Resilience in Ecology and Belief

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Abstract

This paper explores the crucial linkage between societal risk perception and the survival of threatened ecosystems exhibiting non-linear stock dynamics. Perception of beliefs over specie's importance and over its survival chances may be subject to resilience and therefore may differ from actual risks. Whereas, ecosystems stand a higher chance of survival if they aren't stressed beyond their resilience thresholds. When subjective perception of risks and the affected ecosystems are both influenced by competing uses of resources, several equilibriums arise, not all of which may ensure sustainability of the ecosystem.

Keywords: Belief dynamics, ecological hysteresis, water scarcity, groundwater dependent ecosystems, threshold effects

1. Introduction

Climate change induced impacts on natural resources, such as an increased frequency of droughts, pose significant challenges to the survival of the economic and ecological systems. When faced with resource scarcity, competing uses of such resources pose allocational challenges at a societal level, especially when the survival of the economy and the ecological systems is at stake. For instance, reduced rainfall creates pressure not only on agriculture but also on ecosystems in the surrounding habitats. In such a case, ground water dependent ecosystems (GDEs) may face the risk of extinction when the water table drops significantly. Allocating scarce water amongst agricultural and ecological uses could become a challenging task in presence of threshold levels for survival of species and the economic systems. Under these circumstances, resilient systems are more likely to survive under resource scarcity, than those that have lost their resilience.

Climate change related water scarcity is becoming increasingly real in several regions of the world. For instance, the city of Perth in Western Australia is currently dependent upon an underground aquifer system (the Gnangara mound) for meeting a major share of its urban demand for water. However, long periods of sustained droughts have significantly reduced water recharge to the aquifer thereby threatening its long term sustainability. When urban demand for water competes with the GDEs which are also dependent upon Perth's aquifer, it is not only the societal value of such species but also the actual risk posed to them that are being questioned. While scientific information related to such risks is qualitative at best, the public perception of such risks is chiefly conditioned by competing interests and by the amount of information the public has over such risks. Of these two factors, it is the public awareness of such risks which is of higher policy relevance as it could be influenced through focussed communications.

Public policies aimed at preserving the environment may face significant resistance if important resources such as water have competing uses in other sectors like agriculture and urban demand. Under this situation, it is the perceived risk of species extinction rather than the objective risks that becomes an important factor in determining key policies over water allocations. However, perceived risks may significantly differ from the objective risks, thus making water allocation to environmental uses difficult or insufficient at best.

The perception of environmental risks such as natural hazards is influenced by several psychological factors, chief amongst which are resistance to belief revision. One of the main principles behind belief revision- the *principle of minimal mutilation*- is that belief revision must be done so as to leave the original belief least disturbed and yet allowing for accommodation of new information (Rott 2000). Beliefs could change because people have different experiences (Picketty 1995) or due to pressure from interest groups (Benabou and Tirole 2006). It is further argued that direct signals of climate change may be subject to misinterpretation as isolated weather related signals and thus could be discarded if re-interpretation of these signals requires significant organizational changes (Berhout et al 2004).

Public opinion could differ on the basis of gender, race, education, political affiliation, etc. Women have been argued to be more risk averse than men. Beliefs, especially over risky events, are also influenced by individual's adherence to certain cohorts in the society.

Bleda and Shackley (2005) argue that businesses would not change their perceptions towards climate change until affirmative signals are received consistently for a long period of time. They further propose that reality is perceived by businesses after being filtered through a reference frame and is not perceived objectively. Consequently, experienced reality may differ from actual reality due to perceptions which are based upon their interests, etc. Gusfiled (1986) mentions that individual's perceive their status in a society by their adherence to a particular group. Consequently it is possible for risk to be perceived by the impact it would have on their status within a particular group and society. Interpretations of signals or experiences have also been found to be governed by the frame of reference of the receiver and could be resilient to objective revisions (Daft and Weick 1984).

When beliefs are resilient to revision, public policies that are influenced by such beliefs might face significant resistance too. This poses tremendous challenges to sustainably managing ecosystems that are prone to threshold effects, as interaction of belief and ecological thresholds may have implications for the survival of species. Understanding belief dynamics is therefore, crucial for influencing private participation for mitigation of water shortages. Market based instruments such as water prices may not be very effective in comparison as the value of urban water far exceeds the willingness to pay to the environmental provisions of water.

The purpose of this paper is to explore the nature of such linkages between the perception of risks of loss of ecosystems that are ground water dependent and the actual non-linearity exhibited in ecological systems from scarcity of water. Risk perception is modelled as a hazard function, which determines the instantaneous probability of occurrence of an event at time *t*, conditional upon that event not happening before time *t*, and is subject to resilience as defined in the traditional sense in the literature[i].

Ecological stock exhibits non-linearity in stock dynamics and undergoes a shift leading to a reduction in its own stock, thus causing a possible extinction in absence of adequate restoration[ii]. The common linkage between ecological catastrophe and belief resilience is water, as it provides the basis for ecological stock growth and also for perceived-risk dynamics. When water level falls too low, there is a shift in the perception of risks related to water shortages on the ecology. Alternatively, when the water level rises beyond a threshold, there is a downward shift in the risk perception of potential water shortage related hazards. If risk perception and ecological resilience are too low, extinction is certain, however, there are situations where the resultant outcomes may be determined by several factors that not only include the risks and resilience, but also the societal weights on the competing uses of water and starting conditions. Note that we model two shocks to the ecological system in the above approach, one non-linear shock- which is deterministic and the other, extinction shock- which is stochastic. It is more likely that societal awareness of the ecological risks is confined to ecological extinction and not to non-linear dynamic related shocks which might be equally important however.

The analytical approach adopted in this paper is to model the optimal allocation of water to competing uses when the planner incorporates the perceived risks of ecological extinction into the expected long term net benefit maximization problem along with the non-linear constraints faced by the ecological and belief systems. The climate change induced constraints are reflected through the water stock dynamics.

Several important insights arise from this exercise. The intersection of belief and ecological thresholds provides clues toward optimal policy choices and highlights the role of the timing of belief inducement. The importance of incorporating subjective perception of risks rather than objective perceptions, when it comes to environmental management, is the key recommendation of this analysis.

2. Model

The methodology used for modeling the risk of ecological extinction in this system is based on the work of Clarke and Reed (1994), and Tsur and Zemel (1994). The risk of extinction is modeled using a survival function to represent the ecosystem's likelihood of surviving in the pre-extinction state into each time period, *t*. Let *T* be the moment of ecosystem extinction. The cumulative probability distribution associated with extinction is denoted *F(t)*, where $F(t) = \Pr(T < t)$. The survivor function captures the probability that extinction has not yet occurred in time *t*, and represents the upper tail of the cumulative probability distribution:

(1) $S(t) = \Pr(T \geq t) = 1 - F(t)$.

In each time period it is assumed that, conditional upon arriving in time t without yet having been become extinct, the system faces a certain probability of transition into the post-extinction state, denoted $\dot{\lambda}(t)$. This conditional probability, $\dot{\lambda}(t)$, is also referred to as the hazard rate. Resilience in beliefs is determined by this hazard function which is given as:

(2) $$\dot{\lambda} = -w - \theta\lambda + \frac{\eta\lambda^a}{\lambda^a + b} + \tau,$$

where λ is the accumulated hazard over time (which we also refer to as 'belief' in this paper as it is a monotonic transformation of the survival function) and $\dot{\lambda}$ is defined as the perceived probability that the event will happen at time *t*, given that it has not already occurred before. The hazard rate here refers to the breakdown of the ecosystem characterized by a loss in the species stock. Once this happens, society stops receiving any ecological or environmental benefits from ground water dependent ecosystems (GDEs). Notice that the rate of change in hazard rate is negative in water stock (*w*), and also in its own accumulated hazard (λ), but has a positive exogenous component. As the stock of water increases, the perceived risk of an ecological catastrophe falls. The accumulated hazard also has a slowing down or negative impact on the hazard rate but makes it resilient to backward motion once a threshold level has been crossed. This resilience impact is given by the term $\frac{\eta\lambda^a}{\lambda^a + b}$.

The hazard rate should also be influenced by the ecological stock, however, here we incorporate that relationship indirectly through the stock of water. The steady state relationship between water and the stock of accumulated hazard is given in figure 1 for a particular set of parameters as shown in the appendix.

INSERT FIGURE 1 HERE.

Also, note that the perceived risk is over species extinction and not over the non-linear fall in species stock with water shortages.

The stock of the threatened ecological/environmental system (*q*) (for instance ground water dependent species) evolves as:

(3) $$\dot{q} = \xi w + \psi q - \frac{\eta q^a}{q^a + b},$$

where the rate of change of ecological stock is positive in its own stock but undergoes a downward hysteretic shift if the stock falls below a certain threshold[iii]. This threshold is captured by the term $-\frac{\eta q^a}{q^a + b}$.

In this paper we follow the '*ecological resilience*' definition to model the impact on the ecosystem. Parameters η, a and b define the rate and magnitude of this effect and determine whether shift is steep or non-linear. Stock induced shifts in environmental quality is defined in a positive sense here, as beyond a certain threshold of environmental stock the environment shifts into a better state and is more responsive to stock effects. Consequently, resilience here is defined in terms of an improvement in the ability of the system, through enhanced stock effect, to fight back resource scarcity constraints. Maler et al. (2003) use similar functional form as in equations (2) and (3) in their paper to model the negative impact of a pollutant such as an input of phosphorous in a lake which could lead to hysteresis effect once a threshold level of the stock of phosphorous is crossed.

Water has a positive impact on the rate of growth of ecological stock. The steady state relationship between water and the stock of ecological resources is given as shown in figure 2.

INSERT FIGURE 2 HERE

The juxtaposition of the two steady state relationships is shown in figure 3. The comparison of the two steady state relationships over a common denominator of water provides important clues towards the relative influence of the dwindling stock on water on the belief and ecological stocks. If one threshold is crossed before the other, is it possible to predict the outcome before hand? Further, is it possible to perturb the belief system in order to achieve better societal outcomes? We explore these questions in the following sections.

INSERT FIGURE 3 HERE

2.1. Optimization Problem

Society's problem is to maximize the expected inter-temporal benefits from the use of water and the ecological resources subject to the constraints posed by equations (2) and (3). There is an additional constraint over the availability of water and we assume that the long term supply of water from the ground is limited by the climate change impact and there is no significant recharge. This is given as:

(4) $\dot{w} = -h$

where h is the amount of water harvested from the ground[iv]. There may be alternative sources of water that would make unlimited water available for consumption at a higher price (for example, sea water desalination); however, we do not consider this option as a part of equation (4) as we assume that such alternate sources are not available for environmental usage.

The optimization problem is defined as:

(5) $$\max \int_0^{\infty} (\log(h) + q * \theta + \dot{\lambda} \frac{\log(w\rho)}{\rho}) e^{-\lambda(t)} e^{-\rho t} dt,$$

subject to (2), (3) and (4). The environmental stock yields use or non-use benefits θ per time period. The term $\frac{\log(w\rho)}{\rho}$ in the above equation is the long term discounted value ($v(t)$) from groundwater resources after a catastrophic loss of the ecosystem resources and is derived as:

(6) $v(t) = \int_t^{\infty} \log(h(t)) e^{-\rho t} dt$, subject to (4)

The other term in (5), $\int_0^{\infty} \log(h) + q\theta$, is the value from groundwater harvest and the ecological benefits from GDE. We assume the value from water harvest to be increasing at a decreasing rate, which in a sense captures the increasing costs of water extraction. The environmental benefits from the ecological stock are modelled as being linear for the sake of simplicity. The current value Hamiltonian is given as:

(7)

$$(\log(h) + q\theta + \dot{\lambda}\frac{\log(w\rho)}{\rho})e^{-\lambda(t)} + m_1(-w - \theta\lambda + \frac{\eta\lambda^a}{\lambda^a + b} + \tau) + m_2(\xi w + \psi q - \frac{\eta q^a}{q^a + b}) + m_3(-h)$$

The first order condition with respect to groundwater harvest is given as:

(8) $$\frac{1}{h}e^{-\lambda(t)} = m_3$$

This requires that the shadow price of water must be equated to its marginal value from consumption. Note that the shadow price of water is related to the shadow price of the stock of hazard rate and also to the shadow price of the stock of environmental stock as shown in equation (9) below. The no-arbitrage condition with respect to the shadow price of water is given as:

(9) $$\dot{m}_3 = m_1 - \xi m_2 + \rho m_3$$

In steady state the shadow price of stock of water will be given as:

(10) $$m_3 = \frac{-m_1 + \xi m_2}{\rho}$$

This means that the shadow price of the stock of water is the long term discounted sum of the altered shadow prices of the stocks of risks and of the ecological stock from a marginal reduction in water.

(11) $$\dot{m}_2 = -\theta e^{-\lambda(t)} + \rho m_2 - \psi m_2 + m_2 \partial \frac{\frac{\eta q^a}{q^a + b}}{\partial q}$$

(12) $$\dot{m}_1 = (\log(h) + q * \theta + \dot{\lambda} \frac{\log(w\rho)}{\rho}) e^{-\lambda(t)} + \theta m_1 - \partial \frac{\frac{\eta \lambda^a}{\lambda^a + b}}{\partial \lambda} m_1 + \rho m_1$$

In steady state equation (9), (11) & (12) are equated to zero, giving:

(13) $$m_1 = -\frac{(\log(h) + q * \theta + \dot{\lambda} \frac{\log(w\rho)}{\rho}) e^{-\lambda(t)}}{\theta - \partial \frac{\frac{\eta \lambda^a}{\lambda^a + b}}{\partial \lambda} + \rho}$$

(14) $$m_2 = \frac{\theta e^{-\lambda(t)}}{\rho - \psi + \partial \frac{\frac{\eta q^a}{q^a + b}}{\partial q}}$$

and

(15) $$\rho \frac{1}{h} e^{-\lambda(t)} = \xi \frac{\theta e^{-\lambda(t)}}{\rho - \psi + \partial \frac{\frac{\eta q^a}{q^a + b}}{\partial q}} - \frac{(\log(h) + q * \theta + \dot{\lambda} \frac{\log(w\rho)}{\rho}) e^{-\lambda(t)}}{-\theta m_1 + \partial \frac{\frac{\eta \lambda^a}{\lambda^a + b}}{\partial \lambda} m_1 - \rho m_1}$$

Equation (13) requires that in steady state the shadow price of risk must equal the long term discounted sum of per period instantaneous benefits before a catastrophe. That is, an increase in the risk of a catastrophe threatens the value derived before the catastrophe. The discount factor in the denominator of the term on the right hand side includes the partial derivate of the belief resilience factor with respect to its own stock. This partial of the resilience factor is going to be at its maximum just before the threshold level of risk stock when the risk shifts from low to high or vice versa. The larger this shift, or the nearer the perception of the accumulated hazard to this critical threshold, the lower would be the value of the numerator. Intuitively, the cost of increasing the risk increases, the closer the system is towards the resilience threshold. Whereas, the cost of decreasing the risk falls, the farther the system is from the threshold. Note that the shadow price of risk is positive. This may have policy implications in terms of managing risk perception based upon its proximity to the resilient threshold or at least for understanding the nature of these thresholds.

Equation (14) requires that the shadow price of the ecological stock be equated to the discounted benefits to be had from the increasing the stock marginally. The discount element in the denominator also contains the partial of the hysteresis effect and implies that this discounting is going to stronger the closer the system is to the hysteretic threshold. That is, the costs of reducing the environmental quality marginally are higher, the closer is the system to the threshold. Finally, equation (15) requires that the marginal utility from harvesting water be equated to these shadow prices, as derived in equation (10) above.

Another crucial question is over the extent of the influence of the differences in the objective and subjective risks on the actual and perceived survival of the ecosystem. In order to explore this, one simplification could be that the objective risks follow a similar pattern as the perceived risks, but without the resilience effect. While in reality, it may hold that the objective risks lie completely to the left or right of the subjective risks thus implying under or over-estimation. When risks are underestimated, it is likely that the survival of species would be threatened. When risks are over-estimated, adequate measure for species protection would be undertaken only when the benefits of doing so exceed the costs, thereby not ensuring their survival all the time. We turn to numerical simulations next to explore these intuitions further.

3. Numerical Simulations

We select a hypothetical set of parameters as defined in the Appendix (Table 1) to perform numerical simulations over the above optimization problem. We consider three different scenarios that are differentiated by the threshold levels of the stock of water at which there is a shift in the belief and ecological stocks. The first scenario considers a case where the shift in the belief happens too early but its magnitude is too little to have a considerable impact over the long term risk calculus. The second set of simulations involves a larger shift in the belief stock, but the resilient threshold for belief still lies below that of the ecological stock. In the final scenario the resilient threshold for belief lies above that of the ecological stock. The main purpose of this exercise is to explore the role of intersection of the two thresholds in determining equilibria. We also compare the final scenario with the possibility that objective risks are unweighted in order to derive implications for policy intervention.

For the first scenario, figure 4 shows the contour plot of the isoclines for which the belief and ecological stock are in steady state. Notice the discontinuity in the steady state isoclines, signifying possibility of multiple equilibriums.

INSERT FIGURE 4 HERE

Figure 5 shows the time path of belief and ecological stock evolution. The ecological stock falls from it starting value of 8 to a very low level as the stock of accumulated hazard increases. The increasing stock of hazard also implies a continuous withdrawal of water for consumption purposes. The primary reason for such a behaviour is that a marginal shift in the risk perception at a very high level of water makes species preservation costly.

INSERT FIGURE 5 HERE

Figure 6 juxtaposes the time paths of the isoclines in order to show their convergence. Note that the level of risk increases as the stock of environment declines.

INSERT FIGURE 6 HERE

Figure 7 plots the steady state relationship between belief, ecological stock and water level for the second scenario. Notice that the shift in the belief happens at a much lower level of water and at a much higher level of belief than the base case.

INSERT FIGURE 7 HERE

Figure 8 shows the time path of evolution of the ecological stock and belief. Notice the back and forth movement of the environmental stock as the stock of belief shifts upwards. This back and forth movement of the environmental stock happens due to the ecological stock being near its resilient threshold and water being used at an optimal rate that allows the risk to increase steadily. Intuitively, given that the ecological stock falls within the range from where it is possible to gain further increases in stock owing to the effects of water level and its own stock, it is optimal for the manager to allow a slower rate of water extraction in order to maintain the environmental stock at a higher level. However, the risk perception effect in this scenario too falls short of the level that could ensure the eventual survival of the ecosystem and the extinction cannot be avoided in the end.

INSERT FIGURE 8 HERE

Figure 9 shows the time path of ecological stock and belief stock along the steady state contours.

INSERT FIGURE 9 HERE

Figure 10 shows the fluctuations in the ecological stock brought in by the falling water table. Notice that the rate of decrease in the water table is crucial towards determining ecological resilience.

INSERT FIGURE 10 HERE

Figure 11 shows the juxtaposition of the belief and ecological stock steady states for the final scenario. Also depicted is the belief pattern without the resilience component which is the straight line falling with an increase in the water stock. The idea here is to explore the impact of objective risks in influencing species conservation and compare it to the subjective risks case.

INSERT FIGURE 11 HERE

When subjective risks are considered, figure 12 plots the time paths of the ecological and belief stocks along with the steady state balance. In this case, notice that the steady state is not reached as the stock of ecological goods increase steadily over time and the risk is kept low. The perception of risk is now endogenously constrained at low levels through no water withdrawals. The perceived risks and the associated rewards from water conservation are so high as to lead to no water consumption and dedication of all water towards species growth. Notice the fluctuations in the belief over risks related to extinction. These fluctuations are constrained between the upper and lower bounds of approximately 6.5 and 3. It can be verified that the large stock of water has a negative impact on the belief patterns, thus lowering it, whereas the resilience impacts and the exogenous components of risk lead to an increase in the risks. Figure 13 shows the plot of the rate of change of belief stock over water and belief stocks. Notice the convex-concave curve formation when the rate of change of belief cuts the zero-level plane, thus implying negative and positive feedbacks to the rate of change as it crosses its own thresholds in stock of belief. This effect, however, is restricted to a range of stock of water, which for this case is between 70 and 100 units of water approximately. Below this range, risk perception increases significantly and all the water is withdrawn for consumption eventually.

INSERT FIGURE 12 HERE

Because we do not model any constraints on species carrying capacity, the stock of species continues to growth limitlessly. However, in presence of a carrying capacity constraint there is likely to be some water withdrawal for consumption as benefits from ecological conservation would be limited.

INSERT FIGURE 13 HERE

Figure 14 contrasts with the subjective risk case above by plotting the scenario when only objective risks are taken into account. Notice that in this case the steady state involves a very low level of species stock (implying species extinction) and high water withdrawal (as could be deciphered through a high level of belief stock). This clearly highlights the role of risk perception in influencing species conservation. Interestingly, even as the objective risks were lower, a high perception of such risks led to high preservation efforts. This has important implications for policy purposes as it provides clues toward the extent to which belief systems could be perturbed in order to achieve desirable outcomes. This becomes even more apparent when comparing outcomes of the cases depicted in figures 9 and 12. The outcome in figure 9 leads to a low level of environmental stock, whereas the outcome in figure 12 leads to a high level of environmental stock. The difference between the two cases is the parameter η_1 and b_2. It is possible to have similar results even as the parameter b_2 is kept constant in the two cases. In which case, it is the relative resilience in belief shifts between the two cases that is making all the difference between a desirable and an undesirable outcome. Institutions that are able to alter such belief processes in time have a better chance of preserving their threatened ecosystems. How to achieve such belief inducements is, therefore, a very important policy question for future. Perhaps institutional settings that help propagate such subjective belief augmentation are the key toward current and future environmental problems.

INSERT FIGURE 14 HERE

3.1. Extension

In this paper we modelled belief resilience and ecosystem resilience as functions of the stock of water. However, in certain cases it may be the rate of change in water stock that is crucial towards influencing shifts in species composition or changes in beliefs. For instance, the slower the rate of change in stock of water, the more time would species get to adapt to the new environment thereby ensuring their smoother transition. A faster drop in the water level on the other hand may not allow for enough time to adapt thus increasing the chances of extinction. Similarly, perception of risk related to the impact of water shortages is also influenced by the rate at which water level drops; a higher rate of drop would create alarm and thereby force belief revision and shifts. This phenomenon is akin to enhanced perception of global warming related risks when the media chatter over it increase in intensity. A lower rate of drop, on the other hand would create complacency and false expectations. When belief dynamics and ecological resilience are related to the rate of change of water rather than the stock of water, interesting implications may arise. For instance, even when there is sufficient water for public withdrawal, the rate of withdrawal cannot be increased, as it would increase the risk perception. Whereas, even if there is low stock of water, as long as water is withdrawn at a lower rate, thereby allowing time for species to adapt, catastrophic incidents can be avoided. Consequently, if threshold impacts are triggered by the rate of change of a resource, rather than by the stock of it, planner's ability to optimize is constrained. This should be intuitive as rate of resource extraction is the direct tool available to the planner, whereas the stock of resource is the indirect one.

4. Conclusion

This paper highlights the linkages that might exist between environmental preservation and perceived-risk dynamics. Here it is argued that it is not the actual level of objective risks but the subjective perception of risks which is crucial towards environmental decision making. When non-linearities exist in environmental stock dynamics and also in the path of risk evolution, several equilibria might arise, not all which may be socially desirable. Numerical simulations bring to fore some of these equilibriums and highlight the role of relative placement of these non-linear phenomenons to each other in influencing the survival of threatened ecosystems. Understanding the nature of these non-linear effects is the key towards understanding the nature of the outcomes and more importantly towards being able to shape these outcomes.

This emphasizes the role of belief inducement at crucial stages of belief dynamics towards being able to gain maximum shifts in belief patterns for optimizing societal objectives. Several challenges exist towards connecting societal risk perception (or more importantly the risk perception of the stakeholders in dwindling natural resources) to actual management of threatened ecosystems. Understanding risk perception and altering them could be problematic given the current tools available to society, but this is exactly what the future climate change adaptation efforts would be asking for.

Another related implication for the relevance of belief inducement is the role for institutional settings in facilitating such belief formations and inducing optimal policy decisions. However, our understanding of the role of institutions or individuals in leading to aggregate belief formation is fairly limited at this stage, but recent advances in the field of experimental economics hold good promise for further explorations of these ideas.

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Appendix: Table 1: Parameter Values for the Base Case Simulation

Parameters	Definition	Value
a_1	Hysteresis parameter for the environment	**20**
a_2	Hysteresis parameter for belief	**20**
η_1	Hysteresis parameter for the environment	**10**
η_2	Hysteresis parameter for belief	**2.75**
b_1	Hysteresis parameter for the environment	**20**
b_2	Hysteresis parameter for belief	**30**
q_0	Initial value of environmental stock	**8**
w_0	Initial level of water	**85**
λ_0	Initial level of accumulated hazard rate	**1**
ρ	Discount rate	**.15**
θ	Utility parameter from the environmental stock	**2**
w_q	Weight on the environmental stock	**.1**
q_c	Weight on consumption	**.01**
θ	Stock dependent decay in belief	**5**
τ	Exogenous increase in belief	**100**
ψ	Scaling parameter for impact of ecological stock on ecological growth	**.01**
ξ	Scaling parameter for impact of water on ecological growth	**.1**

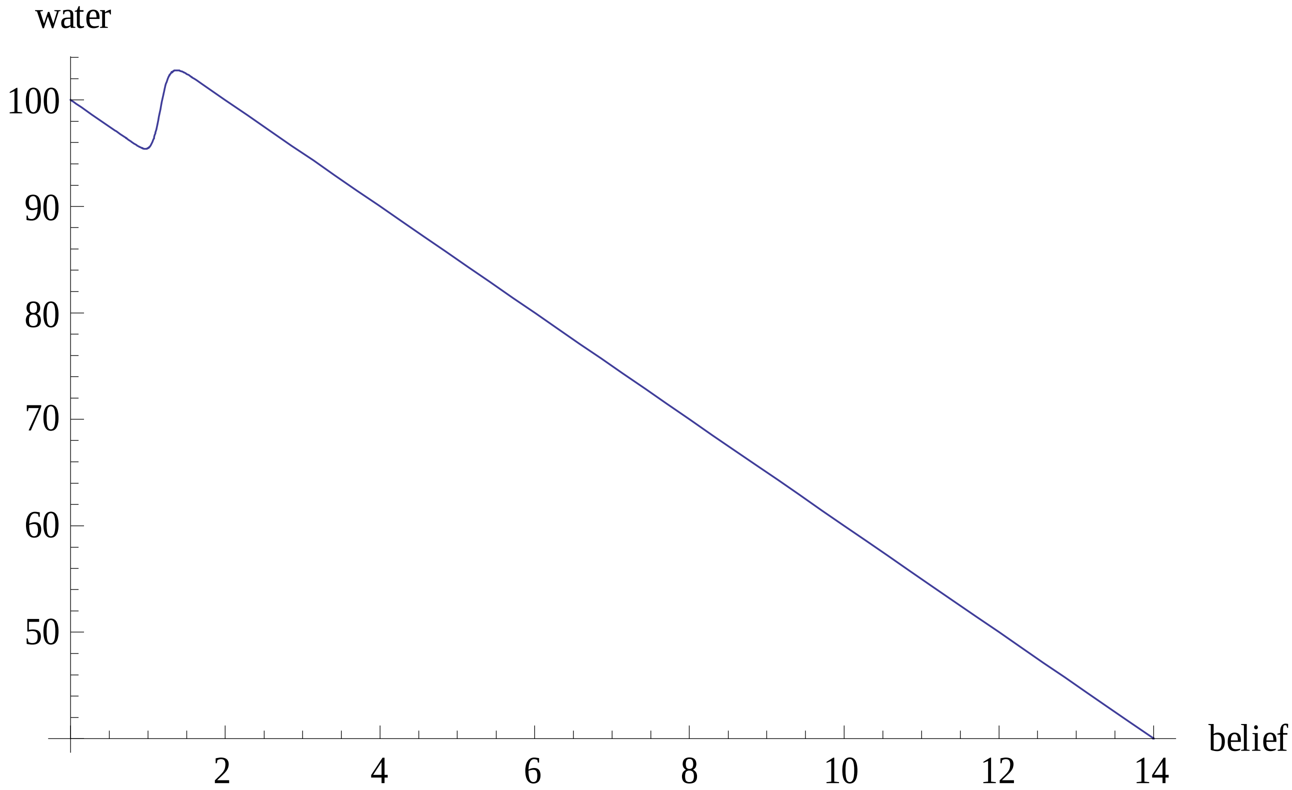


Figure 1: Steady State Relationship between Water and Belief

$\dot{\lambda} = -w - 5\lambda + \frac{\eta\lambda^a}{\lambda^a + b} + 100$, η_2=2.75; a_2=20; b_2=30;

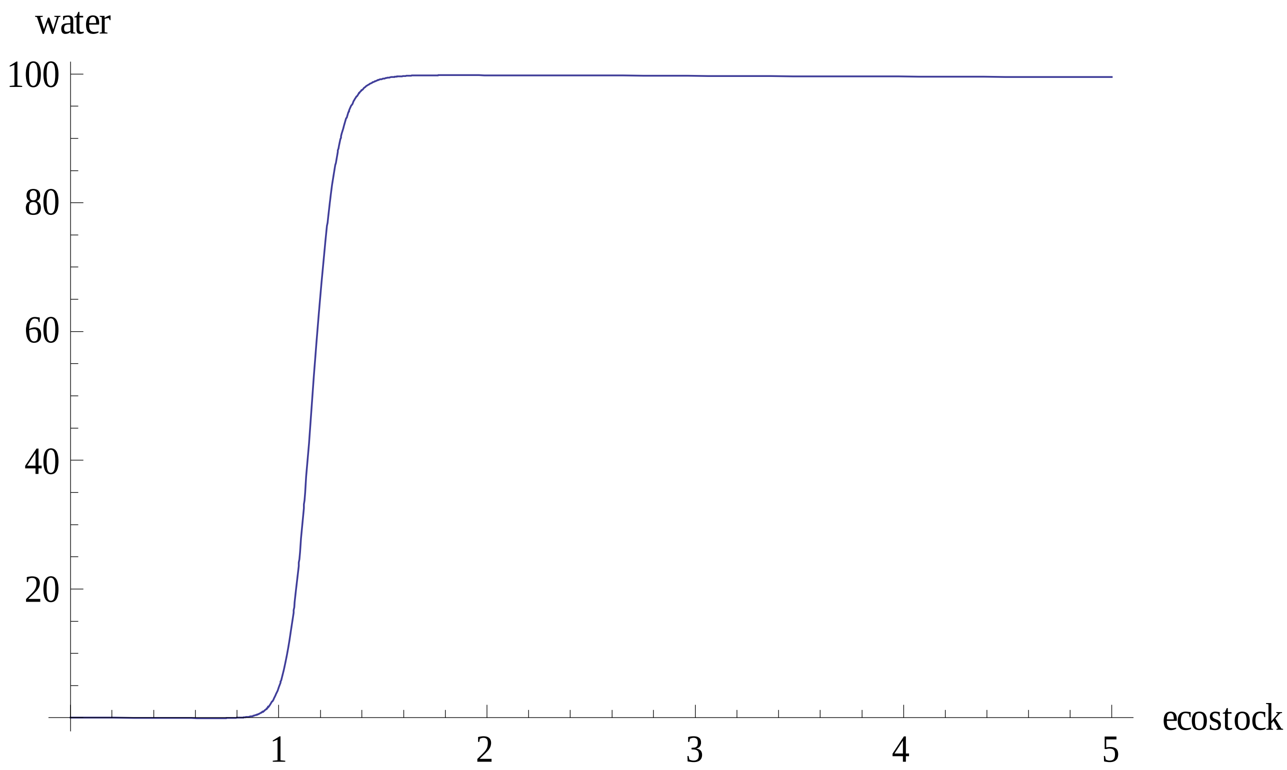


Figure 2: Steady State Relationship between Water and Ecological Stock

η_1=10; a_1=20; b_1=20; $\dot{q} = .1w + .01q - \frac{\eta q^a}{q^a + b}$

Note: ecostock stands for the ecological stock q and belief for the stock of accumulated hazard λ

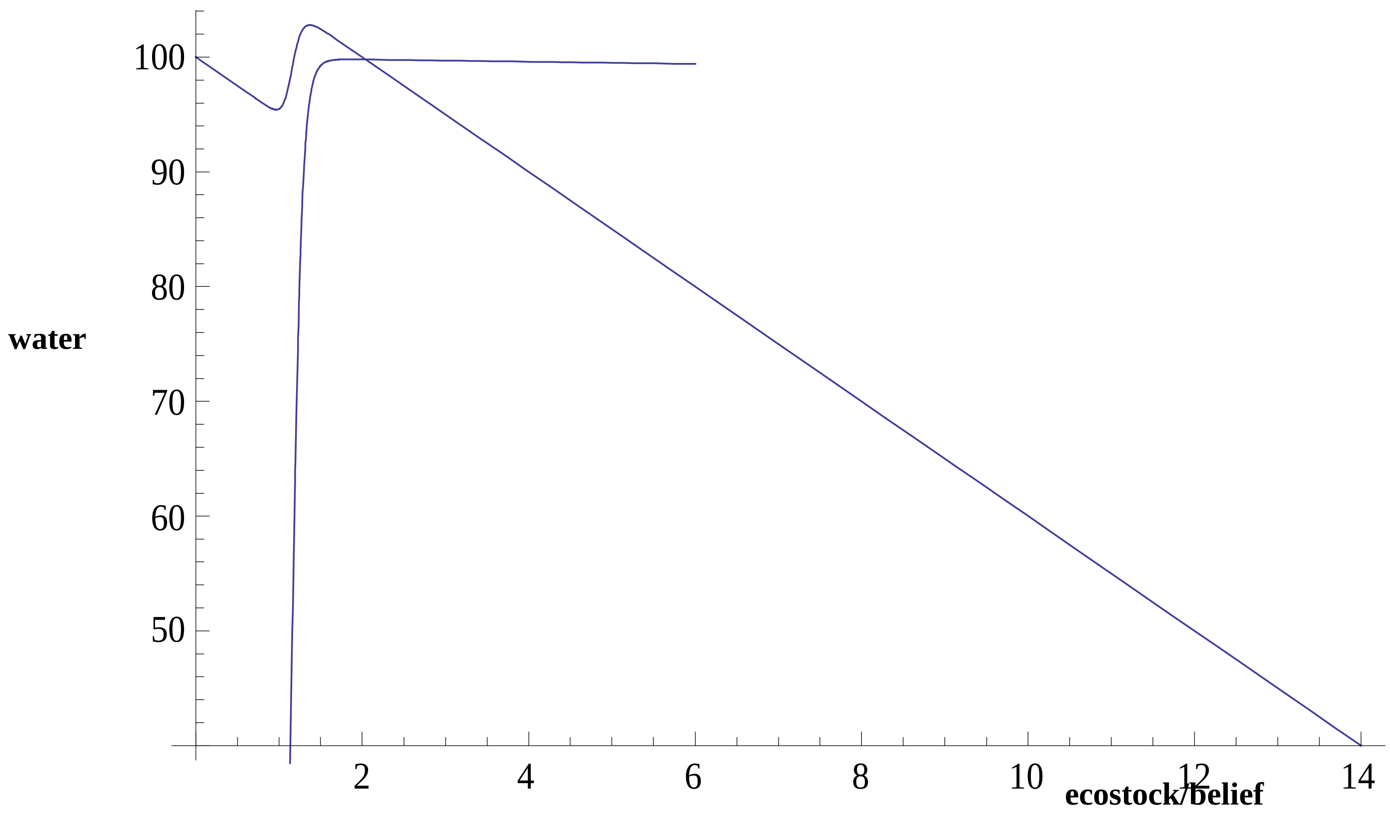


Figure 3: Steady State Relationships between Water, Ecosystem stock and Belief

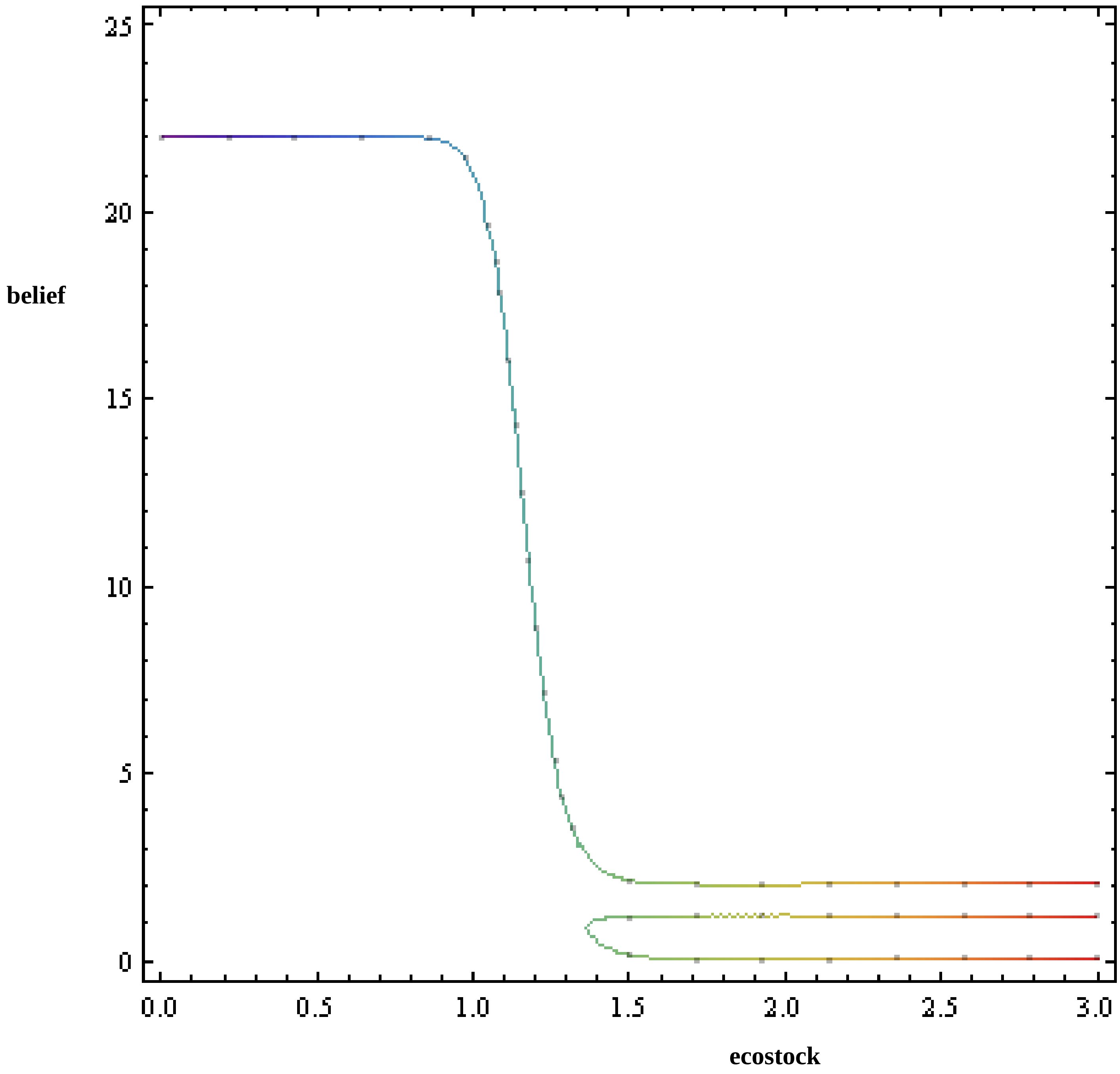


Figure 4: Contour Plot for Isoclines when $\dot{q} = 0, \dot{\lambda} = 0$

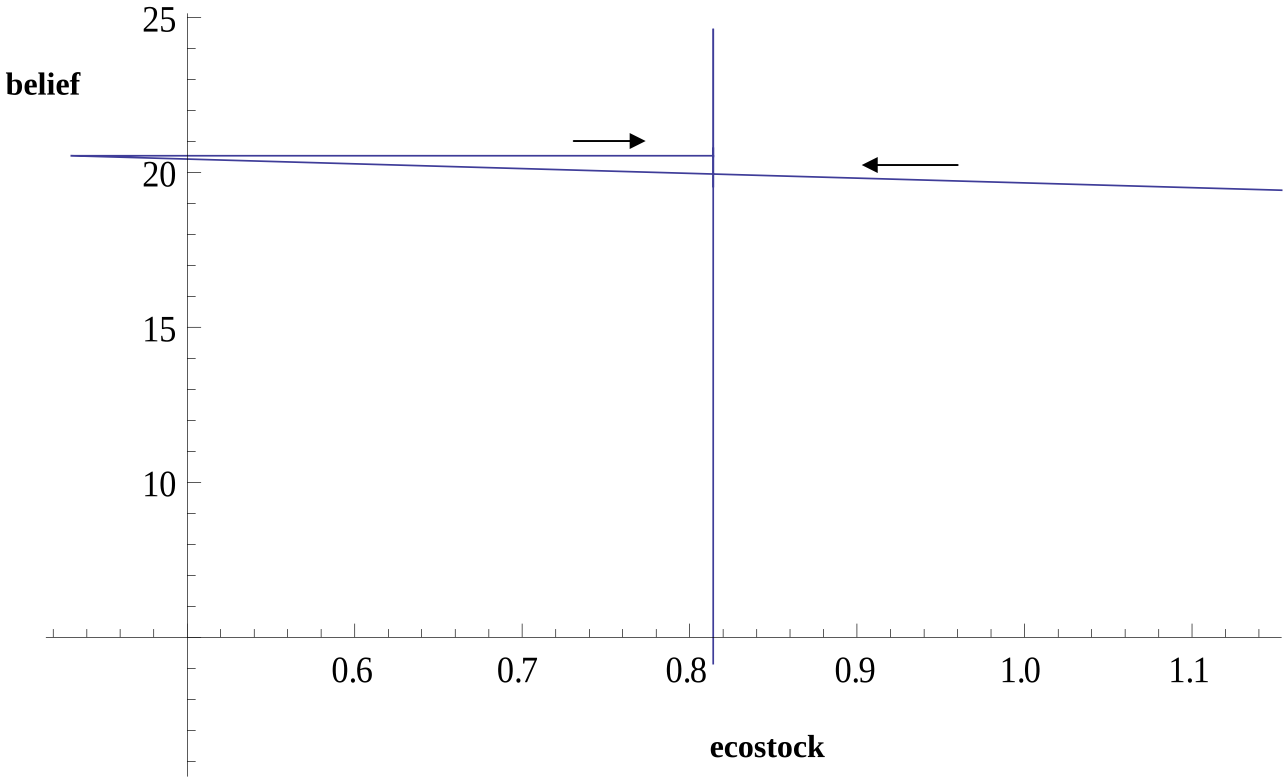


Figure 5: Time Path of Ecological Stock and Belief

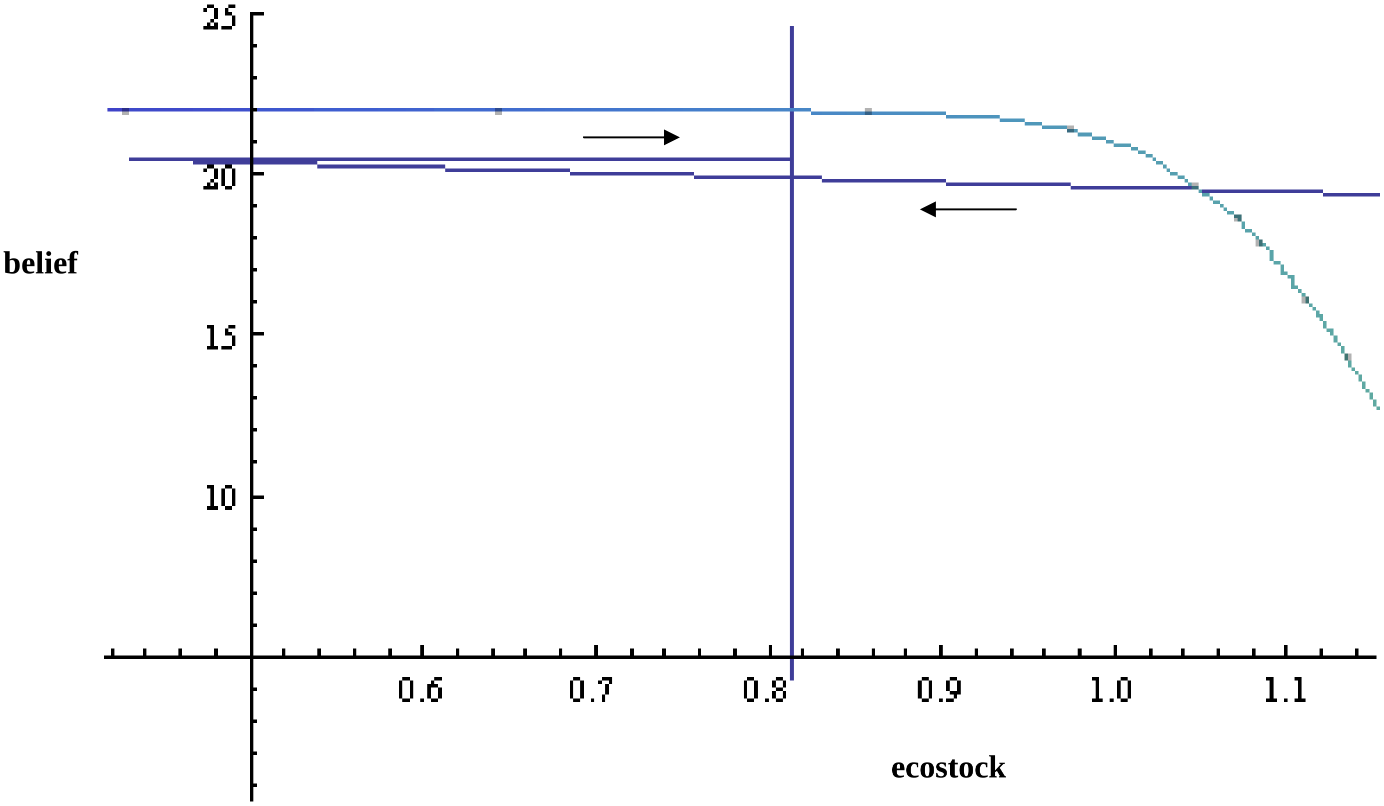
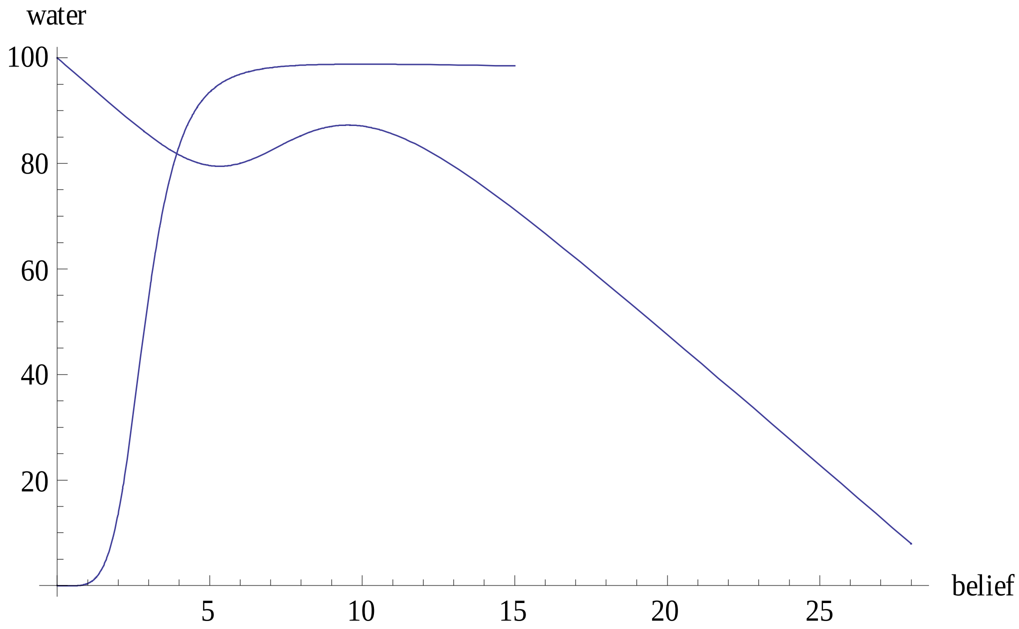


Figure 6: Convergence towards Steady State of the System



η_2**=48;** a_2**=5;** b_2**=**29500**;** η_1=10; a_1=5; b_1=200;

Figure 7: Juxtaposition of the Steady State Curves

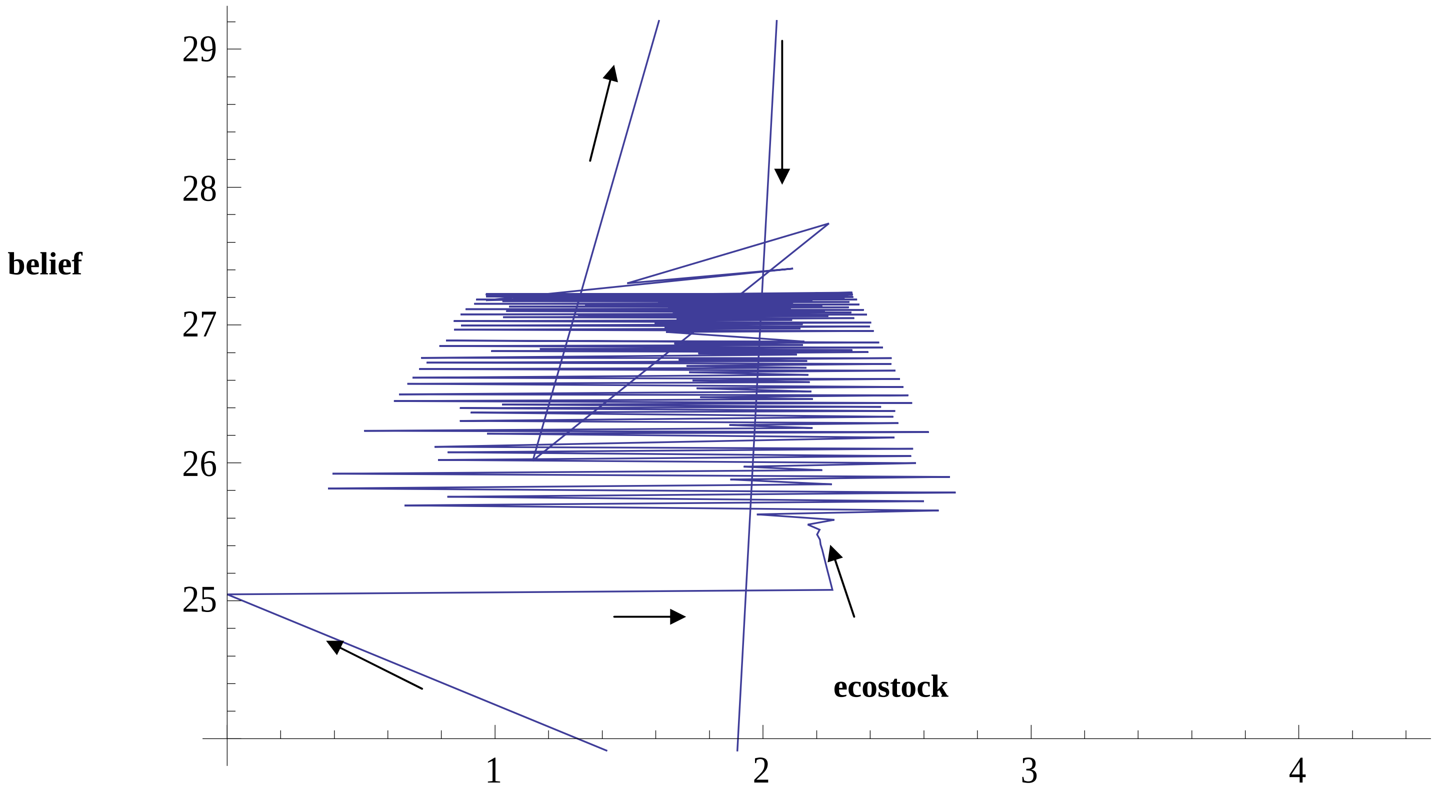


Figure 8: Time Path of Ecological Stock and Belief

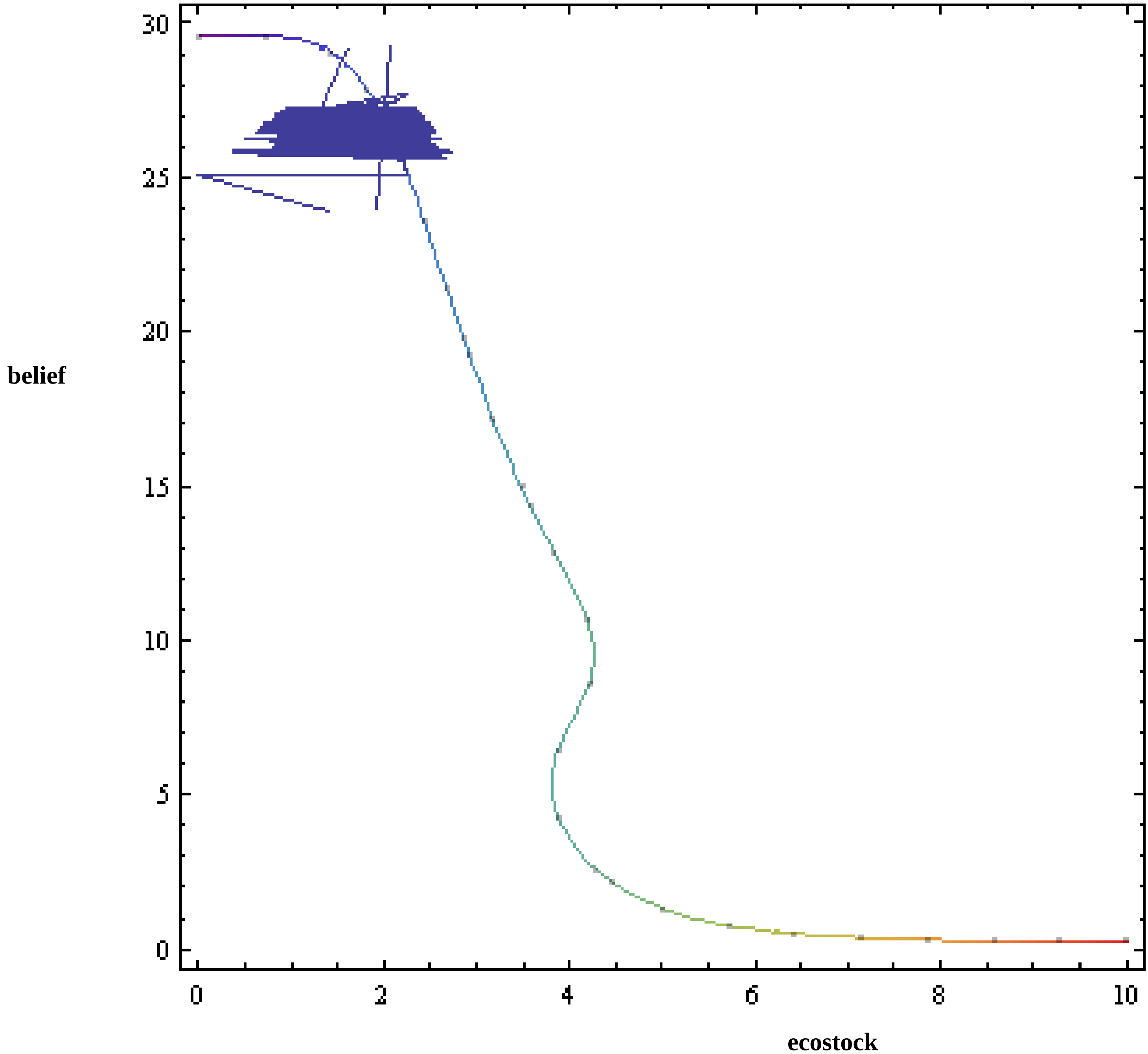


Figure 9: Convergence towards Steady State

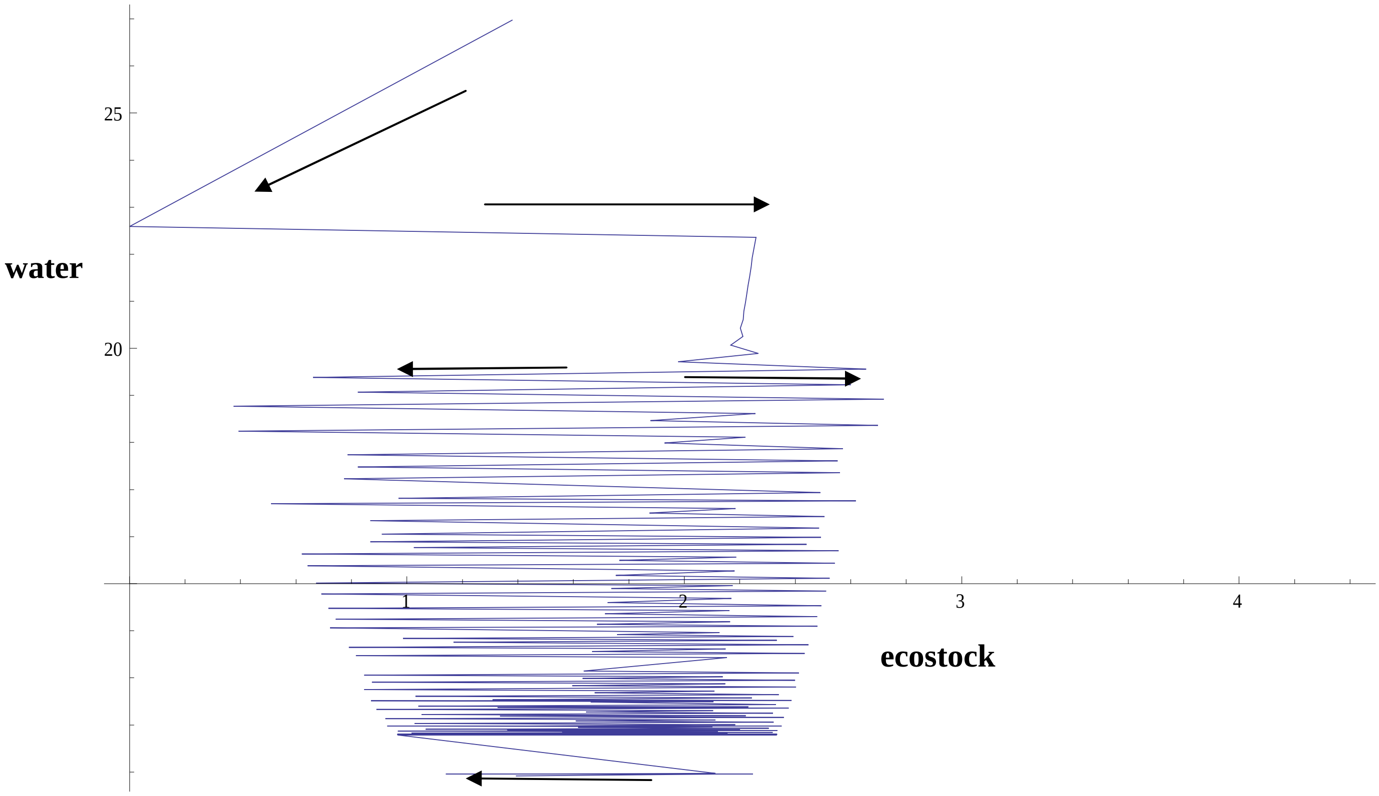


Figure 10: Stock of water and Environment

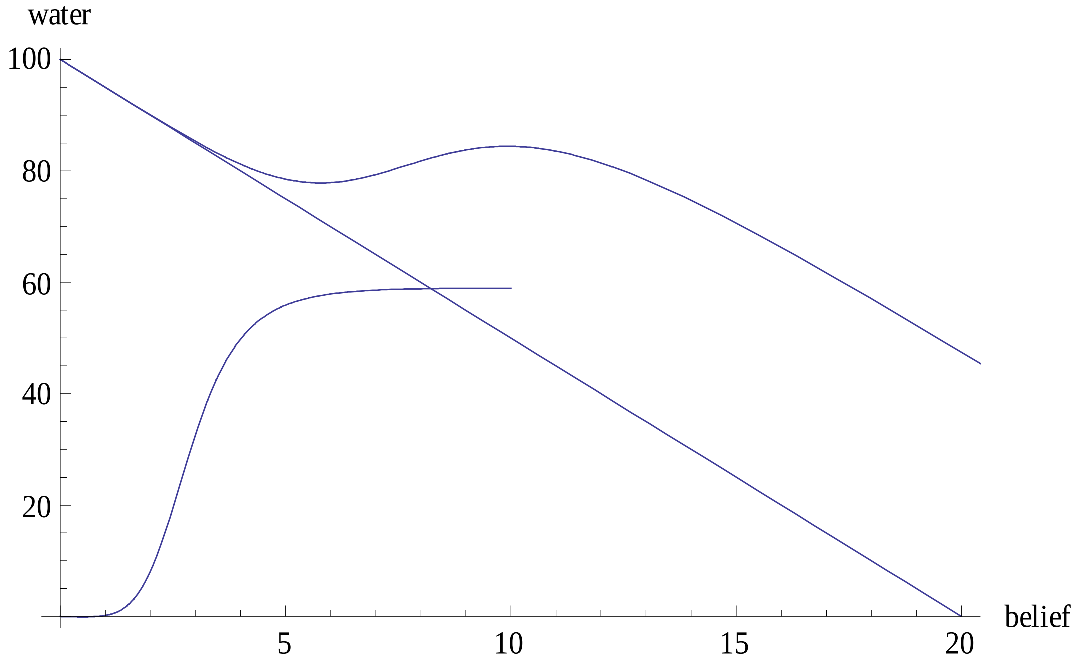


Figure 11: Steady State Relationship for Parameters:

η_2=48; a_2=5; b_2=39500; η_1=6; a_1=5; b_1=200;

Note: The straight line from the water axis to the belief axis the steady state relationship between water and belief stocks when the resilience effect is taken out.

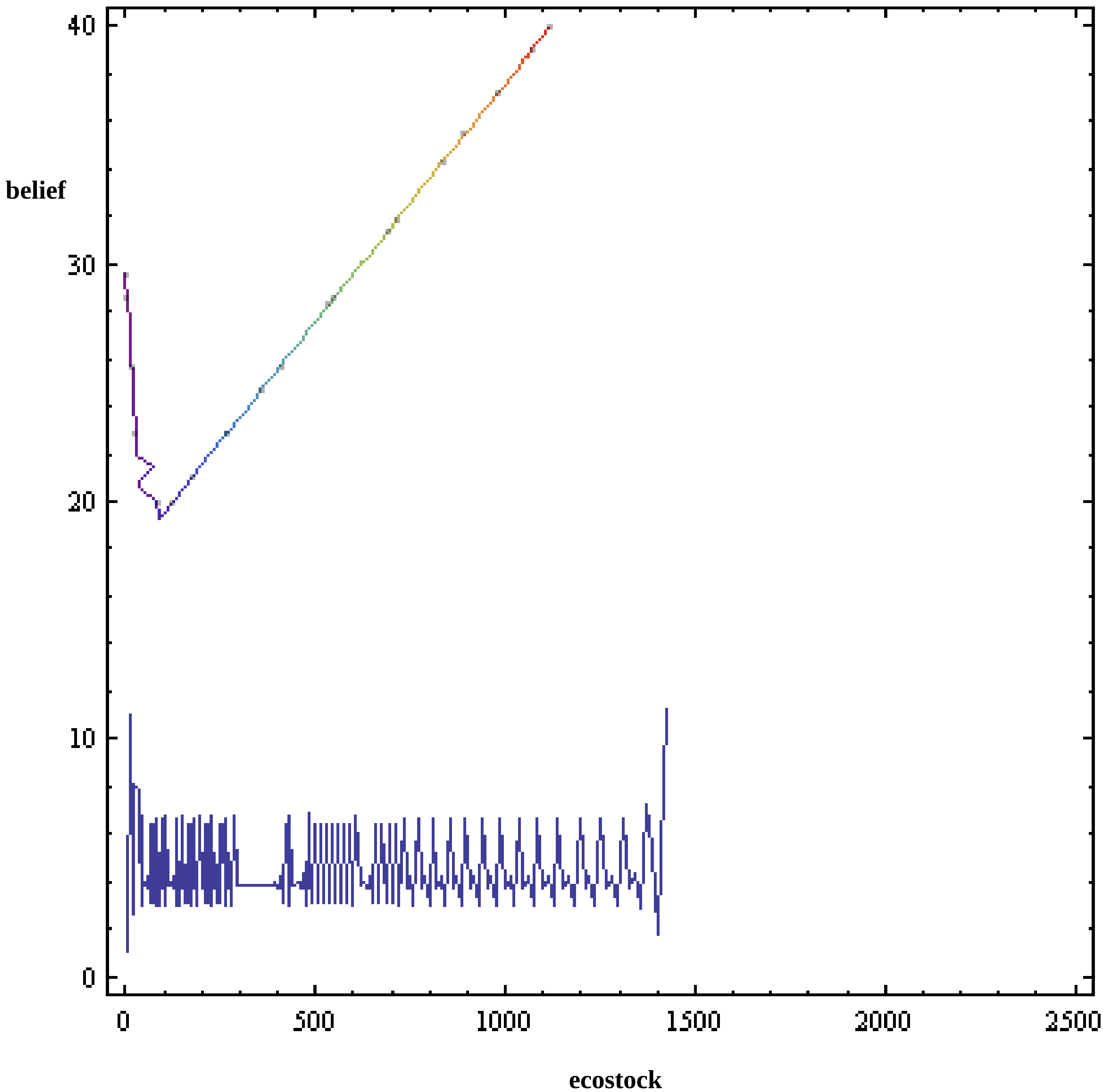


Figure 12: Steady State Convergence and System Dynamics

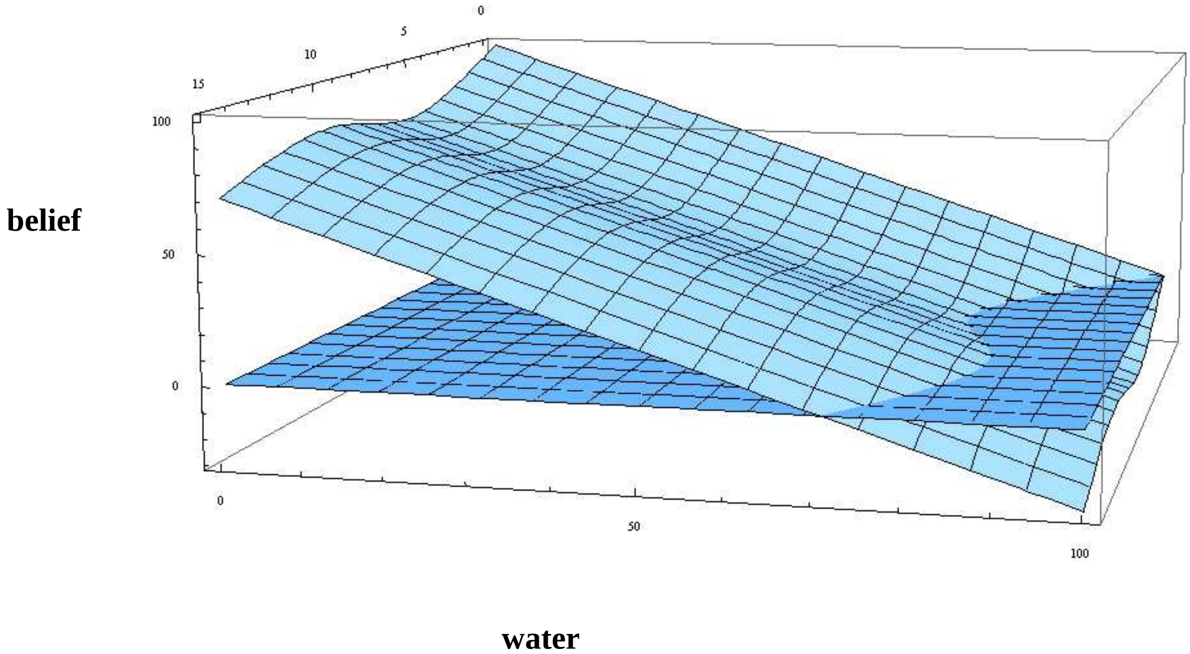


Figure13: Plot of Rate of Change of Belief with Respect to Water and Risk Stock

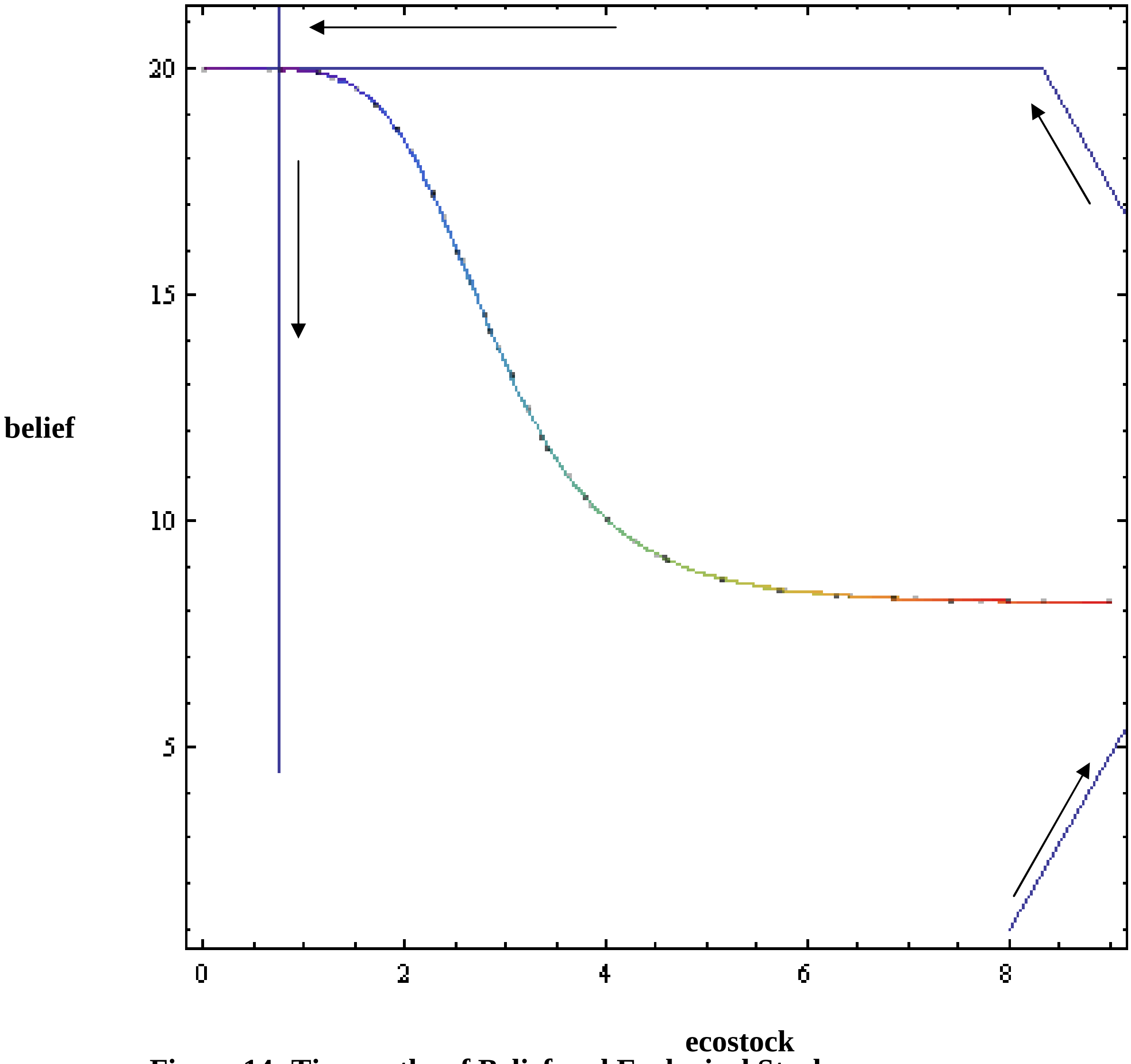


Figure 14: Time paths of Belief and Ecological Stock

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[i] Conventionally, resilience has been defined in two ways in the ecology literature. First one, termed as the '*engineering resilience*' defines it as the speed of bouncing back of any perturbed system (Pimm 1984). The other one, termed the '*ecological resilience*', is about the amount of stress that the system can tolerate before flipping from its original state to another stable but degraded state (Holling 1995, Carpenter and Cottingham 1997).

[ii] Throughout this paper we will be using ecological and environmental stock interchangeably.

[iii] In this paper we will use the terms resilience and hysteresis interchangebly.

[iv] This is actually not too strong an assumption as it might appear to be, because in reality water table may fall despite no water withdrawals if the long term impacts of climate change turn out to be severe.