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Synthesis of System Dynamics Tools for Holistic Conceptualization of Water Resources Problems

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Abstract Out-of-context analysis of water resources systems can result in unsustainable management strategies. To address this problem, systems thinking seeks to understand interactions among the subsystems driving a system's overall behavior. System dynamics, a method for operationalizing systems thinking, facilitates holistic understanding of water resources systems, and strategic decision making. The approach also facilitates participatory modeling, and analysis of the system's behavioral trends, essential to sustainable management. The field of water resources has not utilized the full capacity of system dynamics in the thinking phase of integrated water resources studies. We advocate that the thinking phase of modeling applications is critically important, and that system dynamics offers unique qualitative tools that improve understanding of complex problems. Thus, this paper describes the utility of system dynamics for holistic water resources planning and management by illustrating the fundamentals of the approach. Using tangible examples, we provide an overview of Causal Loop and Stock and Flow Diagrams, reference modes of dynamic behavior, and system archetypes to demonstrate the use of these qualitative tools for holistic conceptualization of water resources problems. Finally, we present a summary of the potential benefits as well as *caveats* of qualitative system dynamics for water resources decision making.

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1 Introduction

An event-oriented view of the world or linear causal thinking cannot address complex problems adequately (Forrester 1961, 1969; Richmond 1993; Sterman 2000). Figure 1 illustrates this unidirectional thinking paradigm, which is grounded on the intuitive assumption that outputs or events are shaped by the collective effect of a series of inputs or causes acting sequentially (Sterman 2000). One artifact of this type of thinking is that many problems, manifested by discrepancies between the present state and an expected or desired state, are singled out and treated in isolation from the surrounding environment. Consequently, no in-depth understanding of root causes of problems is obtained. Thus, managing complex water resources systems using uni-directional, mechanistic models may be doomed to provide unrealistic, or at least, questionable results (Hjorth and Bagheri 2006).

Closed-loop or non-linear causal thinking enables analysts to consider important feedback loops and interconnections characterizing the system's structure, and to account for time delays, collectively shaping the behavior of complex systems (Richmond 1993). This type of thinking is conceptually illustrated in Fig. 2. The growing discrepancy between the existing and ideal states tends to generate a perception of problem, which often leads humans to alter the environment in hopes of reaching the desired state. Although the quick-fix solutions appear to alleviate the symptoms, which may be helpful when responding to emergencies, they often fail to address the problem appropriately and only result in its spatial and/or temporal translation (Richmond 1993; Simonovic 2009). The decisions to modify the environment may have unintended consequences, perhaps with time delays, which may aggravate the original problem or create even more challenging issues (Madani and Mariño 2009). Unlike the quick-fix approach to planning and management of water resources, a non-linear thinking paradigm offers the holistic framework needed to promote sustainable development trajectories.

Systems thinking provides methods and techniques to apply non-linear causal thinking to planning and management problems. In essence, systems thinkers recognize the fact that while problematic systems are comprised of interrelated parts or subsystems, they function as a unit and should ultimately be treated as a whole (Simonovic 2009). Simonovic and Fahmy (1999) consider the systems approach as a discipline for seeing wholes and for seeing structures that underlie complex domains. Further, they state that the systems approach is a framework for seeing patterns of change rather than static snapshots, and for seeing

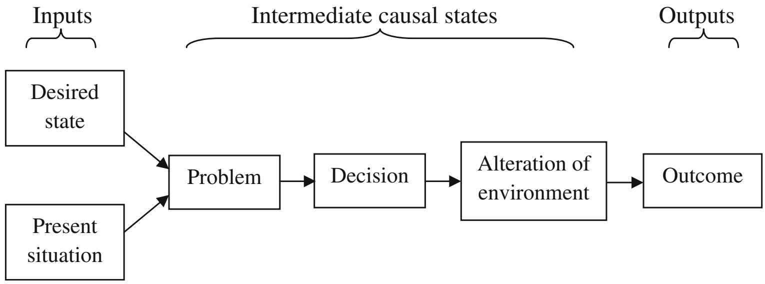


Fig. 1 Linear causal thinking (adapted from Sterman 2000)

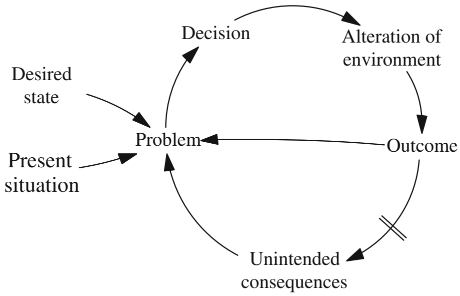


Fig. 2 Non-linear causal thinking; causal states and causal relationships are denoted by words and arrows, respectively. Double bars indicate presence of time delay. (Adapted from Sterman 2000)

processes and interrelationships rather than objects. Thus, the principles of systems thinking are critical to solving problems in water resources systems which inevitably consist of interrelated subsystems.

System dynamics (Forrester 1961, 1969; Meadows et al. 1972; Richmond 1993; Ford 1999; Sterman 2000) is one of the methods that facilitate recognition of interactions among disparate but interconnected subsystems driving the system's dynamic behavior. The method can thus help water resources analysts to identify problematic trends and comprehend their root causes in a holistic fashion. By identifying and capturing feedback loops between components, system dynamics models can provide insights into potential consequences of system perturbations, thereby serving as a suitable platform for sustainable water resources planning and management at the strategic level (Hjorth and Bagheri 2006; Madani and Mariño 2009; Simonovic 2009). To this end, system dynamics offers several qualitative and quantitative tools to identify and explain system behavior over time.

We contend that system dynamics has not been used by most water resources scholars and practitioners to its full capacity. The majority of system dynamics applications in water resources have underutilized the method's qualitative modeling tools. We advocate that the conceptualization or thinking phase of integrated water resources studies is of paramount importance as it provides fundamental understanding of leverage points for sustainable solutions. High-level and qualitative models can be developed relatively quickly and affordably to facilitate trend identification, and to provide insights into root causes of multi-faceted water resources problems, facilitating formulation of preemptive and sustainable solution strategies. In this paper we provide a synthesis of qualitative modeling techniques offered by system dynamics and argue that these techniques offer important insights and should not be overlooked by water resource modelers. To do this, we first present a synopsis of system dynamics applications in water resources. Then, the fundamentals of system dynamics and its qualitative modeling tools such as Causal Loop Diagrams (CLD) and Stock and Flow Diagrams (SFD) are discussed in detail, using tangible examples to illustrate why this approach is well suited for integrated water resources modeling, planning, and management. Furthermore, reference modes of dynamic behavior and merits of using system archetypes for qualitative modeling prior to quantitative analyses are illustrated. Finally, the method's benefits and *caveats*, stemming from application of the approach without proper regard for its philosophy, are discussed.

2 System Dynamics and Water Resources

System dynamics, a sub-field of systems thinking (Richmond 1994; Ford 1999), originated in the 1960's when the concepts of feedback theory were applied by Forrester and his colleagues to understand the underlying structure and dynamics of industrial and urban systems (Forrester 1961, 1969). The method has since been widely used by analysts from various disciplines as a convenient tool to explore the causal relationships forming feedback loops between different components of large systems. In the past 50 years, system dynamics has become a well-established methodology that has been applied in many different practical and scientific fields, including management, ecology, economics, education, engineering, public health, and sociology (Sterman 2000).

Application of system dynamics in water resources engineering and management has grown over the past two decades (Winz et al. 2009). Reviewing the literature, three general approaches to water resources system dynamics modeling can be identified: (i) predictive simulation models; (ii) descriptive integrated models; and (iii) participatory and shared vision models. In the first class of system dynamics models, modelers have successfully used the method as a tool to quantitatively simulate the processes governing particular subsystems within a broader water resources system. For example, Ahmad and Simonovic (2000) used system dynamics to model the interactive components of the hydrologic cycle to develop reservoir operation rules for flood mitigation. Ideally, this type of system dynamics model is developed to help predict the future behavior of the system accurately enough to provide a basis for tactical decisions. Table 1 presents some examples of water resources problems addressed using system dynamics as a convenient simulation tool for analyzing water resources problems and/or physical watershed processes.

In the second class of system dynamics models, analysts have adopted a more holistic approach, striving to identify and characterize the main feedback loops among two or more disparate subsystems, such as hydrological, ecological, environmental, socio-economic, and political subsystems. Typically, these integrated feedback models facilitate testing and selection of water resources management plans and policies at the strategic level. Table 2 summarizes example water resources studies, which have used system dynamics to describe and better understand the feedback structure and long-term behavioral patterns of interacting water resources subsystems.

Additionally, system dynamics models have been used as practical tools for promoting shared vision planning, participatory modeling, and shared learning opportunities for diverse groups of decision makers and stakeholder groups (Werick and Whipple 1994; Lund and Palmer 1997; Creighton and Langsdale 2009). Stakeholders' participation in a group model building activity can increase understanding of the scope and complexity of the problem, increase trust in model results and, subsequently, increase support for the selected policy (Stave 2003; Tidwell et al. 2004). Table 3 presents examples of participatory water resources modeling using system dynamics.

3 Qualitative Modeling Tools in System Dynamics

Qualitative modeling or conceptualization of systems' problematic behavior is useful for describing the problem, its possible root causes, and solutions. System dynamics depends heavily upon both quantitative and qualitative data to characterize feedback loops in complex systems (Forrester 1975; Luna-Reyes and Andersen 2003). In effect, a significant benefit of system dynamics stems from its ability to facilitate conceptualization of multi-disciplinary models by providing a number of qualitative tools to complement quantitative simulations (Wolstenholme 1999; Coyle 2000). Being accustomed to a tradition of developing highly quantified models, however, many water resources system dynamics modelers tend to overlook the approach's useful qualitative tools (Mirchi et al. 2010). Examples of

Table 1 Example applications of system dynamics as a convenient simulation tool for modeling water resources problems and/or physical watershed processes

Issue(s) addressed	Modeling approach	Citation, location	Authors' remarks
Freshwater eutrophication	Simulated the effects of direct discharge of nutrients from sewage and agriculture runoff on phosphorus and plankton dynamics	Vezjak et al. (1998), Slovenia	Facilitated setting standards for nutrient loading; suitable decision support tool for water quality management
Developing reservoir operation rules for flood damage mitigation	Simulated hydrologic behavior of the reservoir and upstream and downstream areas under major historical floods	Ahmad and Simonovic (2000), Canada	Ease of model modification and sensitivity analysis noted, suitable for participatory modeling and building trust into model results
Assessing climate change impacts on an urban flood protection system	Hydrologic processes and flood protection performance simulated under various climate scenarios	Simonovic and Li (2003), Canada	Flexible model structure and ease of sensitivity analysis noted, suitable for flood management policy testing
Adaptive water quality management of a nutrient impaired stream	Total maximum daily load (TMDL) simulation	Tangirala et al. (2003), USA	Facilitated evaluation of alternative options for impairment mitigation
Flood damage estimation	Developed and applied a new methodology for spatiotemporal simulation of processes governing flood propagation	Ahmad and Simonovic (2004), Canada	Innovative generic approach for building distributed system dynamics models, capable of accounting for spatial variability and its impacts on feedbacks in multi-sectoral systems
Adaptive water resources planning and management	Basin-scale hydrologic simulation	Stewart et al. (2004), Mexico Sehlke and Jacobson (2005), USA	Integrated basin-scale water-shed process model capable of incorporating policy, regu-latory, and management crite-ria to form a decision support system
Thermal and mass balance of a spring	Simulated physical processes influencing the spring's geothermal characteristics	Leaver and Unsworth (2006), New Zealand	A lumped parameter model addressing hydrologic and geothermal processes
Salinity load forecast and removal from return flows	Simulated processes governing hydrology, water use, and water quality	Venkatesan et al. (2011a, b), USA	Integrated simulation model providing insights into potential future water shortages, and cost-effective and energy-efficient water re-use plans
Energy use and carbon footprint of different waters supply alternatives	Simulated processes for desalinating sea water, and projected carbon emission of supplying urban water from remote areas	Shrestha et al. (2011, 2012), USA	Guides urban water supply management by facilitating evaluation of energy efficiency, and selection of low-carbon emission water supply management options

these tools and ideas are CLDs, SFDs, reference modes of dynamic behavior, and system archetypes. In this section we provide an overview of the fundamental constructs and qualitative modeling techniques offered by system dynamics.

Table 2 Example applications of system dynamics in integrated or multi-subsystem feedback modeling of water resources systems for strategic policy testing and selection

Issue(s) addressed	Modeling approach	Citation, location	Authors' remarks
Water resources policy analysis and decision making	Object-oriented modeling linking alternative socio-economic development plans with water availability at the national level	Simonovic and Fahmy (1999), Egypt Simonovic and Rajasekaram (2004), Canada	Flexible, transparent framework facilitating participatory modeling; complex due to accounting for several interconnected sectors
Water quality and environmental deterioration due to socio-economic growth	Various regional-scale physical and socio-economic subsystems linked to a water quality model	Guo et al. (2001), China Leal Neto et al. (2006), Brazil	Supported effective regional-scale environmental planning, management, and decision making
Sustainable water resources management in the face of growing demand	Various physical subsystems and water use sectors simulated under different scenarios (i.e., climate and management)	Xu et al. (2002), China Qaiser et al. (2011), USA	Captured main drivers of supply and demand, and provided insights for regional water management roadmap
Effective crisis management in response to flooding	Simulated human behavior during flood emergency evacuation	Simonovic and Ahmad (2005), Canada	Practical framework for monitoring and policy selection for emergency planning
Long-term impacts of interbasin water diversions into a water scarce area	Interactions among various drivers of water shortage analyzed, and sustainable management strategies recommended	Madani and Mariño (2009), Iran	Provided insights for effective regional-scale water resources management and policy selection
Long-term water allocation among various stakeholder groups	Basin-scale hydrological, agricultural, economic, and ecological subsystems simulated	Gastélum et al. (2009), Mexico Ahmad and Prashar (2010), USA	Integrated watershed process model, supporting policy testing and formulating integrated management criteria
Post-disaster water resources management	Simulated post-earthquake changes in water consumption patterns, population, and water infrastructure development	Bagheri et al. (2010), Iran	Facilitates monitoring and policy selection for post-disaster water management to accommodate increased demand due to relief operation and reconstruction
Growing global water scarcity	Simulated different subsystems including climate, carbon cycle, hydrologic cycle, and socio-economic subsystem linked to food production subsystem and global water availability, use, and quality	Davies and Simonovic (2011), N/A	Facilitates global-scale evaluation of feedbacks between water resources and socio-economic and environmental change, providing insights for understanding global water scarcity

3.1 Causal Relationships

At the core of system dynamics models are reinforcing (positive) and balancing (negative) causal relationships. A positive causal relationship means an increase/decrease in model Variable A would result in an increase/decrease in model Variable B, whereas a negative causal relationship signifies that an increase/decrease in model Variable A triggers a

Table 3 Example applications of system dynamics in participatory water resources modeling for integrated policy assessment

Issue(s) addressed	Modeling approach	Citation, location	Author's remarks
Over-appropriation of river flow to diverse stakeholder groups	A system dynamics model of processes governing annual river flow used by participants from agricultural and hydropower production sectors	Ford (1996), USA	Facilitated shared learning and useful participation of a diverse group of stakeholders, simulation results led to constructive discussions about complex water issues
Enhancing public understanding of water management options in a fast growing area	A strategic-level system dynamics model used in a public forum to illustrate the effectiveness of available and proposed management alternatives	Stave (2003), USA	Counterintuitive model results triggered informative discussions among participants, and effective management strategies were identified
The need for public participation in integrated water resources planning and management	Participatory system dynamics simulation of key hydrologic, social, and environmental drivers for quantitative comparison of alternative management options	Tidwell et al. (2004), USA	Facilitated public involvement in decision making, and increased public understanding of water management complexities; facilitated analysis of water supply, demand, and conservation
Incorporating the implications of climate change in integrated water resources planning and management	Participatory, scenario-based approach to build a watershed model to explore water resources futures and basin-scale policy options	Langsdale et al. (2007), Langsdale et al. (2009), Canada	Provided shared learning experience and increased the participants' appreciation of future water management challenges (reduced supply and increased demand)

decrease/increase in model Variable B. For example, if the area of cultivated land in an agricultural district is increased, agricultural water demand will rise (positive causal relationship). Likewise, increase in hydraulic conductivity and temperature will increase groundwater recharge and evaporation, respectively. In contrast, as infiltration increases, the amount of surface runoff into a storage reservoir will decrease. Similarly, increased evaporation will cause the stored water in the reservoir to decrease. In another balancing relationship, as the groundwater table falls, the pumping cost will rise. A summary of the given examples, along with graphical notation of reinforcing and balancing causal relationships and their interpretation, is presented in Table 4.

3.2 Causal Loop Diagrams and Basic Feedback Loops

Developing the system's CLD helps graphically capture the relationships between interactive subsystems, and can thus be considered as the conceptual modeling step. CLDs provide valuable information about the system including the presence of feedback loops, loop dominance, and presence of time delays. They are comprised of words and arrows with appropriate polarity, depicting combinations of positive and/or negative causal relationships. A causal relationship may exist between any two system variables, regardless of their type.

Table 4 Graphical notation and polarity of causal relationships

Connection	Causal relationship	Mathematical definition	Examples
A —+→ B	Any change in the state of A causes the state of B to change in the same direction; if A increases/decreases, B increases/decreases too	$\frac{\partial B}{\partial A} > 0$	Cultivated land —+→ Agricultural water demand Hydraulic conductivity —+→ Groundwater recharge Temperature —+→ Evaporation
A —-→ B	Any change in the state of A causes the state of B to change in the opposite direction; if A increases/decreases, B decreases/increases	$\frac{\partial B}{\partial A} < 0$	Groundwater table —-→ Pumping cost Evaporation —-→ Reservoir's stored water Infiltration —-→ Runoff

In complex systems, combinations of positive and negative causal relationships may form feedback loops. There are two fundamental feedback loops–balancing (negative) and reinforcing (positive) loops. Typically, a balancing feedback loop comprises causal relationships which collectively attempt to reduce the discrepancy between the current state and a desired state. On the other hand, reinforcing feedback loops often characterize continuing trends of growth or decline. As a rule of thumb, a loop is reinforcing if the number of its negative causal links is even, and it is balancing otherwise, provided that the CLD appropriately represents the main drivers and causal relationships between them (Sterman 2000). The ability to observe the structure of systems to identify dominant feedback loops in a representative CLD can provide qualitative information about their typical dynamic behavior. Therefore, when systems are not overly complex, it may be possible by looking at the CLD to determine the behavior of some variables even before quantitative modeling. We will use a simple example to illustrate the behavior of reinforcing and balancing feedback loops, and the use of CLDs in qualitative modeling.

To better understand the behavior of a reinforcing feedback loop, consider a reservoir supplying water for a growing urban area. Net precipitation increases the inflow, raising the reservoir's stored water and increasing the potential for development (positive relationships). Subsequently, new opportunities for development lead to actual development, raising water demand, which then prompts the reservoir operators to allocate more space in the reservoir to storage. Allocating more space to storage would then create potential for more development which, in turn, would ultimately call for still more stored water. In the absence of other operating feedbacks (e.g., flooding, environmental flows, evaporation), the stored water in the system would grow exponentially until storage capacity has completely been used. Figure 3 shows a simple CLD broadly illustrating the interrelationships within the "urban water supply loop" and corresponding behavior of the hypothetical system.

In the "urban water supply loop" it was assumed that the reservoir is solely used for the purpose of water supply. Now suppose the reservoir functions only for flood control. In this case, high inflows raise the reservoir's stored water, increasing flood risk. Consequently, the reservoir release is increased to reduce the stored water and accommodate the future inflows. This is an example of a balancing or negative feedback loop where the reservoir release helps maintain the reservoir's water level below levels that would jeopardize the urban area. Neglecting all other operating loops, a CLD of the "flood control loop," along with behavioral graph of the reservoir system, is shown in Fig. 4.

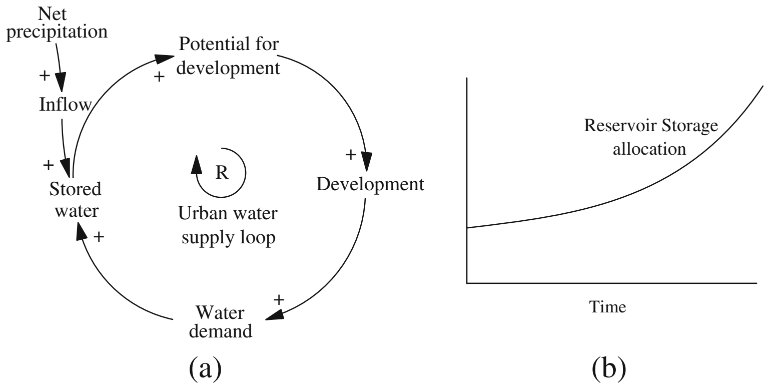


Fig. 3 CLD of the "urban water supply loop" **a** and corresponding behavior of the hypothetical reservoir system **b**. "R" denotes a reinforcing feedback loop

When studied separately, the "urban water supply loop" and "flood control loop" demonstrate distinctively different behavioral patterns (i.e., respectively, exponential growth and decline). However, when both feedback loops are present (Fig. 5a), the system's long-term dynamic behavior may undergo variations depending on which loop is dominant. Figure 5b depicts potential long-term behavior of the system. Although this may seem like a trivial example, it represents the long-term behavior observed in a number of systems affected by development, where reservoir reallocation has been proposed (McMahon and Farmer 2004).

3.3 Stock and Flow Diagrams

Based on the CLD of the problem, a Stock and Flow Diagram (SFD) can be developed to better characterize accumulation and/or depletion of stock(s) and flow of quantities in the system. General steps for translating CLD into SFD are summarized in Table 5. Representing the system in terms of stocks and flows precedes quantification of the processes that have been accounted for in the CLD. Easy-to-learn software programs (e.g., STELLA (High

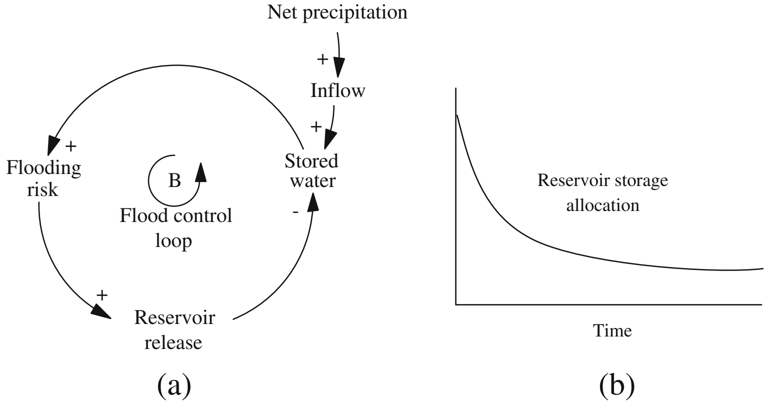
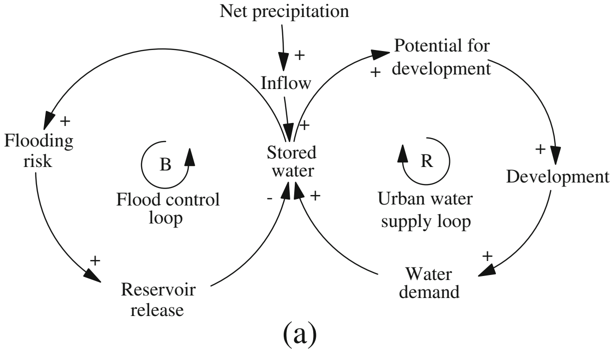


Fig. 4 CLD of the "flood control loop" of the hypothetical reservoir system **a** and corresponding dynamic behavior **b**. "B" denotes a balancing feedback loop



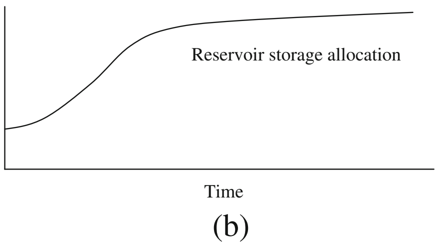


Fig. 5 CLD of "water supply loop" and "flood control loop" **a**, and corresponding long-term behavior of the hypothetical reservoir system **b**. "R" and "B" denote reinforcing and balancing feedbacks, respectively

Performance Systems 1992), Powersim (Powersim Corp. 1996), and Vensim (Ventana Systems 1996)) can be used to facilitate qualitative as well as quantitative system dynamics modeling. These simulation environments provide building blocks for developing quantitative models, obviating the need for learning complex programming languages, and allowing more people to gain hands-on experience with system dynamics modeling. Stocks (levels) are measured at one specific time and represent any variable that accumulates or depletes over time, while flows (rates) are measured over an interval of time and denote activities or variables causing the stock to change. For example, the stored water in a reservoir system can be modeled as a stock with inflow and release being its associated flows. Auxiliary variables, such as flood risk and potential for development, are functions of stocks or constants that help formulate and calibrate the model. Stocks, flows and auxiliary variables are connected by arrows (connectors), which are used to build relationships between the model variables by transferring information such as the value of parameters present in a particular model equation. Figure 6 shows a simple SFD of the reservoir example.

Table 5 Procedure for building SFD using CLD (Adapted from Wolstenholme and Coyle 1983)

Step	Purpose
Key variable recognition	Identify main drivers giving rise to problem symptoms
Stock identification	Identify system resources (stocks) associated with the main drivers
Flow module development	Provide rates of change and represent processes governing each stock
Qualitative analysis	Identify: (i) additional main drivers that may have been overlooked; (ii) causal relationships that require further analyzing by specific methods; (iii) controllable variables and their controllers; (iv) systemic impact of changes to controllable variables; (v) system's vulnerability to changes in uncontrollable variables

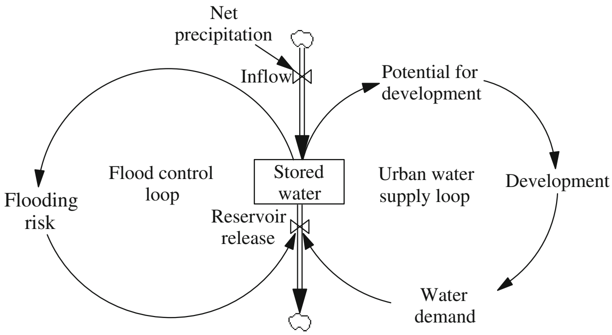


Fig. 6 Stock Flow Diagram (SFD) of the reservoir problem

3.4 Reference Modes

A reference mode is an overall pattern of system's behavior over time as opposed to short historical time series which may be dominated by noise (Sterman 2000; Ford 1999; Simonovic 2009). Saeed (1998) considers a reference mode as a qualitative and intuitive concept facilitating conceptualization processes, which does not represent the precise description/prediction of past/future events. Fundamental reference modes of dynamic behavior include exponential growth, goal seeking, and oscillation. Typically, reinforcing and balancing feedback loops demonstrate continuous growth and goal seeking behavior, respectively. Oscillation is generated by presence of delayed corrective components in balancing loops causing the system to constantly move above and then below its goal. Other common modes of dynamic behavior, which are caused by the fundamental modes, include S-shaped growth, oscillating overshoot, and overshoot and collapse. S-shaped growth is generated when the balancing feedbacks in a system dominate its behavior after it has, under impact of reinforcing loops, grown toward a limiting state (e.g., carrying capacity of an environmental system). When significant time delays hinder the balancing feedbacks to initiate the corrective action on time, the system will likely overshoot the limiting state, demonstrating an oscillatory behavior around the constraining limit (oscillating overshoot). In this situation, if the resource is non-renewable or carrying capacity is irreversibly exceeded, the system will collapse before the balancing feedbacks can salvage it (overshoot and collapse). Figure 7 presents common modes of dynamic behavior.

A water-stressed region's ongoing trend of development, facilitated by continuous supply of imported water, is an example of exponential growth driven by a reinforcing feedback structure (Madani and Mariño 2009). In contrast, irrigation water withdrawal in an agricultural district where appropriate water pricing schemes are applied often follows a goal seeking dynamic behavior (Cai and Wang 2006). An example of oscillatory dynamic behavior is a lake's water level which fluctuates seasonally due to seasonal precipitation patterns and water demands, and perhaps as mandated by lake operation rules (e.g., Watkins and Moser 2006). When water resources limit a region's development (i.e., no water can be supplied from outside the watershed), the water consumption pattern will likely demonstrate S-shaped behavior (Bagheri and Hjorth 2007). If long delays hinder timely response to warning signals (e.g., severe water stress), the system may overshoot its limit, causing social, economic, and/or environmental hardships. On the other hand, if the water resources are eventually replenished, it is likely that continued growth and consumption will exhaust the newly available water, generating alternating periods of replenishment and depletion, characterized by an oscillating overshoot mode of dynamic behavior. In an extreme case,

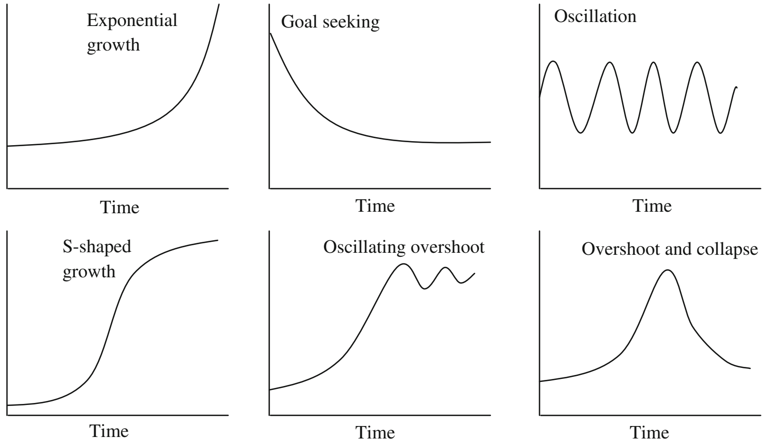


Fig. 7 Common modes of dynamic behavior (Adapted from Sterman 2000)

extensive development in resource-stressed areas can completely exhaust the resources necessary for survival of the system causing it to collapse (Erickson and Gowdy 2000).

3.5 System Archetypes

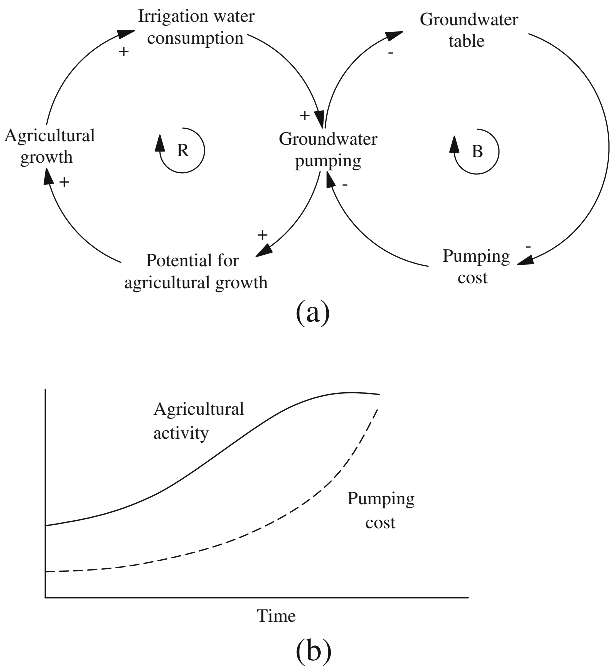
System archetypes are generic system structures showing common patterns of behavior (Senge 1990; Wolstenholme 2003). Reinforcing and balancing feedback loops are essentially the basic system archetypes. In real systems, however, a combination of reinforcing and balancing feedback structures can form more complex dynamic behaviors that can be characterized using more sophisticated system archetypes. Through closely studying the structure of many systems, a number of archetypes have been identified that can serve as diagnostic tools, describing or predicting the system's long-run behavior. Some common archetypes are Limits to Growth, Success to the Successful, Fixes that Backfire, and Tragedy of the Commons (Senge 1990). Knowledge of the governing dynamics of water resources systems may help decision makers prognosticate problematic behavior and take appropriate corrective actions in a timely fashion, leading to more sustainable water resources planning and management. In this section, the applicability of some system archetypes to characterize water resources management problems is illustrated through a number of examples.

Limits to Growth The Limits to Growth archetype hypothesizes that continuous growth, driven by reinforcing feedback loops in natural systems, will eventually push the system toward its limit (e.g., carrying capacity). Once the system has grown beyond a critical level, balancing feedback loops take over and dominate the system's behavior, attempting to prevent its collapse (Meadows et al. 1972). Dynamic behavior of an agricultural system using groundwater as its source of irrigation water is an example of this archetype. A CLD of the Limits to Growth archetype for the given agricultural system is depicted in Fig. 8a. In this system, agricultural growth raises the demand of irrigation water. Farmers may then develop additional groundwater resources and increase pumping, enhancing the potential for agricultural growth and an increase in cultivated land (reinforcing loop). However, pumping excessive amounts of groundwater will cause severe drawdown of the groundwater table, increasing the pumping cost which, in turn, reduces the demand for groundwater (balancing loop). As shown in Fig. 8b, pumping cost increases with continuous agricultural growth until groundwater withdrawal is no longer economical, which then reduces the growth. In an extreme case, if a non-renewable groundwater resource is completely exhausted, the agricultural practice may cease altogether.

Fixes that Backfire The Fixes that Backfire archetype characterizes quick-fix (short-sighted) solutions, stemming from linear causal thinking, which treat the symptoms of a problem rather than addressing its root causes. Interbasin water transfer with unintended consequences (e.g., false perception of water abundance, encouraging continued development and population growth (Madani and Mariño 2009)), can be characterized by a Fixes that Backfire archetype. As shown in Fig. 9a, intense water shortages prompt water managers to initiate water transfer projects to increase water supply, which will temporarily reduce the shortage. However, continuous supply of abundant water in a water-stressed region sends a false message to its current residents and inhabitants of neighboring areas about potential for development. Consequently, in the long run, while water resources are being depleted, increased development and immigration cause water shortages to grow more severe (the reinforcing loop dominates) (Fig. 9b).

Success to the Successful The Success to the Successful archetype states that good performance will earn an entity more resources, making it possible for the entity to generate even better results and gain still more resources. Dominance of this archetype in a natural setting where resources are limited can deprive the weaker competitors of the resources they need to improve their condition and become more competitive. Consequently, the successful entity continuously grows while other entities gradually decline and possibly collapse. This archetype can ultimately result in considerable inequity and imbalance among entities (e.g., water resources stakeholders), threatening the system's sustainability. Supply-

Fig. 8 CLD **a** and behavioral graph of the Limit to Growth archetype **b** for the presented agricultural system



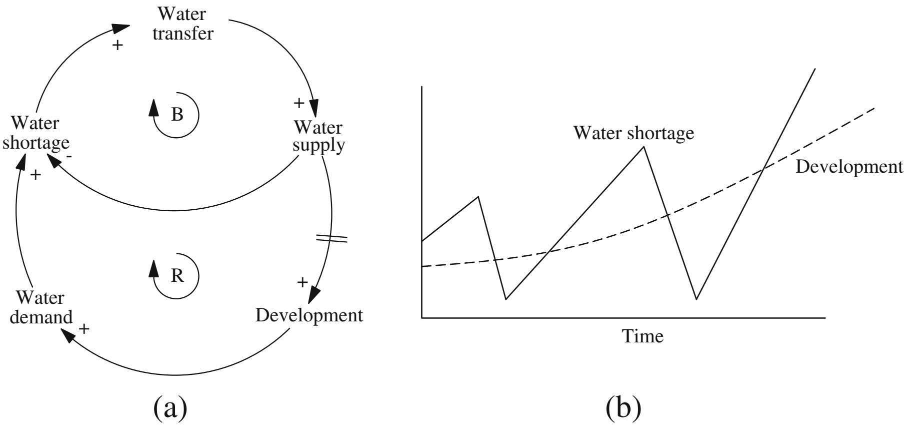
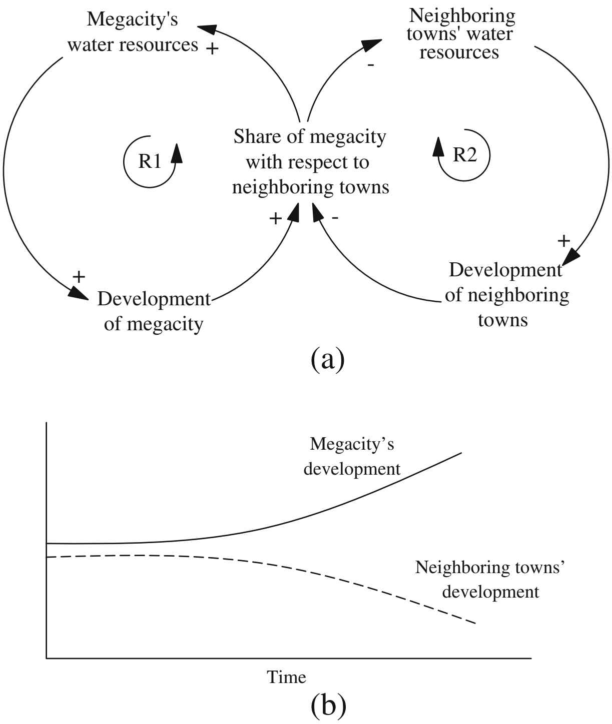


Fig. 9 CLD **a** and long-term behavior of Fixes that Backfire archetype **b** for interbasin water transfer. Note the lag time until unintended consequences are observed, indicated by the double bars

oriented water resources management in a large metropolitan area can be explained using the Success to the Successful archetype, illustrated in Fig. 10a. Water scarcity in less-populated neighboring areas is secondary to the needs of a water-stressed megacity (Bagheri and Hjorth 2007). As the megacity's share of water resources increases, so does potential for development, which in turn adds to the power of the megacity to gain more water resources. Simultaneously, the neighboring towns' share of water resources decreases, hindering their development and ability to gain necessary resources (Fig. 10b). Another real example of a water resources problem based on the Success to the Successful archetype is floodplain development in California, which results in a continuous profit to the local developers (success) and continuous increase in risk of economic loss to the state of California as a result of development behind unreliable levees (Madani et al. 2007).

Tragedy of the Commons This archetype is observed when multiple users exploit a shared water resource. Suppose two farmers use groundwater as the primary source for irrigating their crops. The shared resource can last longer under a regulated groundwater consumption scheme, maximizing the long-term profit of each individual stakeholder. However, in the absence of appropriate regulations, the farmers can pump as much as they want to maximize their profit. This situation is well represented by a Tragedy of the Commons (Hardin 1968) archetype, whereby each party depletes the common pool resource solely based on their own self-interest (Loaiciga 2004; Madani 2010). Figure 11a shows a CLD of the Tragedy of the Commons archetype for the groundwater problem in which two farmers (A and B) compete to maximize their own net profit by exploiting the groundwater resource. Initially, the reinforcing loops R1 and R2 drive the system such that each farmer gains satisfactory profits. This situation holds until the groundwater table is excessively drawn down, at which point the balancing loops B1 and B2 dominate the system's dynamic behavior. Ultimately, increased pumping cost due to pumping from a lower groundwater table reduces the net profit for each individual farmer (Fig. 11b). This archetype can be generalized to qualitatively analyze any common pool resource problem (Madani and Dinar 2012), including transboundary water resources. In an extreme case, the competition between stakeholders can jeopardize local or regional sustainability and wellbeing of inhabitants, potentially initiating political conflicts (Lowi 1993).

Fig. 10 CLD **a** and long-term behavior of Success to the Successful archetype **b** for the urban water development problem



4 Discussion

4.1 Qualitative Versus Quantitative Modeling

Qualitative system dynamics modeling can be used at different levels for different purposes (Richmond 1994). Randers (1980) believes that "most human knowledge takes a descriptive nonquantitative form", and thus analysts should not restrict themselves to numerical data, which is a small fraction of knowledge fit for statistical analysis. However, developing qualitative models may not be enough for complete analysis of the problem. Proponents of quantitative modeling argue that numerical simulation nearly always adds value, even in the face of significant uncertainties about data and important qualitative information used in simulations (Forrester 1975; Homer and Oliva 2001; Dhawan et al. 2011). We recognize the pitfall of oversimplifying a problem and neglecting the value of conducting detailed simulations, which may reveal complex system behaviors that could not be understood through simple diagramming (Homer and Oliva 2001; Forrester 2007). However, to accomplish a successful system dynamics application, extensive computer simulations should be performed only after a clear picture of the integrated water resources system has been established through reasonably simplified conceptual models. Contrary to conventional modeling which may fail to capture the big picture of the problem with important feedback loops, a thorough system dynamics study can provide reliable qualitative and quantitative bases for policy selection. In this way, instead of investing resources prematurely, analysts can prioritize what to study in more detail to ensure an in-depth understanding of the problem is obtained.

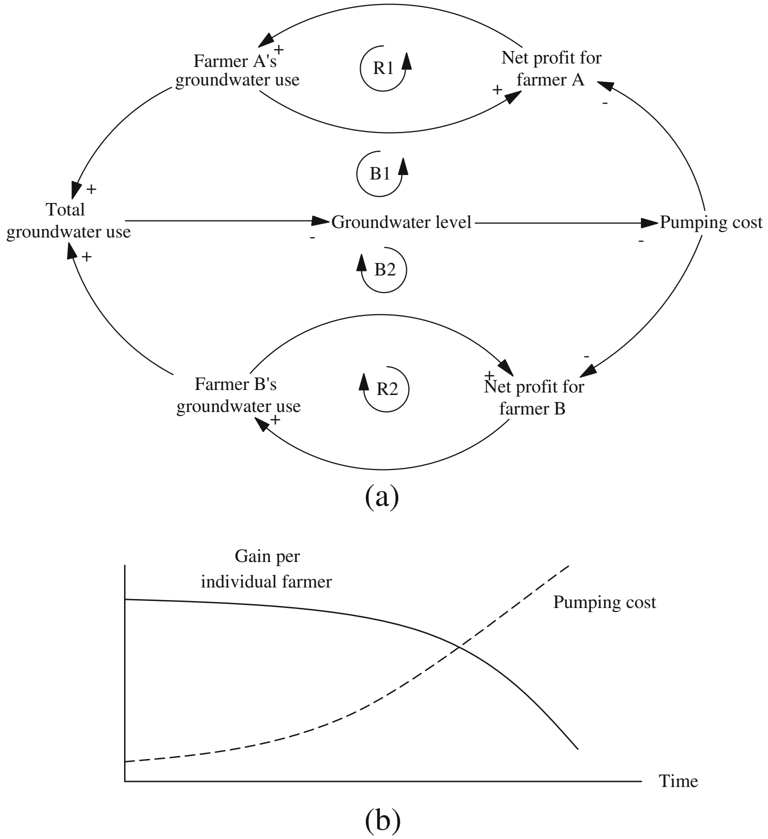


Fig. 11 CLD **a** and the behavioral graph of Tragedy of the Commons archetype **b** for the groundwater problem when two users (farmers A and B) compete to maximize their own share of the resource

System dynamics' qualitative modeling tools, and the insights that they provide, make this approach accessible to a wide range of decision makers and stakeholders. The tools for visually exploring systems are a major distinguishing factor between this approach and traditional simulation methods. These qualitative analysis tools help generate a constructive medium for understanding a system's structure using an iterative approach best implemented through interaction with people who are familiar with the system at different levels (Randers 1980). Therefore, attempts to reveal the main drivers of the problem using CLDs, SFDs, and archetypes are necessary. However, analysts should be aware of the general concerns about using qualitative modeling tools. In particular, problems might be encountered when translating CLDs into SFDs. Richardson (1986) argues that traditional definitions of the polarities of causal links and feedback loops are inadequate. In order to address this inadequacy he suggests that CLDs should account for the accumulating nature of the Flow-to-Stock links. As an alternative way for dealing with this problem, modelers can use CLDs along with reasonably representative SFDs to ensure qualitative insights are properly communicated.

System archetypes provide generic CLDs that reveal qualitative information about the underlying structure of the system, enabling water managers to detect current problematic trends and anticipate future problems. Thus, system archetypes are not meant to address any specific problem, but instead are applicable to classes of problems that share one or more modes of dynamic behavior. For various classes of problems, generic solution archetypes have been reported in the literature (Wolstenholme 2004). As such, system archetypes can be used along with other system dynamics tools such as SFDs to generate a broad, holistic understanding of the system's state and its long-term behavioral pattern. Essentially, once analysts reach a consensus regarding the system archetype that governs their particular system of interest, they can obtain valuable insights into solution strategies, which can be further analyzed and tested using detailed simulations (Wolstenholme 2003). This is a unique characteristic of system dynamics that facilitates conceptual or high-level strategic water resources modeling.

System dynamics models should have comprehensive, and yet simple structures, particularly when presented to non-technical audiences (Stave 2003). In this context, simplicity is not equivalent to misrepresentation of the system's structure. Rather, it is more consistent with Albert Einstein's maxim that "a good explanation is one that is as simple as possible, but not simpler." Often, it is also important for system dynamics water resources models to have transparent structures that facilitate sensitivity analysis, which is critical for adaptive water resources management and scenario-based policy screening (Simonovic and Fahmy 1999). If too much detail is included in the CLD, the structure of the system dynamics model may become overly difficult to understand for people who have not been involved in the model development. In addition to increased data requirements for complex, integrated models, to be able to provide meaningful interpretation of behavioral trends modelers must develop appropriate methods and protocols for quantifying socio-political subsystems–a task which remains a formidable challenge (Hellström et al. 2000; Luna-Reyes and Andersen 2003). Furthermore, regardless of the scope of the problem, modelers need to apply appropriate aggregation and hierarchical decomposition principles to accomplish the modeling task, with the level of aggregation and decomposition varying according to the scale of problem, modeling objectives, and desired model sophistication.

4.2 Validation of System Dynamics Models

Model "verification" or "validation", i.e., testing of the model using an independent data set, is often problematic due to limited data and, in some cases, a lack of appropriate methods for quantifying particular (e.g., socio-political) subsystems. Sterman (2000), in fact, argues that no model can ever be verified or validated, for models are simplified representations of real processes and are thus different from reality in infinitely many ways. Nevertheless, in order for models to be useful as decision support tools for water resources planning and management, it is necessary to verify the model structure to ensure that mathematical equations and interrelationships between subsystems follow logical explanations and are not spurious or erroneous. Unlike purely data-driven black-box models, generating an "accurate" output behavior is not sufficient for validation of causal-descriptive white-box system dynamics models, which in addition to reproducing the system behavior, should explain how the behavior is generated (Barlas 1996). Thus, as Barlas (1996) explains, in the context of system dynamics, model validation is a semi-formal process consisting of a balanced mix of both quantitative tests and qualitative behavioral criteria targeting the system's internal structure. In participatory system dynamics modeling, validation can be done throughout model development by a range of experts and stakeholders, which may be much more reliable than an external review of the model at the end of the process. The verification phase of system dynamics models developed for water resources problems has not always been discussed in detail, but modelers have reported a variety of verification methods, including behavior replication, sensitivity analysis, dimensional consistency, and structure assessment

(Ahmad and Simonovic 2000; Stave 2003; Tangirala et al. 2003). Table 6 summarizes these methods of verification of water resources system dynamics models.

4.3 Strengths and Limitations of System Dynamics Modeling

To summarize, Table 7 lists the major benefits and potential pitfalls of holistic water resources system dynamics models, including problems which might arise due to inappropriate application of the method without proper regard for its philosophy. Caution should be used when interpreting system dynamics models, for it is easy to formulate erroneous dynamic hypotheses due to inadequate information about a complex system, or due to lack of expertise. Biased simulation results may stem from faulty CLDs and SFDs. This *caveat* is particularly important when creating integrated models to simulate feedback relationships among socio-economic, political, natural, and technological subsystems. Tradeoffs among accuracy, breadth, and time must be considered in any modeling study. Nevertheless, although quantification of socio-economic and political components of water resources systems is challenging, and sometimes even speculative (Madani and Mariño 2009), system dynamics modeling helps to prioritize information gathering and holistically investigate interactions and potential impacts of different drivers of the problem.

Table 6 Common methods for verification of water resources system dynamics models (Adapted from Sterman 2000, revised for water resources applications)

Method	Rationale	Procedure(s)	Citation
Behavior replication	Reproduce the system's common modes of dynamic behavior both qualitatively and quantitatively	Perform statistical analyses of model results and observed data (e.g., R^2); qualitatively compare model results with data; investigate anomalies; change equilibrium conditions to disequilibrium conditions	Ahmad and Simonovic (2000), Guo et al. (2001), Stave (2003), Tangirala et al. (2003), Tidwell et al. (2004), Madani and Mariño (2009), Bagheri et al. (2010), Venkatesan et al. (2011a), Qaiser et al. (2011)
Dimensional consistency	Ensure each model equation is dimensionally correct	Perform dimensional analyses; double check conversion factors; ensure correlation coefficients are dimensionally correct	Tangirala et al. (2003)
Sensitivity analysis	Test numerical, behavioral, and policy sensitivity	Conduct univariate and multivariate sensitivity tests; simulate extreme conditions; change time step	Ahmad and Simonovic (2000), Tangirala et al. (2003), Bagheri et al. (2010), Venkatesan et al. (2011a, b)
Structure assessment	Ensure model structure complies with natural laws (e.g., continuity) and represents description of the system, and appropriate aggregation and decision rules are applied	Develop CLDs and SFDs; delineate appropriate boundaries; test performance of each sub-model; change aggregation level and decision rules	Bagheri et al. (2010) Qaiser et al. (2011)

Table 7 Benefits and limitations of integrated water resources system dynamics models

Benefits	Limitations
• Provide tools for graphical representation of systems (CLDs and SFDs) promoting qualitative modeling	• Easy to conceptualize erroneous CLDs and SFDs
• Facilitate flexible, transparent modeling	• Easy to develop faulty models based on wrong CLDs and SFDs
• Facilitate holistic understanding of the problem	• Require experience and expertise to develop sufficiently detailed, insightful, and representative description of the system (dynamic hypothesis)
• Capture long-run behavioral patterns and trends	• Require substantial interdisciplinary knowledge to generate meaningful quantitative predictions due to complexity and multitude of subsystems
• Facilitate clear communication of model structure and results	• Speculative quantification of some subsystems (e.g., socio-economic, and political subsystems).
• Promote shared vision planning, participatory modeling, and shared learning experience	
• Facilitate sensitivity analysis	
• Suitable for policy assessment and/or selection	

5 Conclusions

The traditional linear thinking paradigm lacks the mental and organizational framework for sustainable development trajectories, and may lead to quick-fix solutions that fail to address key drivers of water resources problems. In contrast, systems thinking can help water resources decision makers comprehend the interactions among various interlinked subsystems of a water resources system which drive its long-run dynamic behavior. Applying a systems thinking paradigm to water resources modeling is thus critical in the thinking phase of formulating strategic-level water management policies and plans. System dynamics modeling facilitates the application of systems thinking and holistic conceptualization of water resources systems.

In recent decades, while system dynamics has been widely used by water resources scholars as a tool for quantitative water resources modeling, it has not typically been utilized to its full capacity for scrutinizing the system's structure to provide insights into potential reasons behind problematic behavioral trends. At the strategic level, emphasis should be placed on trend identification and pattern recognition rather than exact quantitative predictions of dynamic variables. Although the quantitative modeling phase using extensive computer simulations is still very important and needed for policy screening, especially when characterizing complex systems, qualitative system dynamics models can improve understanding of general trends and the root causes of problems, and thus promote sustainable water resources decision making.

In this paper, tangible water resources examples were presented to illustrate the fundamentals of system dynamics, emphasizing that developing CLDs and SFDs is necessary for identifying causal relationships forming feedback loops within water resources systems. Furthermore, water managers should use the knowledge of reference modes and system archetypes (e.g., Limits to Growth, Fixes that Backfire, Success to the Successful, and Tragedy of the Commons) to gain insights into sustainable solution strategies by recognizing common patterns of dynamic behavior. Compared to other modeling approaches, perhaps the most significant advantage of system dynamics is that when systems are not too complicated, the qualitative modeling tools can help describe the behavior of many variables, even before quantitative (numerical) modeling begins. This characteristic facilitates conceptual or high-level strategic water resources modeling using multi-disciplinary, multi-sectoral, and participatory approaches critical to sustainable water resources planning and management.

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