rise and dispersal of societies in the presence of technological innovation. A task for future research therefore is to see if the model can explain, and therefore help to understand, other potential patterns of societal development when additional complexities on both the hydrologic and societal fronts are at play.

The model developed in this paper is one of the first models that simulate endogenous growth with technological and

population changes. The conceptualization is parsimonious. It may have its limitations, but the outcomes suggest that endogenous technological change can be linked to increased water scarcity in a systematic, rather predictable way. To what extent and level of detail our current conclusions would change with additional complexities as discussed above remains to be explored. We hope to pursue this in our future work.

Appendix A

The census data for years 1976, 1981 and 1986 for New South Wales, Australia were downloaded from the Australian Bureau of Statistics website (<http://www.abs.gov.au/AUSSTATS/abs@.nsf/ViewContent?readform\&view=ProductsbyCatalogue\&Action=Expand\&Num=2.2>).

The tables on income by occupation statistics were accessed and income levels for agricultural managers and laborers were obtained. Weighted (weighed by number of persons employed by the agricultural sector in a particular income bracket divided by total persons employed by the agricultural sector) sum of agricultural income was thus calculated in Australian dollars per unit agricultural labor for each of the 3 census years.

In order to convert income per unit labor into rice produced per unit labor, the income per unit labor is multiplied by its US dollar value in the December of that year and dividing it by the real price of Thai 5 % rice in (2005 USD mt^{-1}) for that year. The historical data for US dollar value of AUS dollar were obtained from the Reserve Bank of Australia historical monthly exchange rate data set (<http://www.rba.gov.au/statistics/hist-exchange-rates/index.html?accessed=2013-09-17-14-08-00>) and the price for Thai rice was obtained from the World Bank collection of commodity prices from 1960 to present (<http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTDECPROSPECTS/0,,contentMDK:21574907~menuPK:7859231~pagePK:64165401~piPK:64165026~theSitePK:476883,00.html>).

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References

- Aghion, P. and Howitt, P.: Chapter 1: Towards endogenous growth, *Endogenous Growth Theory*, MIT Press, Cambridge, MA, 1997.
- Arrow, K.: The Economic Implications of Learning by Doing, *Rev. Econ. Stud.*, 29, 155–173, 1962.
- Bijker, W. E.: Of bicycles, bakelites, and bulbs. Towards a theory of sociotechnical change, MIT Press, London, Cambridge, 1995.
- Burlingame, R.: Technology: Neglected Clue to Historical Change, *Technol. Culture*, 2, 219–229, 1961.
- Chen, H. and Li, M.: Environmental tax policy, habit formation and nonlinear dynamics, *Nonlin. Anal. Real World Appl.*, 12, 246–253, 2011.
- Cuypers, J. G. M. and Rademaker O.: An analysis of Forrester’s World Dynamics Model, *Automatica*, 10, 195–201, 1974.
- Diamond, P.: National debt in a neoclassical growth model, *Am. Econ. Rev.*, 55, 1126–1150, 1965.
- Eicher, T. S.: Interaction between endogenous human capital and technological change, *Rev. Econ. Stud.*, 63, 127–144, 1996.
- Elshafei, Y., Sivapalan, M., Tonts, M., and Hipsey, M. R.: A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach, *Hydrol. Earth Syst. Sci.*, 18, 2141–2166, doi:10.5194/hess-18-2141-2014, 2014.
- Ertsen, M. W.: Locales of happiness. Colonial irrigation in the Netherlands East Indies and its remains, 1830–1980, VSSD Press, Delft, 2010.
- Ertsen, M. W., Murphy, J. T., Purdue, L. E., and Zhu, T.: A journey of a thousand miles begins with one small step – human agency, hydrological processes and time in socio-hydrology, *Hydrol. Earth Syst. Sci.*, 18, 1369–1382, doi:10.5194/hess-18-1369-2014, 2014.
- Forrester, J. W.: *World Dynamics*, Wright-Allen, Cambridge, Massachusetts, 1971.
- Funk, C. and Brown, M.: Declining Global Per Capita Agricultural Production and Warming Oceans Threaten Food Security, *Food Security*, 1, 271–289, doi:10.1007/s12571-009-0026-y, 2009.
- Giddens, A.: Central problems in social theory: action, structure and contradiction in social analysis, *Contemporary social theory*, MacMillan, London, 1979.
- Giddens, A.: The constitution of society: outline of the theory of structuration, Polity Press, Cambridge, 1984.
- Hayami, Y. and Ruttan, V. W.: Factor Prices and Technical Change in Agricultural Development: The United States and Japan, 1880–1960, *J. Polit. Econ.*, 78, 1115–1141, 1970.
- Hayes, B.: Computation and the human predicament, *Scientific American*, 100, 186–191, 2012.
- Imrohroglu, S., Imrohroglu, A., and Joines, D.: Social Security in an Overlapping Generations Economy with Land, *Rev. Econ. Dynam.*, 2, 638–665, 1999.
- Jaffe, A. B., Newell, R. G., and Stavins, R. N.: Technological change and the environment, in: *Handbook of Environmental Economics*, 1st Edn., Volume 1, edited by: Mäler, K.-G. and Vincent, J. R., Elsevier Science B.V., 461–516, 2003.
- Kaldor, N.: A model of economic growth, *Econ. J.*, 67, 591–624, 1957.
- Kandasamy, J., Sountharajah, D., Sivabalan, P., Chanan, A., Vigneswaran, S., and Sivapalan, M.: Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: a case study from Murrumbidgee River basin, Australia, *Hydrol. Earth Syst. Sci.*, 18, 1027–1041, doi:10.5194/hess-18-1027-2014, 2014.
- Latour, B.: *Reassembling the social. An Introduction to Actor-Network-Theory*, Oxford University Press, Oxford, 2005.
- Lyon, K. and Pande, S.: The costate variable in a stochastic renewable resource model, *Nat. Resour. Model.*, 19, 45–66, 2006.
- Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaeffli, B., Arheimer, B., Boegh, E., Schymanski, S. J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D. A., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., and Belyaev, V.: “Panta Rhei – Everything Flows”: Change in hydrology and society – The IAHS Scientific Decade 2013–2022, *Hydrolog. Sci. J.*, 58, 1256–1275, 2013.
- Nordhaus, W. D.: An Economic Theory of Technological Change, *American Economic Review*, *Am. Econ. Assoc.*, vol. 59, 18–28, 1969.
- Oded, G.: A Two-Sector Overlapping-Generations Model: A Global Characterization of the Dynamical System, *Econometrica*, 60, 1351–1386, 1992.
- Pande, S. and Ertsen, M.: Endogenous change: on cooperation and water availability in two ancient societies, *Hydrol. Earth Syst. Sci.*, 18, 1745–1760, doi:10.5194/hess-18-1745-2014, 2014.
- Pande, S. and McKee, M.: Valuing certainty in a consensus-based water allocation mechanism, *Water Resour. Res.*, 43, W02427, doi:10.1029/2004WR003890, 2007.
- Romer, P. M.: Endogenous Technological Change, in: *Journal of Political Economy*, University of Chicago Press, vol. 98, S71–102, 1990.
- Sachs, J. D. and McArthur, J. W.: Technological advancement and long-term economic growth in Asia, in: *Technology and the new economy*, edited by: Bai, E.-E. and Yuen, C.-W., MIT Press, Cambridge, MA, USA, 157–185, 2002.
- Sewell, J. H.: *Logics of history. Social theory and social transformation*, University of Chicago Press, Chicago, 2005.
- Shell, K.: Inventive Activity, Industrial Organization and Economic Growth, in: *Models of Economic Growth*, edited by: Mirrlees, J. A. and Stern, N., Macmillan, London, New York, John Wiley & Sons, Halsted, 77–100, 1973.

- Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C., Wescoat, J., and Rodriguez-Iturbe, I.: Socio-hydrology: Use-Inspired Water Sustainability Science For the Anthropocene, *Earth's Future*, 2, doi:10.1002/2013EF000164, 2014.
- Smart, J.: Measuring Innovation in an Accelerating World: Review of "A Possible Declining Trend for Worldwide Innovation", Jonathan Huebner, *Technol. Forecast. Social Change*, 72, 988–995, 2005.
- Van de Poel, I.: Changing technologies. A comparative study of eight processes of transformation of technological regimes, Twente University Press, Enschede, 1998.
- Van de Poel, I.: The transformation of technological regimes, *Research Policy*, 32, 49–68, 2003.
- Van der Zaag, P.: Comment on "Endogenous change: on cooperation and water in ancient history" by Pande, S. and Ertsen, M., *Hydrol. Earth Syst. Sci. Discuss.*, 10, 4829–4868, 2013, <http://www.hydrol-earth-syst-sci-discuss.net/10/4829/2013/>.
- van Emmerik, T. H. M., Li, Z., Sivapalan, M., Pande, S., Kandasamy, J., Savenije, H. H. G., Chanan, A., and Vigneswaran, S.: Socio-hydrologic modeling to understand and mediate the competition for water between agriculture development and environmental health: Murrumbidgee River Basin, Australia, *Hydrol. Earth Syst. Sci. Discuss.*, 11, 3387–3435, doi:10.5194/hessd-11-3387-2014, 2014.
- Wright, G.: Towards a more historical approach to technological change, *Econom. J.*, 107, 1560–1566, 1997.