Dear Reviewers and Editor,

Thank you for your thoughtful reading of our draft and for the opportunity to revise our manuscript. We have given serious consideration to all comments and resolved as many as feasible. We have prepared a summary of the reviewer's comments and changes made to address those comments below. Also attached for easy comparison is the revised manuscript with changes tracked.

Comments from and responses to Mr. Van Emmerick:

1. I would like to know whether the authors believe that in the development of all socio-hydrological models in recent years, no one did this based on a research question. E.g., p. 8295, line 11: "much of the work to date… does not posit clear hypotheses or questions". I think there might be a difference between work that didn't use a research question of s/hypothes of is and work that didn't present a research question/hypothesis. I think most model developers agree that a research question and hypothesis are essential in model design. Perhaps the authors can rephrase their statements, emphasizing on the difference between work that implicitly and explicitly use a research question and hypothesis.

    a. You raise a good point. We have re-write the sections motivating our proposed process to reflect the idea that we are addressing explicitly stated research questions and hypotheses while many other studies address questions and hypotheses implicitly within their respective model designs. Please see the addition from P6 L32 to P9, L16.

2. The authors discuss some socio-hydrological models developed in recent years (e.g., Elshafei et al., 2014, Srinivasan et al., 2015, Di Baldassarre et al., 2013, Lui et al., 2014). First, I think some important models and approaches are missing (e.g., O'Connell and O'Donnell, 2014; Van Emmerik et al., 2014; Viglione et al., 2014). Second, if one is to propose a new approach, I think it's important to demonstrate that the authors know, or define, what approaches were used in previous modeling exercises. Recent papers by Troy et al. (2015) and Blair Buytaert (2015) give an excellent overview of socio-hydrological modeling studies, their motivations and approaches. I suggest that the authors try to give a more complete overview of recent socio-hydrological modeling exercises, the approaches used, and the drawbacks or downsides or those approaches (according to the authors). Also, it would be interesting to take into account? some ideas, approaches, and perspectives from the recent special issue on socio-hydrology (Debates – Perspective on Socio-Hydrology) in WRR (see e.g., Montanari, 2015). This might create a clearer context of why the proposed approach is necessary to bring socio-hydrological model development forward.

    a. The comment about the wide range of socio-hydrological models is well-taken. We have provided a much more finely tuned review of approaches used in socio-hydrological modeling studies particularly in light of the recently reported reviews you list. We have expanded our discussion of existing socio-hydrological models and the approaches they use to clarify how ours is different and unique. Please see P6 L6 to L23 for a review of past socio-hydrological modeling studies. We have also drawn upon the recent WRR debate to illustrate the utility of our process. For this addition see P8 L18 to P9 L16.

3. The case study is nicely introduced, and I appreciate that (following the proposed approach) the authors pose a research question that is the basis of the modeling exercise. However, the

dynamic hypothesis is posed very sudden. What makes this hypothesis dynamic? Why did the authors decide to apply a dynamic hypothesis? How do the authors expect the hypothesis to change over time, and what will trigger these changes?

a. You are correct to note the importance of the case study vis a vis illustrating the dynamic hypothesis, and we now recognize that it is introduced abruptly. We have added a transition sentence to make the introduction of the dynamic hypothesis less abrupt, see P12, L9. The question about what makes this hypothesis dynamic is somewhat discussed in the paper, although we have revised the text to make this more explicit on P10, L8-10. The definition of a dynamic hypothesis we use comes from the system dynamics literature, particularly Sterman, 2000; it is a hypothesis that explains observed behavior in terms of feedback processes and the structure of the system. We treat our hypothesis as dynamic because it explains an observed pattern of per capita demand change over time in terms of a feedback between past system shortage or stress and the adoption of conservation technology and practices. The feedback process specified in the dynamic hypothesis is not expected to change over time; however, as described in the paragraph on the demand change equation (P20, L25), the strength and relevance of this feedback may change over time.

4. I suggest to shorten the background information. I think it is more interesting to see how the proposed approach is applied to this case study, rather than read about every single detail of Sunshine City and reservoir management.

   a. We have reviewed the case study description and background information. We have not greatly shortened these sections as most of the information presented is later used to inform the model. However, we have trimmed where feasible, see P13, L10-11 and L21-22.

5. Page 8305, line 4: “Kandasamy et al., 2013” should be “Kandasamy et al., 2014”. Perhaps also refer to the modeling studies of Elshafei et al. (2014) and van Emmerik et al. (2014), which also revealed and discussed the system’s opposing economic and environmental forces.

   a. Thank you, the error in the Kandasamy reference was corrected. The changes to this section responded both to your comments and the comments made by Reviewer 2. Considering both of your perspectives we adjusted this point slightly therefore cited alternate references. See P17, L13-19.

6. The model equations can be described more clearly. Please introduce each symbol when describing the equations (incl. units). Although one can figure out what all symbols mean using the table, it reads more conveniently if the symbols are mentioned in the text describing the equations.

   a. The description of the model equations have been revised to include reference to each symbol and note units. We agree that the reader shouldn’t have to deduce what we mean here. Please see P18 L18-20, L22-23, P19 L4-5, L8-13, L17, and P20 L4-5, L12, L15, L18.

7. The outcome of the coupled socio-hydrological model are compared with results from a non-coupled (simple) model. However, there is no description of this model. I think this is essential.

This should also include some justification for the use of this model. I assume that this classical problem has been solved in many different ways, so a more elaborate discussion would be interesting. Especially to compare this with the outcome from the presented approach.

   a. To make the logic of the non-coupled model clearer we have shifted the description of the non-coupled model to the model development section, P20 L26 to P21 L2.

8. I'm wondering whether it is necessary to present the outcomes of three trials. In my opinion, the paper is not about the developed model, but about how this model is designed and evaluated. To do this one wants to run the model with different settings for Kp to see how the balance of the system might shift. This can then be compared with the model outcome from a 'conventional' approach. Eliminating two trials might perhaps make the paper a bit more structured. I leave it up to the authors to decide whether presenting the three trials are necessary.

   a. Thank you for this comment. Multiple trials were included to illustrate the impact of both the magnitude and timing of fluctuations in streamflow and to show that observed results hold true across a range of those conditions. However, we did not make this very clear and have improved the justification for this approach on P22 L11-12.

9. I would expect that the discussion would mainly be about comparing the results gained from using the proposed question driven approach and a conventional approach. The whole discussion about the behaviour of reservoirs and the differences between SOP and HP is not new or relevant, within the perspective of this paper. I would suggest to explicitly start with "The model outcome of the question driven socio-hydrological model suggest…", continue with "The model outcome of the conventional model approach suggest…", followed by a clear and concise comparison of the two. Now, it's a bit unclear to me what the discussion aims to address.

   a. Thank you, you make a good point on the clarity and focus on the discussion section. We revised the discussion to focus first on the question driven modeling process, see P23 L3-17. Then we proceed to compare the results from the coupled and non-coupled model to illustrate the insights gained using a coupled approach P23 L18 to P24 L3.

10. At the end of the discussion, the authors discuss the use of a socio-hydrological model versus the use of a simple non-coupled model. I think the authors make a strong case here, and I would suggest to emphasize on this finding in the abstract, introduction, and methods too. Examples of how socio-hydrology advance our understanding of systems are valuable for the whole community.

    a. The recommendation that we add some text to explain how this analysis uses socio-hydrology to advance understandings of systems is an excellent recommendation. This point is emphasized in the abstract (P1 L31 to P2 L6) and conclusions (P29, L10-14).

11. I appreciate the authors' critical evaluation of the used case study. When reading the paper I found myself thinking that this case study is "simplified and simplistic", which the authors later on acknowledge. Perhaps it might be nice to already mention this at the beginning of section 3, at the description of the case study.

   a. The case study is greatly simplified, and we have emphasized this on P11 L7.

12. Why did the authors choose to apply the proposed approach only to a hypothetical case? Of course the analysis of toy models might lead to significant and important insights (e.g. Di Baldassarre et al., 2013), I would think that this new approach is especially of value for real life situations. I leave it to the authors to decide whether to (1) include an application to a real case study, or (2) discuss the choice to only apply to a hypothetical case.

    a. We chose to illustrate the modeling process first on one hypothetical case for simplicity and brevity. We have clarified this in the text on P11 L7-10. Our hope is that we will be able to build on this with future versions. While we are also working on a case-based modeling project, we found that explaining the full range of context and assumptions of the case along with the modeling process was beyond the scope of a single paper.

13. Page 8316, lines 12-21: a bit repetitive. As part of the conclusions, I would emphasize on what this paper adds to the current spectrum, instead of focusing on what is lacking in previous work.

    a. There is some repetitiveness in the conclusions, and we have cleaned this up. We have revised the conclusions to emphasize the novelty of the current work and tone down the discussion of what might be lacking in other studies, please see P28 L29 to P29 L6.

14. I don't see a final conclusion that shows that your question driven approach is superior to a conventional approach. I suggest to include at least one crucial finding that makes the case for your presented approach (rather than only concluding that socio-hydrological modeling leads to new insights).

    a. We have thought seriously about this point. As articulated in the discussion section the question driven process aims to broaden researcher's view of the system, to connect modeling assumptions to the model's purpose and to increase the transparency of these assumptions. While we have detailed why we think our process can accomplish these aims earlier in the paper, we, as authors, are not in the best position to judge success. We hope that through this process we were able to move beyond our biases in our conceptualization of the system; we have used the question to make the simplifying assumptions needed and hope that the readers find this linkage both logical and transparent. Therefore, we purposefully leave it to the reader to draw conclusions on the success of the process.

Comments from and responses to Reviewer 2:

1. I feel that the manuscript presents interesting ideas in terms of applying a combination of two SES frameworks to a socio-hydrology question and I would agree that the application of a backward reasoning approach is indeed novel in this space. However a shortcoming of the paper is the seeming omission of the now growing body of sociohydrology (SH) literature. Section 2 reviews the relevant hydrology and SES literature, however makes scarce mention of previous work in the SH space, other than to say that most of the work does not posit clear hypotheses or justification as to model structure, scope and scale. I am not convinced this is the case as arguably all conceptual and deterministic models developed to date for human-water systems

are necessarily formulated on the basis of dynamic hypotheses, with some more grounded in theoretical hypotheses generated by the literature, while others are more guided by observations (e.g. Carey et al (2014); Di Baldassarre et al. (2013a, 2013b, 2015); Elshafei et al. (2014, 2015); Hale et al. (2015); Liu et al. (2014, 2015); Srinivasan (2015); Troy et al. (2015); van Emmerik et al. (2014)). I would urge the authors to acknowledge/ review previous work more fully and clearly distinguish how this approach is different, otherwise it reads as though the authors believe the framework presented here appears in a vacuum. I would also suggest the authors have regard to the recent WRR Debates series and perhaps illustrate how this approach addresses some of the current challenges being discussed (Montanari, 2015).

a. Thank you, this point is well taken. In aiming for brevity we missed an important aspect of the review of modeling approaches. We have incorporated a thorough review of approaches used in socio-hydrological modeling, utilizing the cited references and others, as well as reference to recent review papers on the topic, please see P6 L6 to L23. We agree that the recent WRR Debate series provides an excellent foundation for this review and for discussion of the challenges facing the field, for this addition see P8 L18 to P9 L16.

2. It is not immediately apparent why a hypothetical case has been chosen when the approach seems intuitively geared to a real world case. I would suggest providing a clear justification for this decision in Section 3.

    a. We chose to illustrate the modeling process first on one hypothetical case for simplicity and brevity. We have clarified this in the text on P11 L7-10. Our hope is that we will be able to build on this with future versions. While we are also working on a case-based modeling project, we found that explaining the full range of context and assumptions of the case along with the modeling process was beyond the scope of a single paper.

3. Section 3.1 is very well written and provides a strong justification for the dynamic hypothesis in the literature. Please add a sentence in the opening paragraph (p. 8299 line 12) to explain why the third characteristic of water shortages (i.e. length of the shortage) is not relevant in this examination. Given the statement on p.8303 lines 4-6 regarding the importance of the duration of the shortage in terms of galvanizing conservation behavior, it is worth noting why consideration of this component is not of interest here.

    a. We have deleted the sentence: "In this study we will focus on the frequency and maximum magnitude of shortage events" (see P12 L25). The intention was to focus the discussion of the model results on these two properties as they differ significantly between SOP and HP. However, we now see that this statement can be misleading as all three properties are relevant to the model.

4. In the first and second paragraphs of section 3.2 the authors explain how the research question is used to derive the key outcome metric and processes. However, although the derivation of the outcome indicator is clear, the transition to the definition of the 3 key processes is quite abrupt. Passing reference is made to the SES framework, without any clear explanation on how this has been used in this instance. Give this is arguably the key premise of the paper, i.e. the use of a question-driven modeling approach, I would urge the authors to augment this leap with

a few sentences offering a brief explanation of the framework and tying in specific examples as to how it has been employed to arrive at the 3 processes. Why is population growth included and not economic growth for example? In addition, the authors state on a number of occasions (as early as the abstract) that the merit of this approach is that it provides clear guidance on model scope and detail, however this does not come across in the description of how the processes/ variables are ultimately defined.

   a. Thank you for this comment. As you noted we aim to provide transparency of the model development process and therefore take this comment very seriously. We have expanded our discussion of the determination of these three processes to clarify this step. In doing so we have included a clear explanation of how the SES framework was used in this instance. Please see P16 L6 to P17 L 25.

5. It is interesting to note the broad similarities of Fig. 5 (and the accompanying narrative) and previous feedback loops used in recent SH literature - i.e. Elshafei et al. (2014, Fig 1) and Sivapalan (2015, Fig. 2), defined as positive (Economic-Population) and negative (Community Sensitivity) feedback loops. These are also referred to in terms of destructive and restorative forces in Liu et al. (2015). In the case of this model, population is effectively driving the positive feedback loop/ destructive forces, while shortage awareness is driving the negative feedback/ restorative forces. I believe the authors could enrich their discussion with a more objective comparison of the work presented here with previous work, i.e. acknowledge the similarities and draw parallels, and note the points of difference.

   a. Thank you for this observation. In the discussion section we have compared the feedbacks identified in this case to those identified in studies by Elshafei et al. (2014) and Di Baldassarre et al. (2013). Please see P24 L 20-24 for this addition.

6. p. 8305 lines 1-5: This is an unsubstantiated assumption and in my view not strictly correct. The Murrumbidgee basin is an example of a situation where the cumulative negative consequences of development stimulated water conservation behavior, rather than being an example of a weakening link between economic growth and water demand per se. In this case water demand was overshadowed by other environmental considerations, in much the same way as your approach posits in Fig. 5. I would suggest the authors find a more compelling example of the relationship they are suggesting, or perhaps adopt a different way of justifying the exclusion of the economic process.

   a. This is a fair critique. The relationship of between water consumption and development is a complex one. In the case described by Kandasamy et al. (2014), as well as in other cases, an array of interacting forces, of which development is just one, lead to a change in water consumption as development increases. We have replaced the Kandasamy et al. (2014) reference with a discussion of the mixed effects of development on water consumption, with alternate references, to justify why, in this case, economic development may be reasonably excluded on P17 L13-22.

7. p. 8305 lines 9-11: This is a fair point in order to reduce unnecessary complexity. However, it may be worth noting it in the discussion as part of the model’s limitations given recent studies are finding that agent-based models are important in the examination of human behavior in coupled human-nature models (Kinzig et al. (2013); Tavoni et al. (2012)).

    a. We agree that there is growing evidence that agent based models can be important tools in coupled modeling. However, to keep the discussion focused on the process and the model comparison we have selected to omit discussion of agent based models.

8. p. 8305 lines 23-26: Does this mean that land use changes are also ignored?

    a. Yes, land use changes are not incorporated in the current model formulation. The reason for this is that the geographical area being modeled (a city) is small relative to the size of the watershed. The land use change occurring at the watershed scale is therefore exogenous to the modeled system. In future work the impacts of land use change can be incorporated as an exogenous scenario. This is clarified on P19 L3.

9. In equation 3 it appears as though population dynamics respond to any shortage awareness, rather than being limited to extreme cases as suggested earlier in the manuscript (see p.8304 L22, p.8306 L19). Is this correct? And if so, why is this approach taken given earlier discussion regarding "extreme" events?

    a. Thank you, this is a good point. The original formulation applied the shortage factor to both the rate of immigration to the area (1-M) and the rate of emigration (M) which created a non-linear effect on the net population change rate (low influence for low values of M and high for high values of M). However, you rightly note that the effect should be zero, rather than low, at some levels of shortage. We have reformulates this equation to incorporate a threshold above which population dynamics are affected, and below they are not. Please see P19 L2-7.

10. Given that the manuscript's focus is on a novel approach to the development of a SH model, and its subsequent application to a classic water management question, I think the discussion should really begin with a primary focus on the contribution of a question-driven modeling approach, as opposed to the merits of competing operating policy strategies. I would suggest revising the discussion to emphasize the superiority of employing a coupled SH model versus a traditional model in this application, and the novelty and efficacy of the model formulation approach.

    a. The recommendation to revise the discussion is well taken. We have revised and refocused our discussion on the question driven modeling process and the distinction between the coupled and non-coupled model. The discussion of the competing operating strategies will be trimmed and presented as the outcome of the process. Please see P23 L3 to P24 L3 for this revision.

Technical corrections from and responses to Reviewer 2:

1. References to "the system" would be better phrased as "the coupled system" to make clearer the distinction between traditional and socio-hydrological modeling approaches e.g. p.8292 lines 3, 9, 10; p.8312 L13; p.8316 L11.
    a. This suggestion has been implemented. Please see P3 L3, L9, and P26 L6.

2. p. 8294 line 9: I'm not sure that the Wheater et al., 1993 reference needs to be repeated on lines 14 and 16 given it is referenced at the outset with regard to all modeling approaches discussed in the paragraph.
    a. The repetition has been corrected, see P4 L29-31.
3. p.8296, L10: Arocha et al. 1993
    a. Citation has been revised, P9 L33.
4. p.8296, L24-25: This sentence does not make sense - is there an extra "on"?
    a. The extra "on" was deleted, see P10, L12.
5. p.8301, L2: "consumers' attitudes"
    a. The missing apostrophe was added, see P13 L34.
6. p.8305, L18: "clearly change over the course..."
    a. Revised, see P17, L31.
7. p.8305, L26: delete "of" in "of the selected of operating policy"
    a. Revised, see P18, L4-5.
8. p.8306, L22: delete "a" in "while the logistic function is a commonly used to model resource constrained"
    a. Revised, see P18 L27-28.
9. p.8313, L22: perhaps substitute "with a" with "using" i.e. when we compare SOP and HP using a SH model...
    a. Revised, see P23 L29-30.
10. p.8315, L14: "innovatively"
    a. Revised, see P25, L22-23.
11. Fig. 4: please define "gpcpd" for ease of readability.
    a. The figure caption has been revised.
12. Check date inconsistencies of references: Gal (1972 vs 1979), Kanta and Zechman(2013 vs 2014), Sivapalan (2011 vs 2012)
    a. Date inconsistencies has been resolved.

# A Question Driven Socio-hydrological Modeling Process

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## Abstract

Human and hydrological systems are coupled: human activity impacts the hydrological cycle and hydrological conditions can, but do not always, trigger changes in human systems. Traditional modeling approaches with no feedback between hydrological and human systems typically cannot offer insight into how different patterns of natural variability or human induced changes may propagate through this coupled system. Modeling of coupled human~~ and ~~-hydrological systems, also called socio-hydrological systems, recognizes the potential for humans to transform hydrological systems and for hydrological conditions to influence human behavior. However, this coupling introduces new challenges and existing literature does not offer clear guidance regarding ~~the choice of modeling structure, scope, and detail. A~~model conceptualization. There are no universally accepted laws of human behavior as there are for the physical systems; further a shared understanding of important processes within the field is often used to develop hydrological models, but there is no such consensus on the relevant processes in socio-hydrological systems. Here we present a question driven process to address these challenges. Such an approach allows modeling structure, scope, and detail to remain contingent on and adaptive to the question context. We demonstrate ~~its~~the utility of this process by ~~exploring~~revisiting a classic question in water resources engineering on reservoir operation rules: what is the impact of reservoir operation policy on the reliability of water supply for a growing city? Our example model couples hydrological and human systems by linking the rate of demand decreases to the past reliability to compare standard operating policy (SOP) with hedging policy (HP). The model shows that reservoir storage

acts both as a buffer for variability and as a delay triggering oscillations around a sustainable level of demand. HP reduces the threshold for action thereby decreasing the delay and the oscillation effect. As a result, per capita demand decreases during periods of water stress are more frequent but less drastic and the additive effect of small adjustments decreases the tendency of the system to overshoot available supplies. This distinction between the two policies was not apparent using a traditional non-coupled model.

## 1 Introduction

Humans both respond to and ignore changes in environmental conditions. While humans depend on the natural hydrological cycle to supply water for both personal and economic health (Falkenmark, 1977), they also depend on an array of other natural and human resources to maintain and grow communities. At times water availability can act as the limiting constraint, locally preventing or stalling the expansion of human activity. For example, water availability and variability constrained agricultural development in the Tarim River Basin in Western China before major water storage and transport infrastructure was constructed (Liu et al., 2014). At other times the water related risks rise in the background, disconnected from decision making, while other priorities prevail. For instance, the level of the Aral Sea has continued to decline for decades imposing significant costs on adjacent communities but no coordinated effort to stop the decline ~~has yet~~ emerged (Micklin, 2007). At still other times public policy decisions may work to exacerbate water problems, as when decisions are made to keep municipal water prices artificially low or when "senior water rights" encourage water usage in the face of shortages (Chong & Sunding, 2006; Hughes et al., 2013; Mini et al., 2014).

Human and hydrological systems are coupled. Many impacts of human activity on the hydrological system are now well documented (Tong & Chen, 2002; Wissmar et al., 2004; Vörösmarty et al., 2010; Vahmani & Hogue, 2014) and there is increasing evidence that how and when humans respond individually and collectively to hydrological change has important implications for water resources planning, management, and policy (Srinivasan et al., 2010; Di Baldassarre et al., 2013; Elshafei et al., 2014). These observations have prompted a call to treat humans as an endogenous component of the water cycle (Wagener et al., 2010; Sivapalan et al., ~~2011~~2012). Representing water systems as coupled human–hydrological systems or socio-hydrological systems with two-way feedbacks allows new research questions and potentially transformative insights to emerge.

Traditional modeling approaches assume that there is no feedback between hydrological and human systems and, therefore, ~~offer no~~cannot provide insights into how different patterns of natural variability or human induced change may propagate through the coupled system. Over short timescales, such as a year, many human and hydrological variables can be considered constant and their couplings ~~can~~may be ~~safely~~ ignored (Srinivasan, 2015). However, water resources infrastructure decisions have impacts on longer (decadal to century) timescales; therefore, there is a need for an approach that can handle not only long term variability and non-stationarity in the driving variables (e.g., precipitation, temperature, population) but also addresses how these changes can propagate through the coupled system, affecting the structure and properties of the coupled system (Sivapalan et al., ~~2003~~2012; Thompson et al., 2013). Dynamic modeling of socio-hydrological systems recognizes the potential for humans to transform hydrological systems and for hydrological conditions to influence human behavior. While human behavior ~~can be more easily~~is usually incorporated into a model through scenarios, ~~building~~scenarios cannot include two-way feedback. Building human ~~dynamics~~effects of human behavior into a simulation model can enable testing of ~~hypothesized~~ feedback cycles and can illuminate the impact of feedback and path dependencies that are not easily identifiable in scenario ~~generation.~~ based modeling.

~~However, coupled~~Coupled modeling ~~also~~, on the other hand, introduces new challenges. First, it is not possible to exhaustively model complex systems such as the coupled human–hydrological system (Sterman, 2000; Schlüter et al., 2014). Bounds must be set to develop an effective model but researchers are challenged to objectively define the scope of coupled modeling studies. ~~By~~Second, by definition coupled models cross disciplines and modelers are unable to point to the theoretical framework of any single discipline to defend the relevant scope (Srinivasan, 2015). At the same time researchers must balance the scope and level of detail in order to create a parsimonious and communicable model. ~~Second, not all feedbacks identified will significantly change the result and there is not yet a good understanding of the subset of questions, scales and conditions for which socio-hydrological modeling can be truly insightful. Under certain circumstances, such as water rich environments or periods, feedback from water to human systems may be weak or absent (Troy et al., 2015).~~ Finally, critical assessment of models is more challenging when the theories, empirical methods and vocabulary drawn upon to create and communicate a model span disciplinary boundaries (Schlüter et al., 2014). At the same time, critique is needed to move the field forward as the science is new and lacks established protocols. Transparency of the model aims, the development process, conceptual framework and assumptions are thus particularly important. A structured but flexible modeling process can address these challenges by encouraging modelers to clearly define model objectives, document reasoning behind choices of scale, scope and detail, and take a broad view of potentially influential system processes.

In this paper we present a question driven process for modeling socio-hydrological systems that builds on current modeling tools from both domains and allows the flexibility for exploration. We demonstrate this process by revisiting a classic question in water resources engineering on reservoir operation rules: the tradeoff between standard operating policy (SOP) and hedging policy (HP). Under SOP, demand is fulfilled unless available supply drops below demand; under HP, water releases are reduced in anticipation of a deficit to decrease the risk a large shortfall (Cancelliere et al., 1998). We add to this classic question a linkage between supply reliability and demand. As this question has been asked by numerous researchers before, it offers an excellent opportunity to test the utility of our proposed modeling framework using a hypothetical municipality called Sunshine City as a case study.

## 2 Modeling Socio-Hydrological Systems

Modeling the interactions between human and hydrological systems exacerbates challenges found in modeling purely hydrological systems including setting the model boundary, determining the relevant processes and relationships, and clearly communicating model framing and assumptions. Common approaches to hydrological modeling are reviewed to put socio-hydrological modeling in the context of hydrological modeling practice. ~~Then~~Next, modeling approaches used in system dynamics and social-ecological systems science, both of which address coupled systems, are described. Then, socio-hydrological modeling approaches are reviewed and gaps identified. While no one approach is directly transferrable to socio-hydrological systems, practices from hydrological modeling, along with those from integrative disciplines, serve as a baseline for comparison and inform our socio-hydrological modeling process. We then present our recommendations for socio-hydrological model conceptualization.

### 2.1 Modeling Hydrological Systems

In hydrology the basic steps of model development are: (a) data collection and analysis; (b) conceptual model development; (c) translation of the conceptual model to a mathematical model; (d) model calibration and (e) model validation (Blöschl and Sivapalan, 1995). While the basic steps of model development are generally accepted, in practice approaches diverge, particularly in conceptual model development. In hydrology Wheater et al. (1993), identified four commonly used modeling approaches: physics-based, concept-based (also called conceptual), data driven and hybrid data-conceptual. Physics-based models represent a system by linking small-scale hydrological processes (Sivapalan et al., 2003). Concept-based models use prior knowledge to specify the influential processes and determine the structure (Wheater et al., 1993).. Data driven models are derived primarily from observations and do not specify the response mechanism (Wheater et al., 1993).. Hybrid data-conceptual models use data and prior knowledge to infer model structure (Wheater et al., 1993; Sivapalan et al., 2003).

Modeling purpose typically determines the modeling approach. Environmental models may be developed to formulate and test theories or to make predictions (Beven, 2002). Physics-based models can be used to test theories about small-scale processes or to predict catchment response by scaling up these processes. Concept-based models hypothesize the important elements and processes and their structure of interaction to answer a question or predict a certain property, although hypotheses are often not explicitly stated and tested (Wheater et al., 1993). A reliance on prior knowledge limits the applicability of concept-based modeling in fields lacking consensus on both the presence and relevance of feedback processes. Data driven models are effective in prediction. While they have potential for hypothesis testing, a focus on black box input-output models limits insight into system processes and the ability to extrapolate beyond observed data (Sivapalan et al., 2003). Hybrid data-conceptual models use data and other knowledge to generate and test hypotheses about the structure of the system (Wheater et al., 1993; Young, 2003). As socio-hydrology is a new area of research, prior knowledge alone is insufficient and the focus is on modeling to enhance understanding through hypothesis generation and testing; hybrid data-conceptual modeling tactics aimed at enhancing understanding therefore inform our proposed process.

## 2.2 Modeling Coupled Systems

While coupling of natural and human systems is in its infancy in hydrology, there is a strong tradition of studying coupled systems in the fields of system dynamics and social-ecological systems. These fields have developed approaches to understand and model complex systems and can inform a socio-hydrological modeling process. First, in both fields the research question or problem drives modeling decisions. Much of the work to date on socio-hydrological systems explores observed dynamics but does not posit clear hypotheses or questions (Haleis exploratory and aims et al., 2015). While this approach may contribute to hypothesis generation the resulting models have little defense against the inevitable critiques over the choiceexplain evidence of model structure, scope and scale.system coupling seen in case data. Developing a model to answer a question or testsolve a hypothesisproblem allows a more structured and defensible framework to support the modeling decisions ~~as well as provide~~and provides a benchmark for model validation (Sterman, 2000; Hinkel et al., 2015). ~~2015).~~For example, Jones et al (2002), in modeling the sawmill industry in the Northeastern United States, focus on understanding if the system has the structural potential to overshoot sustainable yield. While the resulting model is a significant simplification of a complex system, the reason for inclusion of tree growth dynamics, mill capacity and lumber prices and the exclusion of other variables is clear. Second, system dynamics and social-ecological systems science use multiple data sources, both quantitative and qualitative, to specify and parameterize model relationships. Omitting influential relationships or decision points due to lack of quantitative data results in a greater error than their incorrect specification (Forrester, 1992). Third, system dynamics focuses on developing a dynamic hypothesis that explains the system behavior of interest in terms of feedback processes (Sterman, 2000). Finally, social-ecological systems science has found that the use of frameworks as part of a structured model development process can aid transparency and comparability across models (Schlüter et al., 2014).

## 2.3 Progress and Gaps in Socio-Hydrological Modeling

Several research teams have operationalized the concepts of socio-hydrology using approaches ranging from simple generic models to contextual data-driven models. Di Baldassarre et al. (2013) developed a simple generic model to explore the dynamics of human-flood interactions for the purpose of showing that human responses to floods can exacerbate flooding problems. Viglione et al. (2014) extended this work to test the impact of collective memory, risk-taking attitude and trust in risk reduction measures on human-flood dynamics. Kandasamy et al. (2014) analyzed the past one hundred years of development in the Murrumbidgee river basin in eastern Australia and built a simple model of the transition from the dominance of agricultural development goals, through a slow realization of adverse environmental impacts, to emergence of serious ecological restoration efforts. Elshafei et al. (2014) proposed a conceptual socio-hydrological model for agricultural catchments and applied it to the Murrumbidgee and the Lake Toolibin basins; they then built upon this conceptual model to construct a detailed semi-distributed model of the Lake Toolibin basin (Elshafei et al., 2015). Srinivasan and collaborators analyzed water security in the city of Chennai, India. By modeling the feedback between household level coping mechanisms and regional scale stressors, the team explained the counterintuitive effects of policy responses such as the observation that reduced groundwater recharge caused by fixing leaky pipelines decreased household’s ability to use wells to cope with water system interruptions (Srinivasan et al., 2010; Srinivasan et al., 2013).

Researchers have also addressed the methodological questions of how to frame and model socio-hydrological systems. Blair and Buytaert (2015), provide a detailed review of the model types and modeling methods used in socio-hydrology and those that may have utility in the field. Sivapalan and Blösch (2015) offer guidance on framing and modeling socio-hydrological systems from stating framing assumptions to model validation techniques and highlight the specific challenges of scale interactions found in these coupled systems. Elshafei et al. (2014) and Liu et al. (2014) detailed the development of conceptual models, giving readers insight into the framing of their case study work.

These methodological advances have begun to address the many challenges of translating the concept of feedback between human and hydrological systems into actionable science. However, obstacles remain; principally, expanding the scope of modeling to include societal systems and human decision making exacerbates the challenges of setting the model boundary and process detail, and of evaluating those choices. The source of this challenge is twofold. First, there are fundamental differences between natural and social systems. The laws governing physical, chemical and biological systems such as conservation of mass and energy are broadly applicable across contexts; the relevance of rules influencing social systems varies by context. Second, the modeling of coupled human—hydrological systems is new intellectual territory. At this intersection the norms and unstated assumptions instilled by disciplinary training must be actively questioned and examined within a transparent model development, testing, and validation process.

There are no universally accepted laws of human behavior as there are for the physical and biological sciences (Loucks, 2015). While institutions (formal and informal rules) influence behavior, the impact of institutions on the state of the system depends on whether people follow the rules (Schlager and Heikkila, 2011). Additionally, these rules are not static. In response to outcomes of past decisions or changing conditions, actors change both the rules that shape the options available for practical decisions and the rules governing the collective choice process through which these operation rules are made (McGinnis, 2011). Further, water policy decisions are not made in isolation of other policy decisions. Decisions are interlinked as the same actors may interact with and get affected differently depending on the contexts (McGinnis, 2011b). The outcome of a related policy decision may alter the choices available to actors or the resources available to address the current problem. The state of the hydrological system, particularly extreme events, can spark institutional changes; yet, other factors such as political support and financial resources as well as the preparedness of policy entrepreneurs also play a role (Crow, 2010; Hughes et al., 2013). Given this complexity, Pahl-Wostl et al. (2007) argue that recognizing the unpredictability of policy making and social learning would greatly improve the conceptualization of water management. Nevertheless, some dynamics persist across time and space; water management regimes persist for decades or centuries and some transitions in different locations share characteristics (Elshafei et al., 2014; Kandasamy et al., 2014; Liu et al., 2014). Further, modeling is a useful tool to gain insight into the impacts of these dynamics (Thompson et al., 2013; Sivapalan and Blöschl, 2015). However, complex systems such as socio-hydrological systems cannot be modeled exhaustively (Sterman, 2000; Schlüter et al., 2014). Rather model conceptualization must balance sufficient process representation and parsimony (Young et al., 1996; Ostrom, 2007).

Model conceptualization is based on general assumptions about how a system works. Often these assumptions are implicit and not challenged by others within the same research community (Kuhn, 1996). This works well when research stays within the bounds of the existing methods, theories and goals of one's research community; when working in new intellectual territory, research community norms cannot be relied upon to guide assumptions. Further disciplinary training is highly successful at teaching these community norms and researchers working on interdisciplinary projects must actively question the framing assumptions they bring to the project (Lélé and Norgaard, 2005; McConnell et al., 2009). By its integrative nature socio-hydrological modeling crosses disciplines and modelers are unable to point to the theoretical framework of any single discipline to make simplifying assumptions (Srinivasan, 2015). In absence of research community norms, we must return to modeling fundamentals. Models are simplifications of real systems that, in a strict sense, cannot be validated but the acceptability of model assumptions for the question at hand can be assessed (Sterman, 2000). Careful articulation of the research questions links the assessment of important variables and mechanisms to the question context. This allows critique to focus on the acceptability of these choices relative to model goals and enables critical assessment of the range of applicability of identified processes through case and model comparison.

The recent Water Resources Research Debate Series offers an excellent illustration of this point. Di Baldasarre et al. (2015) catalyze the debate by presenting a generic model of human flood interaction. This model incorporates both the "levee effect" in which periods of infrequent flooding (sometimes caused by flood protection infrastructure) increase the tendency for people to settle in the floodplain and the "adaptation effect" in which the occurrence of flooding leads to an adaptive response. In the model they link flood frequency and adaptive action through a social memory variable which increases with the occurrence of floods and decays slowly overtime; flood occurrence directly triggers levee heightening in technological societies and indirectly, through the social memory, decreases floodplain population density (Di Baldassarre et al., 2015).

In the debate this modeling approach is both commended as an impressive innovation and critiqued for its simplification of social dynamics (Gober and Wheater 2015; Loucks 2015; Sivapalan 2015; Troy et al., 2015). Gober and Wheater (2015), note that while social or collective memory is an important factor in flood resilience it does not determine flood response; flood awareness may or may not result in an adaptive response based on the way individuals, the media and institutions process the flood threat, the social capacity for adaptation and the preparedness of policy entrepreneurs, among other factors. Loucks (2015) observes that data on past behavior is not necessarily an indicator of future behavior and suggests that observing stakeholder responses to simulated water management situations may offer additional insight. Troy et al. (2015) and Di Baldassarre (2015) et al. note that the human flood interaction model presented represents a hypothesis of system dynamics which allows exploration and that simple stylized models enable generalization across space and time. In sum the debate presents different perspectives on the acceptability of the modeling assumptions.

A close look at how the debate authors critique and commend the human flood interaction model illustrates that the acceptability of modeling assumptions hinges upon the model's intended use. For example, Gober and Wheater (2015) critique the simplicity of social memory as a proxy for social system dynamics but acknowledge the utility of the model in clarifying the tradeoffs of different approaches to meet water management goals. As we can never have comprehensive representation of a complex and coupled human and hydrological system, we need transparency of the abstracting assumptions and their motivation. This is not a new insight; however, a question driven modeling process allows the flexibility and transparency needed to examine the acceptability of model assumptions while acknowledging the role of context and the potential for surprise.

## ~~2.1~~2.4 A Question Driven Modeling Process

Our proposed process begins with a research question. The research question is then used to identify the key outcome metric(s). A dynamic hypothesis is developed to explain the behavior of the outcome metric over time; a framework can be used to guide and communicate the development of the dynamic hypothesis. Remaining model processes are then specified according to established theory.

As emphasized by both system dynamics and social-ecological systems researchers, the research question drives the process of system abstraction. One way to think about this process of abstraction is through the lens of forward and backward reasoning. Schlüter et al. (2014) introduced the idea of forward and backward reasoning to develop conceptual models of social-ecological systems. In a backward-reasoning approach, the question is first used to identify indicators or outcome metrics; next, the analysis proceeds to identify the relevant processes and then the variables and their relationships, as seen in Fig. 1 (Schülter et al., 2014). These three pieces then form the basis for the conceptual model. In contrast, a forward reasoning approach begins with the identification of variables and relationships and then proceeds toward outcomes. Forward reasoning is most successful when there is expert knowledge of the system and backward reasoning is useful primarily when prior knowledge is insufficient (Arocha~~, Patel and Patel,~~ et al., 1993). As few researchers have expert knowledge of all domains involved in socio-hydrological modeling and data is often sparse, a backward reasoning approach is here used to conceptualize a socio-hydrological model. Additionally, this outcome oriented approach will focus the scope of the model on the question relevant variables and processes.

The research question helps to define the outcome metric(s) of interest; however, determining the relevant processes and variables requires further analysis. One tool to identify influential processes and variables is the dynamic hypothesis. A dynamic hypothesis is a working theory, informed by data, of how the system behavior in question arose (Sterman, 2000). It is dynamic in nature because it explains changes in behavior over time in terms of ~~processes dependent on variables~~the structure of the system (Stave, 2003). The dynamic hypothesis could encompass the entire socio-hydrological model, but in practice many processes within a model will be based on established theory such as rain-fall runoff or evaporation processes. The intent is to focus~~ on~~ the dynamic hypothesis on a novel theory explaining observed behavior. Stating the dynamic hypothesis clarifies which portion of the model is being tested.

A framework can aid the development of the dynamic hypotheses and the communication of the reasoning behind it. ~~Frameworks are tools that guide, and increase the transparency of, theory and model development, by prescribing a set of elements and general relationships to consider when studying one class of systems (Ostrom, 2011). Several research teams in social-ecological systems science use frameworks to determine the relevant processes and variables for a given research question (Schülter et al., 2014).~~ The use of frameworks enhances the transparency of model development by clearly communicating the modeler's broad understanding of a system. Socio-hydrological modelers can develop their own framework (Elshafei et al., 2014) or draw on existing frameworks that address coupled human–hydrological systems such as the Social-Ecological Systems (SES) Framework, the Management Transition Framework, or the integrated Structure-Actor-Water framework (Ostrom, 2007; Pahl-Wostl et al., 2010; Hale et al., 2015). ~~Frameworks enhance the transparency of model development by clearly communicating the modeler's broad understanding of a system.~~

~~In sum, our~~To illustrate how a framework may be used in model conceptualization we will focus on the SES framework. The SES framework is a nested conceptual map that partitions the attributes of a social-ecological system into four broad classes: 1) resource system, 2) resource units, 3) actors, and 4) the governance system (McGinnis and Ostrom, 2014). Each of the four top tier variables has a series of second tier (and potentially higher tier) variables; for example, storage characteristics and equilibrium properties are second tier attributes of the resource system (Ostrom, 2009). The SES framework prescribes a set of elements and general relationships to consider when studying coupled social and ecological systems (Ostrom, 2011). The variables defined in the SES framework, were found to impact the interactions and outcomes of social-ecological systems in a wide range of empirical studies (Ostrom, 2007). ~~proposed process begins with a research question. The research question is then used to identify the key outcome metric(s). A dynamic hypothesis is developed to explain the behavior of the outcome metric over time; a framework can be used to guide and communicate the development of the dynamic hypothesis. Remaining model processes are then specified according to established theory.~~ In addition to specifying candidate variables, the SES framework specifies broad process relationships (Schlüter et al., 2014). At the broadest level SES specifies that the state of the resource system, governance system, resource unit properties and actor characteristics influence interactions and are subsequently influenced by the outcomes of those interactions. To operationalize the SES framework for model conceptualization one must move down a level to assess the relevance of the tier two variables against case data and background knowledge. This review aims to check the dynamic hypothesis against a broader view of coupled system dynamics and to inform determination of remain model processes.

The following case presents the development of a simple socio-hydrological (coupled) and a traditional (non-coupled) model to illustrate this process. While this process is developed to study real world cases a hypothetical case is used here for simplicity, brevity, and proof of concept.

## 3 Sunshine City: A Case Study of Reservoir Operations

Sunshine City is located in a growing region in a semi-arid climate. The region is politically stable, technologically developed, with a market economy governed by a representative democracy. Sunshine City draws its water supply from the Blue River, a large river which it shares with ~~upstream and~~ downstream neighbors. The water users must maintain a minimum flow in the Blue River for ecological health. Sunshine City can draw up to 25% of the annual flow of the Blue River in any given year. A simple prediction of the year's flow is made by assuming that the flow will be equal to the previous year's flow; the resulting errors are corrected by adjusting the next year's withdrawal.

The city Water Utility is responsible for diverting, treating and transporting water to city residents and businesses. It is also tasked with making infrastructure investment decisions and, setting water prices. Water users receive plentiful supply at cost and there have been no shortages in recent years. While located in a semi-arid environment, the large size of Sunshine City's Blue River water availability and allocation created a comfortable buffer. The city Water Utility is also responsible for setting water efficiency codes and other conservation rules. The current building code includes only basic efficiencies required by the national government. The Blue River, along with other regional sources, is fully allocated making future augmentation of supplies unlikely. See Table 1 below for a summary of key characteristics of Sunshine City.

Along with the rest of the region, Sunshine City's population, and its water demand, has grown rapidly over the past few years. Managers at the Water Utility are concerned they will no longer be able to meet its reliability targets as demands rise and have added a reservoir to increase future reliability. They now must decide how to operate the reservoir and are considering two options: Standard Operating Policy (SOP) and Hedging Policy (HP). The selected operating policy must satisfy downstream user rights and maintain minimum ecological flows. In addition to meeting the legal requirements, the Water Utility managers are concerned with finding a policy that will enable the city to provide the most reliable water supply throughout the lifetime of the reservoir (50 to 100 years). From experience they have observed that both water price and reliability affect demand. A key puzzle that emerges for water managers from this experience is:

> *How do operational rules governing use of water storage influence long term water supply reliability when consumers make water usage decisions based on both price and reliability?*

AlongAs the question implies, the Water Utility managers have a working hypothesis relating demand change with water shortages. Therefore, along with the research question the following dynamic hypothesis is considered:

> H: the occurrence of water shortages increases the tendency of users to adopt water conservation technologies and to make long term behavioral changes. HP triggers shortages sooner than SOP thus triggering earlier decreases in demand.

### 3.1 Background

The decision of how much water to release for use each time period is deceptively complex due to the uncertainty of future streamflows and the nonlinear benefits of released water (Shih & ReVelle, 1994; Draper & Lund, 2004). In making release decisions, water utilities must fulfill their mandate to maintain a reliable water supply in a fiscally efficient manner. Reliability is the probability that the system is in a satisfactory state (Hashimoto, Stedinger & Loucks, 1982). In this case, a satisfactory system state is one in which all demands on the system can be met. The definition of an unsatisfactory state is more nuanced. Water shortages have a number of characteristics that are important to water management including frequency, maximum shortage in a given time period, and length of shortage period (Cancelliere et al., 1998). ~~In this study we will focus on the frequency and maximum magnitude of shortage events.~~ Long term reliability here refers to the projected reliability over several decades. The timeframe used for long term projections varies between locations and utilities (i.e. Boston uses a 25 year timeframe, Denver uses a 40 year timeframe, and Las Vegas uses a 50 year timeframe) and a 50 year timeframe is used here (MWRA, 2003; SNWA, 2009; Denver Water, 2015).

Two operational policies, SOP and HP, are commonly used to address this decision problem. Under SOP, demand is always fulfilled unless available supply drops below demand; under HP, water releases are limited in anticipation of an expected deficit (Cancelliere et al., 1998). Hedging is used as a way to decrease the risk of a large shortfall by imposing conservation while stored water remains available. ~~-~~Figures 2 and 3 illustrate SOP and HP respectively. For this simple experiment only linear hedging, where $K_P$ is the slope of the release function, is tested. ~~The impact of other approaches, such as non-linear hedging functions, is not considered here.~~

The traditional argument for hedging is that it is economical to allow a small deficit in the current time period in order to decrease the probability of a more severe shortage in a future time periods (Bower et al., 1962). This argument holds true if the loss function associated with a water shortage is nonlinear and convex; in other words that a severe shortage has a larger impact than the sum of several smaller shortages (Shih & ReVelle, 1994). Gal (~~1972~~1979) showed that the water shortage loss function is convex, thereby proving the utility of hedging as a drought management strategy. Other researchers have shown that hedging effectively reduces the maximum magnitude of water shortages and increases total utility over time (Shih & ReVelle, 1994; Cancelliere et al., 1998). More recent work by Draper & Lund (2004) and You & Cai (2008) confirms previous findings and demonstrates the continued relevance reservoir operation policy selection.

Researchers and water system managers have for decades sought improved policies for reservoir operation during drought periods (Bower et al., 1962; Shih & ReVelle, 1994; You & Cai, 2008). We add to this classic question the observation that water shortages influence both household conservation technology adoption rates and water use behavior. In agreement with Giacomoni, et al. (2013), we hypothesize that the occurrence of water shortages increases the tendency of users to adopt water conservation technologies and to make long term behavioral changes. Household water conservation technologies include low flow faucets, shower heads and toilets, climatically appropriate landscaping, greywater recycling and rainwater harvesting systems (Schuetze & Santiago-Fandiño, 2013). The adoption rates of these technologies are influenced by a number of factors including price, incentive programs, education campaigns and peer adoption (Campbell et al., 2004; Kenney et al., 2008). A review of studies in the U.S., Australia and U.K. showed that the installation of conservation technologies results in indoor water savings of 9 to 12% for fixture retrofits and 35 to 50% for comprehensive appliance replacements (Inman & Jeffrey, 2006). In some cases offsetting behavior reduces these potential gains; however, even with offsetting, the adoption of conservation technologies still results in lower per capita demands (Geller et al., 1983; Fielding et al., 2012). Water use behavior encompasses the choices that individuals make related to water use ranging from length of showers and frequency of running the dishwasher to timing of lawn watering and frequency of car washing. Water use behavior is shaped by knowledge of the water system, awareness of conservation options and their effectiveness, and ~~consumers~~consumer's attitudes toward conservation (Frick et al., 2004; Willis et al., 2011). Changes to water use behavior can be prompted by price increases, education campaigns, conservation regulations, and weather (Campbell et al., 2004; Kenney et al., 2008; Olsmtead & Stavins, 2009).

As a city begins to experience a water shortage, the water utility may implement water restrictions, price increases, incentive programs or education campaigns to influence consumer behavior. While staff within the water utility or city may have planned these measures before, the occurrence of a water shortage event, particularly if it aligns with other driving forces, offers a window of opportunity to implement sustainable water management practices (Jones & Baumgartner, 2005; Hughes et al., 2013). In addition, water users are more likely to respond to these measures with changes in their water use behavior and/or adoption of conservation technologies during shortages. Baldassare and Katz (1992) examined the relationship between the perception of risk to personal well-being from an environmental threat and adoption of environmental practices with a personal cost (financial or otherwise). They found that the perceived level of environmental threat is a better predictor for individual environmental action, including water conservation, than demographic variables or political factors. Illustrating this effect, Mankad and Tapsuwan (2011) found that adoption of alternative water technologies, such as on-site treatment and reuse, is increased by the perception of risk from water scarcity.

Evidence of individual level behavior change can also be seen in the results of a 2013 national water policy survey conducted by the Institute for Science, Technology and Public Policy at Texas A&M University. The survey sampled over 3,000 adults from across the United States about their attitudes and actions related to a variety of water resources and public policy issues. Included in the survey were questions that asked respondents how recently, if ever, they personally experienced a water shortage and which, if any, household efficiency upgrade or behavioral change actions their household had taken in the past year. Efficiency upgrade options offered included low-flow shower heads, low-flush toilets and changes to landscaping; behavioral options given included shorter showers, less frequent dishwasher or washing machine use, less frequent car washing and changes to yard watering (ISTPP, 2013). As seen in Table 3, respondents who had recently experienced a water shortage were more likely to have made efficiency investments and to have changed their water use behavior. This finding is corroborated by a recent survey of Colorado residents. Of the 72% of respondents reporting increased attention to water issues, the most cited reason for the increase (26% of respondents) was a recent drought or dry year (BBC Research, 2013). Other reasons cited by an additional 25% of respondents including news coverage, water quantity issues and population growth may also be related water shortage concerns or experiences.

The increased receptivity of the public to water conservation measures and the increased willingness of water users to go along with these measures during shortage events combine to drive changes in per capita demands. The combined effect of these two drivers was demonstrated in a study of the Arlington, TX water supply system (Giacomoni, et al., 2013; Kanta & Zechman, 2014). Additional examples of city and regional scale drought response leading to long term demand decreases include the droughts of 1987-1991 and the mid-2000s in California and of 1982-1983 and 1997-2009 in Australia (Zilberman et al., 1992; Turral, 1998; Sivapalan et al., ~~2011~~2012; Hughes et al., 2013). It is often difficult to separate the relative effects of the multiple price and non-price approaches applied by water utilities during droughts (Olmstead & Stavins, 2009). The point is, however, that the response generally points to lower per capita water demands.

One example of lasting water use reductions after a shortage is the 1987 to 1992 drought in Los Angeles, California. An extensive public awareness and education campaign sparked both behavioral changes and the adoption of efficient fixtures such as low-flow shower heads and toilets and increasing block pricing introduced after the drought helped maintain conservation gains (LADWP, 2010). Evidence of the lasting effect can be seen in Fig. 4. Per capita water demands do not return to 1990 levels after the drought ends in 1992. Note that the data below also contains a counter example. The 1976 to 1977 drought caused a sharp drop in water consumption in Los Angeles, however, consumption quickly returned to pre-drought levels when the rainfall returned in 1978. While the 1976 to 1977 drought was more intense than any year in the 1987 to 1992 drought, the long duration of the later drought caused deeper draw downs in the city's water reserves ultimately prompting transformative action (LADWP, 2010). This may indicate that the impact of the 1976–1977 drought was below the threshold for significant action or that other priorities dominated public attention and resources at the time. In sum, the Los Angeles case serves both to illustrate that hydrological change can prompt long term changes in water demands and as a reminder that multiple factors influence water demands and ~~that~~ hydrological events will not always dominate.

## 3.2 Model Development

The Sunshine City water managers want to understand how the operational rules governing use of water storage influence long term water supply reliability when consumers make water usage decisions based on price and reliability. A model can help the managers gain insight into system behavior by computing the consequences of reservoir operation policy choice over time and under different conditions. As described in the background section, many supply side and demand side factors affect water system reliability. However, not all variables and processes are relevant for a given question. A question driven modeling process uses the question to determine model boundary and scope rather than beginning with a prior understanding of the important variables and processes. A question driven process is here used to determine the appropriate level of system abstraction for the Sunshine City reservoir operations model.

From the research question it is clear that **reliability** is the outcome metric of interest and that the model must test for the hypothesized link between demand changes and reliability. Reliability, as defined above, is the percent of time that all demands can be met. The SES Framework is used to guide the selection of processes and variables, including the dynamic hypothesis. Given this wide range, the framework was then compared against the variables and processes found to be influential in urban water management and socio-hydrological studies (Brezonik and Stadelmann, 2002; Abrishamchi et al., 2005; Padowski and Jawitz, 2012; Srinivasan et al., 2013; Dawadi and Ahmad, 2013; Elshafei et al., 2014; Gober et al., 2014; Liu et al., 2014; Pande et al., 2013; van Emmerik et al., 2014). Based on this evaluation two second tier variables were added to the framework: land use to the resource system characteristics and water demand to interactions; other variables were modified to reflect the language typically used in the water sciences (i.e. supply in place of harvesting). See Table 2 for urban water specific modification of the SES framework.

We then assess the relevance of the tier two variables against case data and background knowledge (summarized in Sections 3.0 and 3.1 respectively) by beginning with the outcome metric, reliability. Within the framework reliability is an outcome variable, specifically a social performance metric, and it is the direct result of water supply and water demand interaction processes. The SES framework prescribes a set of elements and general relationships to consider when studying coupled social and ecological systems (Ostrom, 2011). The variables defined in the SES framework, were found to impact the interactions and outcomes of social-ecological systems in a wide range of empirical studies (Ostrom, 2007). The types of interaction processes listed in the SES framework help to determine the processes influencing reliability. Based on the dynamic hypothesis, three processes influence reliability including water supply, per capita water demand, and population growth.

Water supply encompasses the set of utility level decisions on reservoir withdrawals and discharges. TheseAs detailed in the case description, these decisions are shaped by the selected reservoir operating policy, streamflow, the existing environmental flow and downstream allocation requirements, reservoir capacity, water in storage, and water demands. PerStreamflow is a stochastic process that is a function of many climatic, hydraulic and land surface parameters. However, given the driving question and the assumption that the city represents only a small portion of the overall watershed, a simple statistical representation is sufficient and streamflow is assumed independent of other model variables.

Total water demand is a function of both population and per capita demand. As described in the background section, per capita water demand changes over time in response to household level decisions to adopt more water efficient technologies and water use behavior change made by individuals in each time interval.; these decisions may be influenced by conservation policies. As conditions change water users reassess the situation and, if they choose to act, decide between available options such as investment in efficient technology, changing water use behavior and, in extreme cases, relocation. Therefore, waterper capita demand is a function of price and historic water reliability as well as available technologies, and water user's perception of the water system. Since the focus of the question is on system wide reliability individual level decisions can be modeled in the aggregate as total demand, which is also influenced by population. Population increases in proportion to the current population, as regional economic growth is the predominate driver of migration trends. However, in extreme cases, perceptions of resource limitations can also influence growth rates. ~~These~~The SES variables used in the conceptual model are highlighted in Table 2 and the resulting processes are summarized in Fig. 5.

~~Streamflow also influences reliability. Streamflow is~~Only a ~~stochastic process that is a function~~subset of ~~many climatic, hydraulic~~the variables and ~~land surface parameters. However, given the driving question and~~ processes articulated in the ~~assumption that~~SES framework are included in the ~~city represents only a small portion of the overall watershed, a simple statistical representation is sufficient and streamflow is assumed independent of~~conceptual model; other ~~model~~ variables~~.~~

~~Other~~ and processes were considered but not included. For example, economic development drives increasing per capita water demands in many developing regions but the relationship between economic growth and water demands in highly developed regions is weaker~~,~~, due to the increased cost of supply expansion and ~~in cases such as the Murrumbidgee basin in Australia reversed (Kandasamy~~greater pressure for environmental protection (Gleick, 2000). The income elasticity of water can lead to increased water demands if rates do not change proportionally (Dalhuisen et al., ~~2013). Since~~2003); here prices are assumed to keep pace with inflation. Given this ~~case focuses~~assumption, and the focus on a city in a developed region, economic development likely plays a minor role. Similarly group decision making and planning processes such as public forums, voting and elections can shape the responses to reliability changes over time. This model aims to answer a question about the impact of a policy not the ease or likelihood of its implementation. Once the policy is established through whatever process that is used, the question here focuses on its efficacy. Therefore, group decision making processes need not be included.

In addition to determining the appropriate level of detail of the conceptual model, we must determine which variables change in response to forces outside the model scope (exogenous variables), which variables must be modeled endogenously (state variables) and which can be considered constants (parameters). Again the nature of the question along with the temporal and spatial scale informs these distinctions. Variables such as stored water volume, per capita water demand, shortage awareness will clearly change ~~of the course of~~over the 50 year study period. The population of the city is also expected to change over the study period. Under average hydrological conditions the population growth rate is expected to be driven predominately by regional economic forces exogenous to the system; however, under extreme conditions water supply reliability can influence the growth rate. Therefore, population is considered a state variable. Streamflow characteristics may change over the 50 year time scale in response to watershed wide land use changes and global scale climatic changes. Streamflow properties are first considered stationary parameters in order to understand the impact of the selected ~~of~~ operating policy in isolation from land use and climate change. Climate scenarios or feedbacks between population and land use can be introduced in future applications of the model to test their impact on system performance. Reservoir operating policy, summarized as the hedging slope, $K_P$, is considered a parameter in the model. Alternate values of parameter $K_P$ are tested but held constant during the study period to understand the long term impacts of selecting a given policy. Reservoir properties such as capacity and slope are also held constant to hone in on the effect of operating policy. See Table 4 ~~and 4~~ and Table 5 for a summary of variable types. From these model relationships, general equations are developed by drawing from established theory, empirical findings and working hypotheses.

Streamflow, Q, is modeled using a first order autoregressive model, parameterized by mean ($\mu_H$, $km^3yr^{-1}$), standard deviation ($\sigma_H$, $km^3yr^{-1}$), and lag one autocorrelation ($\rho_H$). The final term, $a_t$, is a normally distributed random variable with a mean zero and a standard deviation of one.

$$Q_t = \rho_H(Q_{t-1} - \mu_H) + \sigma_H(1 - p_H^2)^{0.5}a_t + \mu_H \quad (1)$$

At each time step the amount of water in storage, V, in the reservoir is specified by a water balance equation where W is water withdrawal~~, $\eta_H A$~~ ($km^3$), $\eta_H$ ($km\ yr^{-1}$) is evaporation, A is area ($km^2$), $Q_D$ ($km^3$) is downstream demand and $Q_E$ ($km^3$) is the required environmental flow.

$$\frac{dV}{dt} = \sout{Q - W - \eta_H A - Q_D}\ Q_t - W_t - \eta_H A_t - Q_D - Q_E$$

(2)

Population is the predominant driver of demand in the model. Population (P) changes according to average birth~~,~~ ($\delta_B$, $yr^{-1}$), death~~,~~ ($\delta_D$, $yr^{-1}$), emigration ($\delta_E$, $yr^{-1}$) and immigration ($\delta_I$, $yr^{-1}$) rates. However, immigration is dampened and emigration accelerated by high values of perceived shortage risk, as would be expected at extreme levels of resource uncertainty (Sterman, 2000). The logistic growth equation, which simulates the slowing of growth as the resource carrying capacity of the system is approached, serves as the basis for the population function. While the logistic function is ~~a~~ commonly used to model resource constrained population growth, the direct application of this function would be inappropriate for two reasons. First, an urban water system is an open system; resources are imported into the system at a cost and people enter and exit the system in response to reductions in reliability and other motivating factors. Second, individuals making migration decisions may not be aware of incremental changes in water shortage risk; rather, perceptions of water stress drive the damping effect on net migration. Finally, only at high levels does shortage perception influence population dynamics. To capture the effect of the open system logistic damping is applied only to immigration driven population changes~~.~~ when shortage perception crosses a threshold, $\tau_P$. To account for the perception impact the shortage awareness variable, M, is used in place of the ratio of population to carrying capacity typically used; this modification links the damping effect to perceived shortage risk.

$$\frac{dP}{dt} = \sout{P[(\delta_B - \delta_D) + \delta_I(1-M) - \delta_E(M)]}$$

$$\begin{cases} P_t[\delta_B - \delta_D + \delta_I - \delta_E] & for\ M_t < \tau_P \\ P_t[(\delta_B - \delta_D) + \delta_I(1-M_t) - \delta_E(M_t)] & for\ M_t \geq \tau_P \end{cases} \quad (3)$$

Water withdrawals, W, are determined by the reservoir operating policy in use. As there is only one source, water withdrawn is equivalent to the quantity supplied. The predicted streamflow for the coming year is 0.25*$Q_{t-1}$, accounting for both downstream demands and environmental flow requirements. Under SOP, $K_P$ is equal to one which sets withdrawals equal to total demand, DP (per capita demand multiplied by population), unless the stored water is insufficient to meet demands. Under HP, withdrawals are slowly decreased once a pre-determined threshold, $K_P$DP, has been passed. For both policies excess water is spilled when stored water exceeds capacity, $V_{MAX}$.

$$\sout{W = \begin{cases} V - V_{Max} & for\ V \geq DP + V_{Max} \\ DP & for\ DP + V_{Max} > V \geq K_P DP \\ \frac{V}{K_P} & for\ K_P DP > V \end{cases} \quad (4)}$$

$$W_t = \begin{cases} V_t + 0.25Q_{t-1} - V_{Max} & for\ V_t + 0.25Q_{t-1} \geq D_t P_t + V_{Max} \\ D_t P_t & for\ D_t P_t + V_{Max} > V_t + 0.25Q_{t-1} \geq K_P D_t P_t \\ \frac{V_t + 0.25Q_{t-1}}{K_P} & for\ K_P D_t P_t > V_t + 0.25Q_{t-1} \end{cases} \quad (4)$$

When the water withdrawal is less than the quantity demanded by the users, a shortage, S, occurs.

$$\sout{S = \begin{cases} DP - W & for\ DP > W \\ 0 & otherwise \end{cases}} \quad S_t = \begin{cases} D_t P_t - W_t & for\ D_t P_t > W_t \\ 0 & otherwise \end{cases}$$

(5)

Di Baldassarre et al. (2013) observed that in flood plain dynamics awareness of flood risk peaks after a flood event. This model extends that observation to link water shortage events to the awareness of shortage risk. The first term in the equation is the shortage impact which is a convex function of the shortage volume. The economic utility of hedging hinges on the assumption that the least costly options to manage demand will be undertaken first. As both water utilities and water users have a variety of demand management and conservation options available and both tend to use options from most to least cost-effective, a convex shortage loss is also applicable to the water users (Draper & Lund, 2004). It is here assumed that the contribution of an event to shortage awareness is proportional to the shortage cost. At high levels of perceived shortage risk only a large shortage will lead to a significant increase in perceived risk. The adaptation cost is multiplied by one minus the current shortage awareness to account for this effect. The second term in the equation incorporates the decay of shortage, $\mu_S$ ($yr^{-1}$), awareness and its relevance to decision making that occurs over time (Di Baldassarre et al., 2013).

$$\frac{dM}{dt} = \left(\frac{S}{DP}\right)^2 (1-M) - \mu_S M \left(\frac{S_t}{D_t P_t}\right)^2 (1-M_t) - \mu_S M_t \qquad (6)$$

Historically, in developed regions per capita water demands have decreased over time as technology improved and as water use practices have changed. As described above, this decrease is not constant but rather is accelerated by shocks to the system. To capture this effect there are two portions to the demand change equation: shock stimulated logistic decay with a maximum rate of α ($yr^{-1}$) and a background decay rate~~.~~, β ($yr^{-1}$). Per capita water demand decrease accelerates in a time interval if water users are motivated by recent personal experience with water shortage (i.e. M > 0). As a certain amount of water is required for basic health and hygiene, there is ultimately a floor to water efficiencies~~.~~, specified here as $D_{min}$ ($km^3yr^{-1}$). Reductions in per capita water usage become more challenging as this floor is approached; a logistic decay function is used to capture this effect. When no recent shortages have occurred (i.e. M = 0), there is still a slow decrease in per capita water demands. This background rate, β, of demand decrease is driven by both the replacement of obsolete fixtures with modern water efficient fixtures and the addition of new more efficient building stock. This background rate is similarly is slowed as the limit is approached; this effect is incorporated by using a percentage based background rate. Note that price is not explicitly included in this formulation of demand. As stated above, because price and non-price measures are often implemented in concert it is difficult to separate the impacts of these two approaches, and in this case unnecessary.

$$\frac{dD}{dt} = -D\left[M\alpha\left(1-\frac{D_{min}}{D}\right)+\beta\right] D_t\left[M_t\alpha\left(1-\frac{D_{min}}{D_t}\right)+\beta\right] \qquad (7)$$

As a comparison, a non-coupled model was developed. In this model population and demand changes are no longer modeled endogenously. The shortage awareness variable is removed as it no longer drives population and demand changes. Instead the model assumes that population growth is constant at 3% and that per capita demands decrease by 0.5% annually. While these assumptions may be unrealistic they are not uncommon. Utility water management plans typically present one population and one demand projection. Reservoir storage, water withdrawals, and shortages are computed according to the equations described above. A full list of model variables and parameters can be found in Table 4 and Table 5, respectively.

## 3.3 Results

The model was run for SOP ($K_P$ = 1) and three levels of HP where level one ($K_P$ = 1.5) is the least conservative, level two ($K_P$ = 2) is slightly more conservative and level three ($K_P$ = 3) is the most conservative hedging rule tested. Three trials were conducted with a constant parameter set to understand the system variation driven by the stochastic streamflow sequence~~.~~ and to test if the relationship hypothesized was influential across hydrological conditions. For each trial streamflow, reservoir storage, shortage awareness, per capita demand, population and total demand were recorded and plotted. As a comparison, each trial was also run in ~~a traditional water systems~~the non-coupled model in which demand and population changes are exogenous.

In the first trial, shown in Fig. 6a, there were two sustained droughts in the study period: from years 5 to 11 and then from years 33 to 37. Higher than average flows in the years preceding the first drought allowed the utility to build up stored water as seen in Fig. 6b. The storage acts as a buffer and the impacts are not passed along to the water users until year 18 under SOP. Under HP the impacts, as well as water users' shortage awareness, increase in years ~~16, 14~~15, 13 and ~~11~~12 based on the level of the hedging rule (slope of $K_P$) applied, as shown in Fig. 6c. The impact of this rising shortage awareness on per capita water demands is seen in the acceleration of the decline in demands in Fig. 6d. This demand decrease is driven by city level policy changes such as price increases and voluntary restrictions in combination with increased willingness to conserve. The impacts of this decrease on individual water users will depend on their socio-economic characteristics as well as the particular policies implemented. While the aggregation hides this heterogeneity it should be considered in the interpretation of these results. The increased shortage awareness also has a small dampening effect on population growth during and directly after the first drought, Fig. 6e. Changes to both per capita demands and population result in total demand changes (see Fig. 6f). After the first drought the system begins to recover under each of the three hedging policies as evidenced by the slow increase in reservoir storage. However, as streamflows fluctuate around average streamflow and total demands now surpass the average allocation reservoir storage does not recover when no hedging restrictions are imposed. Several years of above average flow ending in year 29 drive further recovery. The second prolonged drought has the most pronounced effect under the SOP scenario. Shortage impacts are drastic driving further per capita demand decreases and a ~~reversal~~temporary decline in population~~ growth. Only~~.. A slight population decrease is also seen under level ~~three HP does~~one hedging but the ~~system completely avoid population contraction, although~~results demonstrate that all hedging strategies dampen the effect.

In the second trial there are two brief droughts in the beginning of the study period, beginning in years 4 and 10, as seen in Fig. 7a. Under SOP and the first two hedging policies there is no change in operation for the first drought and the reservoir is drawn down to compensate as seen in Fig. 7a-b. Only under level three HP are supplies restricted triggering an increase in shortage awareness and a subsequent decrease in per capita demands~~ and dampening of population growth~~, as found in Fig. 7c, and d~~ and f~~. When the prolonged drought begins in year 20, the four scenarios have very different starting points. Under SOP, there is less than 0.5 $km^3$ of water in storage and total annual demands are approximately 0.65 $km^3$. In contrast, under level three HP there is 1.4 $km^3$ of water in storage and total annual demands are ~~almost 0.7 $km^3$. In contrast, under level three HP there is 1.5 $km^3$ of water in storage and total annual demands are ~~just ~~above~~under 0.~~5~~6 $km^3$. Predictably the impacts of the drought are both delayed and softened under HP. As the drought is quite severe, all scenarios result in a contraction of population. However, the rate of decrease and total population decrease is lowered by the use of HP.

In the third and final trial there is no significant low flow period until year 36 of the simulation when a moderate drought event occurs, as shown in Fig. 8a. Earlier in the simulation minor fluctuations in streamflow only trigger an acceleration of per capita demand declines under level three HP, as seen in Fig. 8c-d. A moderate drought begins in year 36. However, the reservoir levels drop and shortage awareness rise starting before year 20, as seen in Fig. 8b and c. Then~~,~~ when the drought ~~begins in year 36, reservoir storage is quickly drawn down and ~~occurs the impacts are ~~passed along to water users, as depicted in Fig. 8b-c. It is important to note that the drought observed is a moderate one, similar in scale to the first drought observed in trial 1. However, the impacts here are ~~far greater than in the comparably moderate drought in trial 1 because a prolonged period of steady water supply enabled population growth and placed little pressure on the population to reduce demands. ~~At the start of the drought annual total demand for SOP is 0.6 $km^3$, well above the average allocation of 0.5 $km^3$. In fact, if we look closely at the shortage awareness, population and total demand figures, we can see that in~~In the SOP scenario, the system was in shortage before the drought occurred and total demands peaked in year ~~26~~30 at

0.882 km$^3$. The subsequent drought exacerbated an existing problem and accelerated changes already in motion.

As a comparison, Fig. 9 presents results of a non-coupled simulation model. Fig. 9 presents results of the non-coupled model simulation. In this model population and demand changes are no longer modeled endogenously. The shortage awareness variable is removed as it no longer drives population and demand changes. Instead the model assumes that population growth is constant at 3% and that per capita demands decrease by 0.5% annually. While these assumptions may be unrealistic they are not uncommon. Utility water management plans typically present one population and one demand projection. Reservoir storage, water withdrawals, and shortages are computed according to the equations described above. While the control model was also run for all three trials, the results of only trial three are included here for brevity. In the non-coupled model, the HP decreases water withdrawals as reservoir levels drop and small shortages are seen early in the study period, as seen in Fig. 9 b-c. In the second half of the study period significant shortages are observed, as in Fig. 9c. However, inspection of the streamflow sequence reveals no severe low flow periods indicating that the shortages are driven by increasing demands, as in Fig. 9a. As expected changes to per capita demands, population, and total demands are gradual and consistent across the operating policy scenarios, found in Fig. 9e-f.

## 4 Discussion

Reservoirs, and other forms of water storage, are used as a buffer to insulate water users from interruptions in supply. Water storage can smooth small declines in streamflows, minimizing the number of interruptions. It can also decrease the magnitude of impact from major drought events. While reservoirs can serve both purposes, this examination of SOP and HP demonstrates that there are tradeoffs between the two. As prior studies demonstrated, using stored water to hold off interruptions as long as possible increases the maximum magnitude of shortage in severe droughts. However, traditional modeling approaches assume that there is no feedback between supply reliability and demand and therefore, offer no insights into how these different patterns of shortage impacts may propagate through the system.

Seeing evidence of a positive feedback between supply reliability and demand in both the theoretical and empirical literature (Sivapalan et al., 2011; BBC Research, 2013; Giacomoni et al., 2013; Hughes et al., 2013; ISTPP, 2013; Kanta & Zechman, 2014) we take a socio-hydrological approach to modeling to understand if and how the selection of reservoir operating policy impacts the evolution of demand over the course of decades. In the three trials discussed above, we findThe proposed question driven modeling process has three aims: to broaden researcher's view of the system, to connect modeling assumptions to the model's purpose and to increase the transparency of these assumptions. A socio-hydrological model was developed to examine the difference in long term reliability between two reservoir operating policies, SOP and HP. This question focused the conceptual model on processes influencing reliability at the city scale over the 50 year planning period. As part of the conceptual model development, the SES framework was used to check framing assumptions. The wide range of candidate variables included in the SES framework was reviewed against case data and background information. The model's intended use then informed decisions of which processes to include in the model, which processes were endogenous to the system and which variables could be held constant. The point here is not that the logic presented by the modeler using this process is unfailing but that it is clear and can inform debate. The questions raised about both the functional form of model relationships and the variables excluded during the manuscript review process indicate that some transparency was achieved. However, the reader is in the best position to judge success on this third aim.

A socio-hydrological model of the Sunshine City water system was developed using the question driven modeling process and compared to a non-coupled model. The non-coupled model included assumes that both population growth and per capita demand change can be considered exogenous to the system. Both models show, as prior studies demonstrated, that by making small reductions early on HP reduces the chance of severe shortages. The socio-hydrological model also demonstrates that in the HP scenarios the moderate low flow events trigger an acceleration of per capita demand decrease that shifts the trajectory of water demands and in some instances slows the rate of population growth. In contrast, SOP delays impacts to the water consumers and therefore delays the shift to lower per capita demands. When extreme shortage events, such as a deep or prolonged drought occur, the impacts to the system are far more abrupt in the SOP scenario because per capita demands and population are higher than in hedging scenarios and there is less stored water available to act as a buffer. When we compare SOP and HP using a socio-hydrological model we see that HP decreases the magnitude of the oscillations in demand and population. Hedging reduces the threshold for action thereby decreasing the delay and the oscillation effect. This distinction between the two policies was not apparent when using a traditional non-coupled model. The significance of this observation is that a decrease in oscillation means a decrease in the magnitude of the contractions in population and per capita water demands required to maintain sustainability of the system. It is these abrupt changes in water usage and population that water utilities and cities truly want to avoid as they would hamper economic growth and decrease quality of life.

Examining the structure of the system can explain the differences in system response to SOP and HP. As seen in Fig. 5, there are one positive and two negative feedback loops in the system. Positive feedback loops, such as population in this model, exhibit exponential growth behavior~~.~~ ~~There~~ but there are few truly exponential growth systems in nature and~~, as is the case in this model,~~ through interaction with other feedback loops most systems ultimately reach a limit (Sterman, 2000). Negative feedback loops generate goal seeking behavior. In its simplest form a negative feedback loop produces a slow approach to a limit or goal akin to an exponential decay function. In this case, the goal of the system is to match total demand with average supply. The fact that supply is driven by streamflow, a stochastic variable, adds noise to the system. Even if streamflow is correctly characterized with stationary statistics, as is assumed here, the variability challenges the management of the system. ~~When flows drop below average, there is little utility managers can do to forecast the ultimate magnitude and duration of the low flow period.~~ Reservoir storage helps utilities manage this variability by providing a buffer~~. However, storage can~~ but it also ~~act~~acts as a delay.~~The addition of delays to a system leads to oscillation around goal values.~~ The delay between a change in the state of the system and action taken in response allows the system to overshoot its goal value before corrective action is taken~~.~~, leading to oscillation around goal values. While water storage decreases the impact of a drought, changes to water consumption patterns are ~~typically~~ required to ~~manage serious droughts.~~address demand driven shortages. Water storage ~~proves to be a double edged sword, buffering~~simultaneously buffers variability ~~but also delaying~~and delays water user response by delaying impact. There are parallels between the feedback identified in this urban water supply system and the feedback identified by Elshafei et al. (2014) and Di Baldassarre (2013) in agricultural water management and human flood interactions respectively. Broadly the three systems display the balance between the interaction between opposing forces, in this case articulated as positive and negative feedback loops.

~~When we compare SOP and HP with a socio-hydrological model we see that HP decreases the magnitude of the oscillations in demand and population. Hedging reduces the threshold for action thereby decreasing the delay and the oscillation effect. This distinction between the two policies was not apparent when using a traditional non-coupled model. The significance of this observation is that a decrease in oscillation means a decrease in the magnitude of the contractions in population and per capita water demands required to maintain sustainability of the system. It is these abrupt changes in water usage and population that water utilities and cities truly want to avoid as they would hamper economic growth and decrease quality of life.~~

The case of Sunshine City is simplified and perhaps simplistic. The limited number of available options for action constrains the system and shapes the observed behavior. In many cases water utilities have a portfolio of supply, storage and demand management policies to minimize shortages. Additionally, operating policies often shift in response to changing conditions. However, in this case no supply side projects are considered and the reservoir operating policy is assumed constant throughout the duration of the study period. As there are physical and legal limits to available supplies ~~this~~the first constraint reflects the reality of some systems. Constant operational policy is a less realistic constraint but can offer new insights by illustrating the limitations of maintaining a given policy and the conditions in which policy change would be beneficial.

Despite these drawbacks a simple hypothetical model is justified here to clearly illustrate the proposed modeling process. ~~Following the question driven modeling process, the modeling purpose, assumptions and framing are clearly communicated. The research question focuses the model on reliability over the lifespan of a reservoir. The SES Framework illustrates the broad understanding of the system that informs the dynamic hypothesis and the dynamic hypothesis shows that the theory to be tested is a feedback between reliability and demand. Finally, remaining model processes and variables are linked to established theory.~~

There are several limitations to the hypothetical case of Sunshine City. First, the hypothetical nature of the case precludes hypothesis testing. Therefore, an important extension of this work will be to apply the modeling ~~approach~~process presented here on a real case to fully test the resulting model against historical observations before generating projections. Second, only one set of parameters and functions was presented. Future extensions to this work on reservoir policy selection will test the impact of parameter and function selection through sensitivity analysis. Finally, we gain limited understanding of the potential of the model development process by addressing only one research question. We can further test the ability of the modeling process to generate new insights by developing different models in response to different questions. In this case, the narrow scope of the driving question leads to a model that just scratches the surface of socio-hydrological modeling as evidenced by the narrow range of societal variables and processes included. For example, this model does not address the ability of the water utility or city to adopt or implement HP. HP impacts water users in the short term. These impacts would likely generate a mix of reactions from water users and stakeholders making it impossible to ignore politics when considering the feasibility of HP. However, the question driving this model asks about the impact of a policy choice on the long term reliability of the system not the feasibility of its implementation. A hypothesis addressing the feasibility of implementation would lead to a very different model structure.

While there is significant room for improvement, there are inherent limitations to any approach that models human behavior. The human capacity to exercise free will, to think creatively and to innovate means that human actions, particularly under conditions not previously experienced, are fundamentally unpredictable. ~~Therefore, predictability is not our intent. The utility of socio-hydrological modeling instead lies in its capability to project a trajectory based on our best understanding of how people have reacted to hydrologic changes in the past and of the structure of the system. This approach can offer insights into how our selection of rules governing collective choices, such as water allocations, and our decisions to change our physical environment, such as building infrastructure or modifying natural systems, shape that trajectory. By using a socio-hydrological modeling approach we can highlight conditions in the future where creative response will be needed. We can also identify influential policy levers and test potential policies for both efficacy and unintended consequences.~~Further, as stated above we can never fully capture the complexity of the socio-hydrological system in a model. Instead we propose a modeling process that focuses socio-hydrological model conceptualization on answering questions and solving problems. By using model purpose to drive our modeling decisions we provide justification for simplifying assumptions and a basis for model evaluation.

## 5 Conclusions

Human and water systems are coupled. The feedbacks between these two subsystems can be, but are not always, strong and fast enough to warrant consideration in water planning and management. Traditional, non-coupled, modeling techniques assume that there are no significant feedbacks between human and hydrological systems. They therefore offer no insights into how changes in one part of the system may affect another. Dynamic socio-hydrologic modeling recognizes and aims to understand the potential for feedbacks between human and hydrological systems. By building human dynamics into a systems model, socio-hydrological modeling enables testing of hypothesized feedback cycles and can illuminate the way changes propagate through the coupled system.

Recent work examining a range of socio-hydrological systems demonstrates the potential of this approach. However, ~~lack~~there are significant challenges to modeling socio-hydrological systems. First, there are no widely accepted laws of ~~clarity in~~ human systems as there are for physical or chemical systems. Second, common disciplinary assumptions must be questioned due to the ~~reasoning behind the choice~~integrative nature of ~~scale, level of detail and scope make these studies hard to replicate and hard to critique. As the science is new and lacks established protocols~~

~~replication and critique are particularly important.~~socio-hydrology. Transparency of the model development process~~, conceptual framework~~ and assumptions can facilitate the replication and critique needed to move this~~.~~ young field forward. We assess the progress and gaps in socio-hydrological modeling and draw lessons from ~~two~~ adjacent fields of study, hydrology, social-ecological systems science and system dynamics, to inform a question driven model development process. We then illustrate this process by applying it to the hypothetical case of a growing city exploring two alternate reservoir operation rules.

By revisiting the classic question of reservoir operation policy, we demonstrate the utility of a socio-hydrological modeling process in generating new insights into the impacts of management practices over decades. This socio-hydrological model shows that HP offers an advantage not detected by traditional simulation models: it decreases the magnitude of the oscillation effect inherent in goal seeking systems with delays. Through this example we identify one class of question, the impact of reservoir management policy selection over several decades, for which socio-hydrological modeling offers advantages over traditional modeling. ~~Even with good modeling practices, not all feedbacks identified will significantly change the result and be worth the additional effort. It will take exploration and iteration to determine the types of questions, time horizons and conditions for which socio-hydrological modeling is truly insightful.~~The model developed, and the resulting insights, are contingent upon the question context. The dynamics identified here may be more broadly applicable but this is for future cases and models to assess.

## ~~Supplemental Materials~~

~~For interactive model and code please see: https://mgarcia.shinyapps.io/ReservoirOperations~~

## Acknowledgements

We would like to thanks Brian Fath, Wei Liu, and Arnold Vedlitz for reviewing an early version of this paper. We would also like to thank the two reviewers for their careful reading and thoughtful comments. Financial support for this research comes from the NSF Water Diplomacy IGERT grant (0966093).

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**Table 1: Summary of Sunshine City Properties**

| Sunshine City Properties | | |
|---|---|---|
| **Variable** | **Value** | **Units** |
| Blue River mean flow | 2 | $km^3 yr^{-1}$ |
| Blue River variance | 0.5 | $km^3 yr^{-1}$ |
| Blue River Lag 1 Autocorrelation | 0.6 | - |
| Average evaporation rate | 1 | $m\ yr^{-1}$ |
| Population | 1,000,000 | people |
| Average annual growth rate | 3 | % |
| Per capita water usage | 400 | $m^3 yr^{-1}$ |
| Water price | 0.25 | $\$\ m^{-3}$ |
| Reservoir capacity | 0.2 | $km^3$ |
| Reservoir slope | 0.1 | - |

**Figure 1: Backward Reasoning Process (adapted from: Schlüter et al., 2014)**

**Figure 2: Standard Operating Policy, where D is per capita demand, P is population and $V_{MAX}$ is reservoir capacity (Adapted from Shih & ReVelle, 1994)**

**Figure 3: Hedging Policy, where $K_P$ is hedging release function slope (Adapted from Shih & ReVelle, 1994)**

## Table 2: SES Framework, Modified for Urban Water Systems

| First Tier Var. | Second Tier Variables | Third Tier Variables (Examples) |
|---|---|---|
| Socio, economic & political settings | S1 – Economic development | Per capita income |
| | S2 – **Demographic trends** | Rapid growth |
| | S3 – Political stability | Frequency of government turnover |
| | S4 – **Other governance systems** | Related regulations |
| | S5 – Markets | Regional water markets |
| | S6 – Media organizations | Media diversity |
| | S7 – Technology | Infrastructure, Communications |
| Resource Systems | RS1 – Type of water resource | Surface water, groundwater |
| | RS2 – Clarity of system boundaries | Groundwater-surface water interactions |
| | RS3 – Size of resource system | Watershed or aquifer size |
| | RS4 – **Human-constructed facilities** | Type, Capacity, Condition |
| | RS5 – ~~Productivity of system~~ Catchment Land Use | Urbanization, Reforestation |
| | RS6 – **Equilibrium properties** | Mean streamflow, Sustainable yield |
| | RS7 – **Predictability of system dynamics** | Data availability, historic variability |
| | RS8 – **Storage characteristics** | Natural/built, Volume |
| | RS9 – Location | |
| Governance Systems | GS1 – Government organizations | Public utilities, Regulatory agencies |
| | GS2 – Nongovernment organizations | Advocacy groups, Private Utilities |
| | GS3 – Network structure | Hierarchy of organizations |
| | GS4 – ~~Property~~ *Water*-rights systems | Prior appropriation, Beneficial use |
| | GS5 – **Operational-choice rules** | Water use restrictions, Operator protocol |
| | GS6 – **Collective-choice rules** | Deliberation rules, Position rules |
| | GS7 – Constitutional-choice rules | Boundary rules, Scope rules |
| | GS8 – Monitoring and sanctioning rules | Enforcement responsibility |
| Resource Units | RU1 – ~~Resource unit mobility~~ Interbasin Connectivity | Infrastructure, Surface-groundwater interactions |
| | RU2 – ~~Growth or replacement rate~~ | |
| | RU3 – ~~Interaction among resource units~~ | |
| | RU4 – **Economic value** | Water pricing, Presence of markets |
| | RU5 – ~~Number of units~~ Quantity | Volume in storage, Current flow rate |
| | RU6 – Distinctive characteristics | Water quality, Potential for public health impacts |
| | RU7 – **Spatial and temporal distribution** | Seasonal cycles, Inter-annual cycles |
| Actors | A1 – **Number of relevant actors** | |
| | A2 – Socioeconomic attributes | Education level, Income, Ethnicity |
| | A3 – **History or past experiences** | Extreme events, Government intervention |
| | A4 – Location | |
| | A5 – Leadership/entrepreneurship | Presence of strong leadership |
| | A6 – Norms (trust-reciprocity)/social capital | Trust in local government |
| | A7 – **Knowledge of SES/mental models** | Memory, Mental models |
| | A8 – Importance of resource (dependence) | Availability of alternative sources |
| | A9 – **Technologies available** | Communication technologies, Efficiency technologies |
| | A10 – *Values* | Preservation of cultural practices |
| Action situations: Interactions -> Outcomes | I1 – ~~Harvesting~~ ***Water Supply*** | Withdrawal, transport, treatment, distribution |
| | I2 – Information sharing | Public meetings, Word of mouth |
| | I3 – Deliberation processes | Ballot initiatives, Board votes, Public meetings |
| | I4 – Conflicts | Resource allocation conflicts, Payment conflicts |
| | I5 – Investment activities | Infrastructure construction, Conservation technology |
| | I6 – Lobbying activities | Contacting representatives |
| | I7 – Self-organizing activities | Formation of NGOs |
| | I8 – Networking activities | Online forums |
| | I9 – Monitoring activities | Sampling, Inspections, Self-policing |
| | I10 – ***Water Demand*** | Indoor/Outdoor, Residential/Commercial/Industrial |
| | O1 – **Social performance measures** | Efficiency, Equity, Accountability |
| | O2 – Ecological performance measures | Sustainability, Minimum flows |
| | O3 – Externalities to other SESs | Ecosystem impacts |
| Related Ecosystems | ECO1 – **Climate patterns** | El Nino Impacts, Climate change projections |
| | ECO2 – Pollution patterns | Urban runoff, Upstream discharges |
| | ECO3 – **Flows into and out of focal SES** | Upstream impacts, Downstream rights |

**Note:** Variables removed or replaced are crossed out, variables added are in italic, variables key to the conceptual model are in bold. Examples of third tier variables are given for clarification.

**Table 3: Household Conservation Action by Shortage Experience (ISTPP, 2013)**

| Last Experienced a Water Shortage | % of Households, over the past year, that have | | |
|---|---|---|---|
| | Invested in Efficient Fixtures or Landscapes | Changed Water Use Behavior | Taken No Action |
| Within a Year | 56% | 88% | 11% |
| 1 to 2 years ago | 52% | 87% | 11% |
| 2 to 5 years ago | 51% | 78% | 17% |
| 6 to 9 years ago | 50% | 79% | 18% |
| 10 or more years ago | 42% | 74% | 24% |
| Never Experienced | 36% | 66% | 31% |

**Figure 4: Historical City of Los Angeles Water Use (LADWP, 2010)**

**Figure 5: Causal loop diagrams: (a) water demand, shortage and conservation, (b) water demand, shortage and population, (c) population and growth rate**

**Table 4: State and Exogenous Model Variables**

| Variable | Description | Units | Equation | Variable Type |
|---|---|---|---|---|
| Q | Streamflow | $km^3\,yr^{-1}$ | 1 | Exogenous |
| V | Reservoir Storage Volume | $km^3$ | 2 | State |
| P | Population | persons | 3 | State |
| W | Withdrawal | $km^3\,yr^{-1}$ | 4 | State |
| S | Shortage Magnitude | $km^3\,yr^{-1}$ | 5 | State |
| M | Shortage Awareness | | 6 | State |
| D | Per capita demand | $m^3\,yr^{-1}$ | 7 | State |

**Table 5: Model Parameters**

| Parameters | Description | Value | Units | Equation |
|---|---|---|---|---|
| $\mu_H$ | Mean streamflow | 2.0 | $km^3\,yr^{-1}$ | 1 |
| $\sigma_H$ | Standard deviation of streamflow | 0.5 | $km^3\,yr^{-1}$ | 1 |
| $\rho_H$ | Streamflow lag one autocorrelation | 0.6 | - | 1 |
| $\eta_H$ | Evaporation rate | ~~1.~~0.001 | ~~m~~km $yr^{-1}$ | 2 |
| $Q_D$ | Downstream allocation | 0.50Q | $km^3$ | 2 |
| $Q_E$ | Required environmental flow | 0.25Q | $km^3$ | 2 |
| $\sigma_T$ | Average slope of reservoir | 0.1 | - | Stage-Storage curve |
| $\delta_I$ | Regional birth rate | 0.01 | $yr^{-1}$ | 3 |
| $\delta_E$ | Regional death rate | 0.01 | $yr^{-1}$ | 3 |
| $\delta_I$ | Regional immigration rate | 0.03 | $yr^{-1}$ | 3 |
| $\delta_E$ | Regional emigration rate | 0.03 | $yr^{-1}$ | 3 |
| $\tau_P$ | Threshold | 0.4 | - | 3 |
| $V_{MAX}$ | Reservoir Capacity | 2.0 | $km^3$ | 4 |
| $K_P$ | Hedging slope | variable | - | 5 |
| $\mu_S$ | Awareness loss rate | 0.05 | $yr^{-1}$ | 6 |
| $\alpha_D$ | Fractional efficiency adoption rate | 0.15 | - | 7 |
| $\beta_D$ | Background efficiency rate | 0.0001 | - | 7 |
| $D_{MIN}$ | Minimum water demand | 200 | $m^3\,yr^{-1}$ | 7 |

**Figure 6: Model Results, Trial 1: (a) annual streamflow, (b) reservoir storage volume, (c) public shortage awareness, (d) per capita demand, (e) annual city population, (f) total demand.**

**Figure 7: Model Results, Trial 2: (a) annual streamflow, (b) reservoir storage volume, (c) public shortage awareness, (d) per capita demand, (e) annual city population, (f) total demand.**

**Figure 8: Model Results, Trial 3: (a) annual streamflow, (b) reservoir storage volume, (c) public shortage awareness, (d) per capita demand, (e) annual city population, (f) total demand.**

**Figure 9: Non-coupled Model Results, Trial 3: (a) annual streamflow, (b) reservoir storage volume, (c) shortage volume (demand – supply), (d) per capita demand, (e) annual city population, (f) total demand.**