System Archetypes in the Conceptualization Phase of Water-Energy-Food Nexus Modeling

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Abstract

Water, energy and food are prerequisites for prosperity and wellbeing of the societies. Despite the strong interlinkages among these sectors decisions for future developments are usually made without sufficient consideration of these interdependencies. The aim of this paper is to reflect on the most fundamental causalities and decision variables which govern the dynamics of Water-Energy-Food (WEF) nexus. For this purpose, channels through which water, energy and food sectors influence each other are introduced. "Accidental Adversaries" and "Limit to Success" archetypes are used in the conceptualization phase of the modeling WEF nexus. Further, several development issues, potential bottlenecks, trade-off and synergies in WEF system are discussed. System archetypes found to be effective tools in structuring the fragmented knowledge of causalities and relationships which is evident in WEF system. Accidental Adversaries, in particular, holds a great potential to capture trade-offs and synergies which are central issues in the WEF nexus approach. This study is the first step to establish the framework for building a quantitative system dynamics (SD) model for integrated management and development of WEF system.

Keywords: Water-Energy-Food nexus, System Dynamics, Conceptualization, Accidental Adversaries archetype, Limit to Success archetype

Introduction

While global availability of water and energy is not a limiting factor (the available water in the water cycle is much higher than the humanity's demand, and global technical potential for renewable energy production is substantially higher than global energy demand (2009a; Mitigation, 2011)), relative scarcity might become a bottleneck due to uneven geographical distribution or varied temporal availability (2014a) of the resources. Water and energy availability are constrained by the technical potential to utilize them. Massive amount of investment is required to overcome this constraint and to meet the projected future demand. Constraints on water availability can delimit energy production potential or the choice of technology, and vice versa (Gleick, 1994; Mielke, Anadon, and Narayanamurti, 2010; Mitigation, 2011). The magnitude of increase in demand in the coming decades is expected to be substantial: 35-40% increase in global energy demand and 70% increase in electricity demand by 2035 (2014b; Conti *et al.*, 2011; Madani and Khatami, 2015). Water consumption is likely to rise as much as 55% by 2050 (compared to 2000) (Allan, Keulertz, and Woertz, 2015).

Strong interdependencies between water, energy and food systems have been identified by several authors (Keairns, Darton, and Irabien, 2016; Rasul, 2014; Rasul and Sharma, 2015; Ringler, Bhaduri, and Lawford, 2013). Regarding water-energy nexus, on the one hand, water is needed in every stage of energy provision, e.g., for mining, refining, processing, liquefaction, gasification, carbon sequestration, and during direct power generation in coal, natural gas, oil, nuclear, biomass, and central solar power plants. On the other hand, each segment of water cycle, e.g. abstraction, conveyance, treatment, distribution, end-use, and disposal, consumes significant amount of energy (McMahon and Price, 2011; Siddiqi and Fletcher, 2015). There is a heavy reliance between food system, water and energy. Globally, agriculture accounts for 70% of fresh water withdrawal in average (varies between 10% and 88 % in various countries) (2009b) and 30% of energy use (2012b). With the advent of bioenergy technologies, already stressed water resources will be under greater pressure and the arising competition over land will be expanded to energy sector. Considering food system in terms of demand, production and supply, we gain a perspective on water and energy as processed matters within the complex socioeconomic consumption systems.

The interlinkages between water, energy and food are fully acknowledged not only by scientific community, but also by policy makers. The Bonn2011 Nexus Conference, for instance, initiated the global debate on WEF nexus and the need for interlinked thinking and action (2012a). While recognition of water, energy and food systems as a nexus is a major step towards systemic policy making, the challenge remains as to how the interlinkages between systems should be made explicitly.

One approach could be quantifying the required input of water/energy for operation of each system. Literature on water, energy and food has been largely concentrated on this issue. Rio Carrillo and Frei (2009) analyzes the water needs for energy production in Spain; Mielke *et al.* (2010) gives a comprehensive overview of water consumption in each segment of energy production cycle including extraction, processing and conversion; Macknick *et al.* (2011) and Inhaber (2004) give estimations of water use in conventional and renewable electricity generation technologies; Zhai and Rubin (2010) calculates the water required for wet and dry cooling systems for pulverized coal power plants; McMahon and Price (2011) surveyed the water consumption for fuel production and electricity generation.

Energy demand for operating water system has also been extensively documented: Siddiqi and Fletcher (2015) highlights key findings on energy intensity of water end-use in urban and agricultural sectors; Plappally and Lienhard V (2012) surveys the available literature on energy intensity for water use in the municipal and agricultural sectors, disaggregated by water supply, water treatment, residential end use, waste water treatment, and agriculture end use. Energy and water intensity of agriculture complement this picture (Chang *et al.*, 2016; Conforti and Giampietro, 1997; Khan and Hanjra, 2009; Wallace, 2000). Figure 1 illustrates these dependencies.

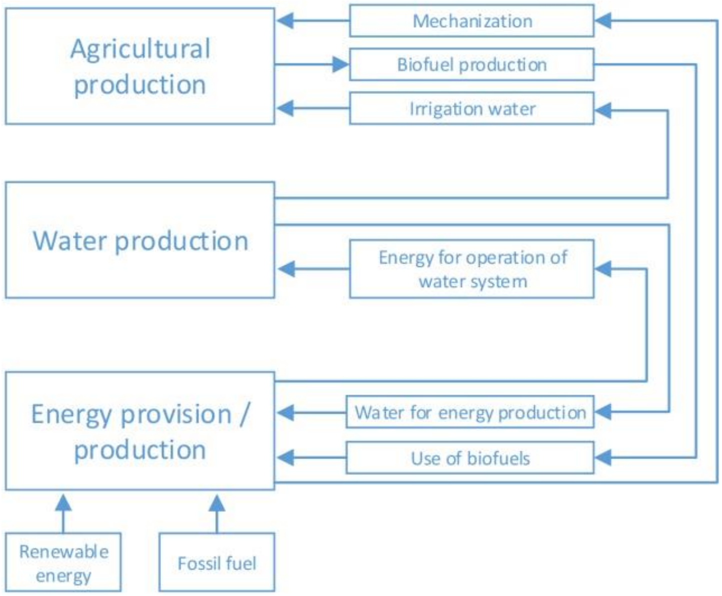

Figure 1: Input-Output perspective on WEF system (Hermann et al., 2012) (strongly modified)

Though the quantification of relationships provides valuable insights and solid basics for any system analysis, it should be highlighted that the relationships within WEF system cannot be reduced to linear ones. Indeed, several nonlinearities coexist within and between systems.

Strong interdependencies within WEF system highlight the necessity of holistic and systemic perspective, otherwise there is a high chance for unforeseen consequences as a result of locally rational decisions. After reviewing existing literature on integrated resource assessment and modeling of WEF, Bazilian *et al.* (2011) conclude that analytical tools used to support decision-making are fragmented and the focus is generally only on one sector ignoring interconnections with other resources. This is also true regarding the application of system dynamics, which has been used to analyze each sector in isolation; water system (Cheng, 2010; Feng, Zhang, and Luo, 2008; Kojiri *et al.*, 2008; Sahin, Stewart, and Porter, 2015; Sušnik *et al.*, 2012; Winz and Brierley; Xi and Poh, 2013; Zarghami and Akbariyeh, 2012; Zhang *et al.*, 2008), food system (Li, Dong, and Li, 2012; Rozman *et al.*, 2008; Shi and Gill, 2005), and energy system (Aslani, Helo, and Naaranoja, 2014; Chapman, 1978; Chyong Chi, Nuttall, and Reiner, 2009; Jeon and Shin, 2014; Qudrat-Ullah, 2015; Robalino-López, Mena-Nieto, and García-Ramos, 2014; Wenpei *et al.*, 2011), leaving its application in WEF nexus out of scope.

Channels of influences among the sectors

There are several channels of influence in WEF system, which can be identified in one of the following categories:

1. *Adjusted demand for the final products of the other sectors:*

This is the input-output approach presented in Figure 1. Any adjustment of demand for the final products of the other sectors resulted from new capacity, efficiency gain, changes in the technology mix, etc., fall in this category. Investment decisions play the principal role here. For instance, choice of energy technology dramatically influences future water demand in energy industry, as there is a huge difference in water demand by different energy technologies (from negligible amount for wind and photovoltaic to 17,000 liter/megawatt-hour for hydroelectric) (McMahon and Price, 2011).

2. *Competition for the shared resources*:
   In extreme cases, this leads to what we know as tragedy of the commons, the situation in which "there is a commonly shared resource, every user benefits directly from its use, but shares the costs of its abuse with everyone else. The consequence is overuse of the resource, eroding it until it becomes unavailable to anyone" (Meadows and Wright, 2008). The possibility of overexploitation of resources, however, should be addressed by environmental regulations, but there are other competitive situations in which the competition does not escalate to such an extreme extent, rather, it simply raises the prices. For instance, expansion of biofuel production will raise the competition over land and thus, increase the cost of food production (Rathmann, Szklo, and Schaeffer, 2010).
3. *Impairment of the future opportunity of other sectors to practice their full potential:*
   Effects of climate change and environmental degradation as external factors fall in this category. Political situations, external shocks, natural catastrophes fall in this category as well, but these factors are not discussed further in this study with the possible outlook for future investigations.

There are many cases in which the influence of a particular decision or strategy falls within more than one category. As an example, intensification of agriculture would increase energy input through both mechanization and fertilizer input, but it also reduces land competition, therefore open up the opportunity for bioenergy production or other uses (Hermann *et al.*, 2012). Another issue is multiplicity of influence due to specific change in one part of the system, e.g. a single decision or strategy. Here intensification of agriculture sets again an example.

Model description

In this section we develop a tentative dynamic hypothesis for integrated WEF system. Using system archetypes, we develop building blocks of more elaborated CLD, which adds value to the issue structuring and behavior assessment even without specifying quantitative relationships. Introducing circular causality which provides opportunity to externalize mental models, facilitation of inference of behavior modes by assisting mental simulation of the maps, and identification of policy links for intervention to redesign the system are well facilitated by CLDs (Wolstenholme, 1999). Qualitative diagrams put a very complex problem into a condensed form which helps to identify relationships and explain behavior. Later on, where appropriate, it could be a basis for quantitative model by transforming it into equations. Description of the system using diagramming tools is the first step in SD modeling (Spector *et al.*, 2001). In the modeling process, Archetypical structures are used as a starting point towards model conceptualization by transferring insights from other models (Wolstenholme, 2003). We developed the qualitative system dynamics model of WEF system based on Accidental Adversaries and Limit to Success archetypes, aiming to summarize the current understanding of WEF system. Nevertheless, we believe that quantitative SD model of WEF system will have significant advantages over qualitative model, thus, it is planned for our future work.

Accidental Adversaries; capturing trade-offs

Accidental Adversaries archetype refer to the situation in which two parties working together aiming to receive mutual benefits from collaboration, become accidentally adversaries due to their effort to fix local performance gaps. These efforts have unintended consequences which undermine the success of the partner on whom the group depends. Ultimately, the success of the initiator of fixes also suffer (Wolstenholme, 2003). Figure 2 illustrates the CLD for this archetype. The benefits of collaboration (R1) gradually declines as the local corrective actions (B1 & B2) form the reinforcing loop of unintended consequences (R2).

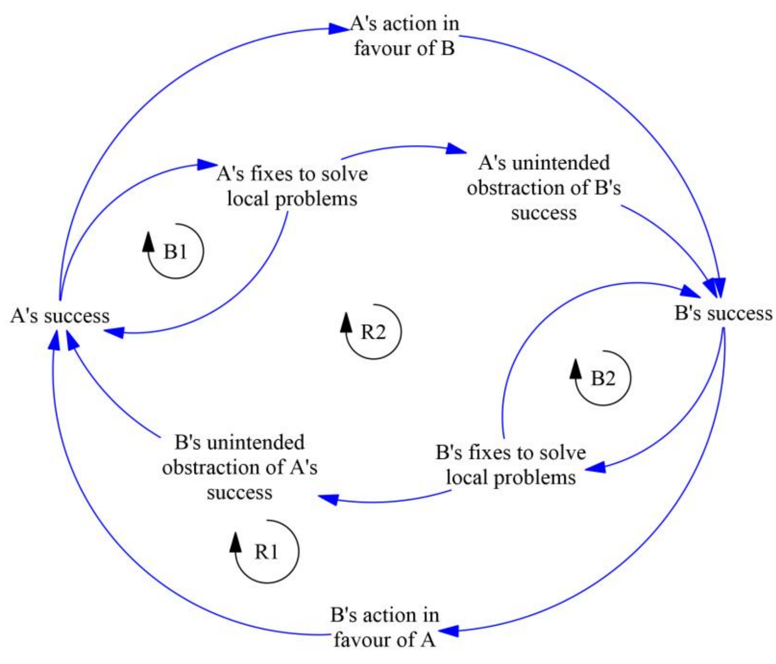

Figure 2 CLD for Accidental Adversaries
R1: reinforcing loop for mutual benefit for partnership; B1 & B2: Balancing loop of local corrective actions each parties undergo to solve their own problems; R2: Reinforcing loop of unintended consequences resulting from local corrective actions which undermine success of each party

While there are important differences between collaborating organizations and water, energy and food systems which could make the generalization of Accidental Adversaries to WEF questionable, we will illustrate the effectiveness of Accidental Adversaries in describing key characteristics of WEF system.

One critique of this generalization could be the heterogeneity of water, energy and food systems which makes it incomparable to autonomous organizations which Accidental Adversaries is generally considered for. Each of the water, energy and food systems is managed by a huge number of stakeholders with different level of information, aspirations, authority to make decisions and responsibilities. Validity of this critique depends on the scope, scale and the level of decision making the model is considered for. At the strategic level of decision making in which establishing guideline for future developments are concerned, such aggregation level appears to be reasonable, whereas in many other situations the opposite is true. In short, the suggested structure is capable of capturing dynamic complexity and long-term evolution of WEF system, but not the detail complexity at operational level of management.

Another critique could be the fact that Accidental Adversaries describe the explicit collaboration between parties, while water, energy and food systems, despite their heavy reliance on each other, are barely in such an explicit collaborative terms. Organizations can decide to stay in or leave the collaboration, but this is not the case for water, energy and food systems, because usually there is no other option: the collaboration here is unavoidable. A good example for this is water being bulky, difficult to store and transport. Thus, the only option for energy production and agriculture is to rely on the local water supply. Although globalization of trade of agricultural products and energy sources have weakened the magnitude of reliance, water, energy and food sectors are still heavily dependent on each other.

To evaluate WEF system in an integrated manner, developing conceptual models and robust analytical tools are among the most important steps (Bazilian *et al.*, 2011). Accidental Adversaries is used as a conceptual model which later on can be converted to an analytical tool (quantitative SD model). It provides the basis to include trade-offs and synergies between systems and development decisions, which is widely discussed in the scientific community in the context of WEF nexus. Rasul and Sharma (2015) state that identifying integrated policy solutions to minimize trade-offs and maximize synergies across sectors is among the key principles of nexus approach. Allan *et al.* (2015) argues that trade-off have to be understood to increase water, energy and food security. Gheewala, Berndes, and Jewitt (2011) put emphasis on the necessity of considering trade-off between climate change mitigation and water stress in relation to bioenergy. They assert that high land use efficiency in bioenergy production (i.e. maximizing bioenergy production per unit of land) to avoid the risk of land-use change emission leads to preference for high-yielding systems employing large input of fertilizers, pesticides, and irrigation water. As a result, large demand on local water resources and increased pollution load from fertilizer and pesticides leakage, introduce a trade-off between bioenergy production for mitigating climate change and water resources. Hanjra and Qureshi (2010) suggest that in response to climate change, the link between water programs, food security, energy security, and climate change research should be strengthened to highlight the synergies and trade-offs. Technical aspects, similar to managerial aspects, include elements of trade-offs as well; choosing cooling system for energy production technology involve trade-offs between water withdrawal and water use. Once-through cooling system requires high water withdrawal and moderate water use, whereas wet cooling towers require less water withdrawal but consume more water. Another alternative, dry cooling system, needs no water withdrawal and consumption, but it requires high capital investment and it has low efficiency compared to other cooling systems (Delgado Martín, 2012).

Structure of Accidental Adversaries archetype provides the necessary framework to capture multiplicity and simultaneity of numerous interacting and mutually dependent variables in WEF system. In summary, main advantages of this framework are as follow:

- It put the efforts to meet sectoral goals in a wider context of WEF nexus, enabling decision makers to evaluate multiple channels through which other sectors of WEF system would benefit or suffer from a decision or policy. Therefore, capturing trade-offs and synergies, as a fundamental principle of nexus approach, become possible.
- The role of collaboration across the nexus, which is an important but mostly missing factor in decision making (Bazilian *et al.*, 2011; Rasul and Sharma, 2015), is underlined.
- The explicit inclusion of goals, performance measures or success, and available policy options in each sector and relating the sectoral strategies to sectoral goals and overall goals of the WEF system.

Figure 3 illustrates the qualitative stock and flow diagram of extended Accidental Adversaries archetype applied to WEF system. The stock variables representing success of each sector are connected to the inflow rates of success of other sectors, implying the "*interdependencies in progress*". The inflow rate of success depends on success in other sectors as well as the measures taken by the sector itself to improve its own performance. Each of these three variables could consist of several factors (e.g. price, availability, reliability, etc.) that form a nonlinear inflow of success. Interaction of variables in a multiplicative way, which could be the case here depending on the exact specification of variables and decision rules, is one of the source of nonlinearity in System dynamics (Forrester, 1987). The outflow rate of success, in the same way, is determined by interaction between measures taken by the sector itself and consequences of actions taken by the other sectors to narrow their own performance gaps. Note that "actions to narrow the performance gap" in each sector contribute to both inflow and outflow of success for that sector, representing the sectoral trade-offs of different decisions (i.e. development policies, investment strategies, etc.) and/or unintended consequences.

However, the introduction of circular causalities in the system must be highlighted; if the actions taken by one sector to narrow its performance gap have adverse effects on the performance of the other sectors, it may undermine the performance of that sector as well after a time delay due to "interdependencies in progress". This property offers a compelling argument to support WEF nexus approach as well.

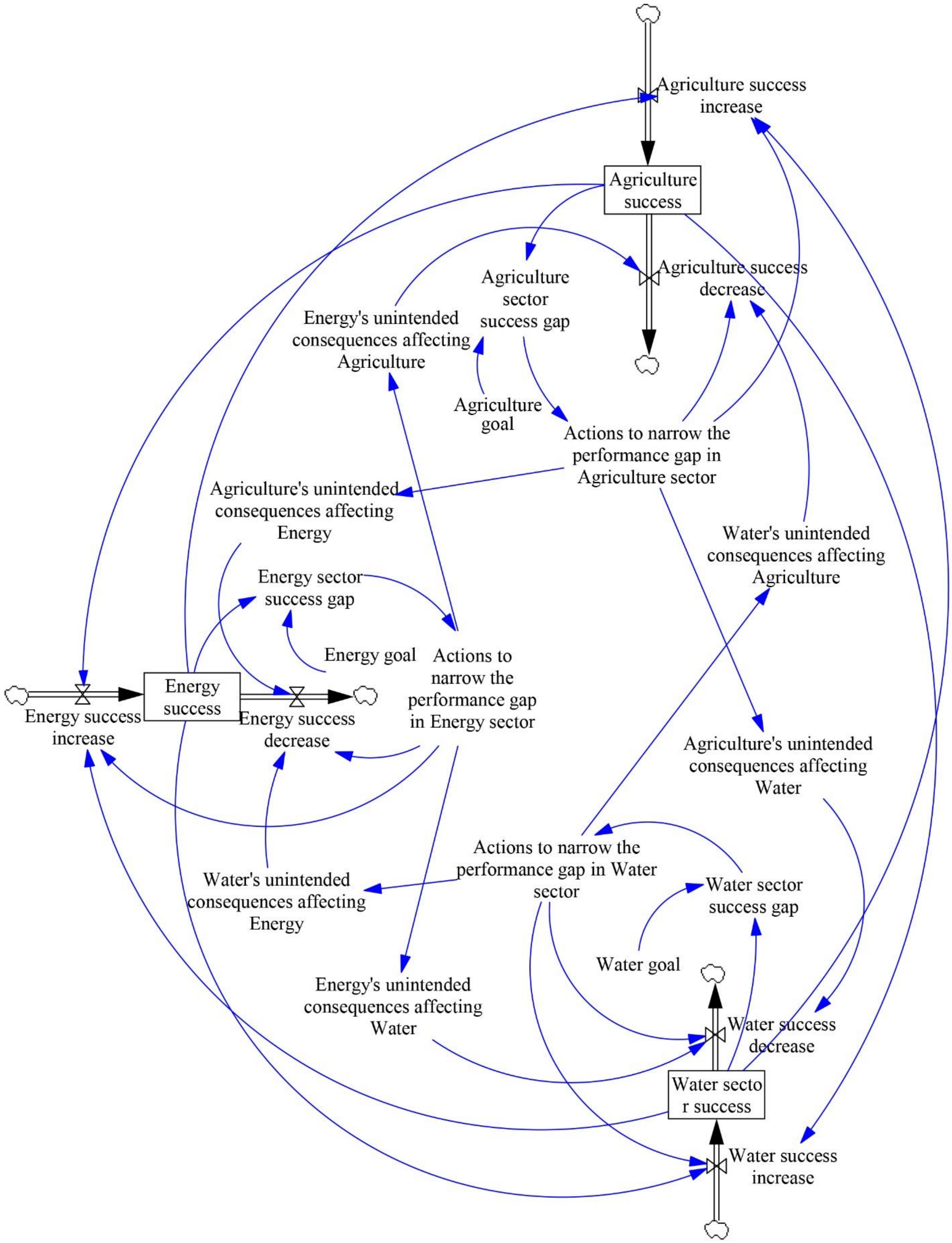

Figure 3 Qualitative stock and flow diagram of extended Accidental Adversaries for WEF system.

Qualitative diagram represented in Figure 3 can be transformed into fully quantitative SD model, which requires explicit specification of success, goal and actions to narrow the performance gap in each sector in the first place. For that, there might be several success indicators, goals and actions depending on the specific circumstances. The next step is to identify channels of influence, i.e. how the actions and policies to improve performance affect other sectors. As an example, if the water sector adopts the policy to switch from fresh water to waste water reuse to meet the goal of provision of specific amount of water or to decrease the environmental pressure resulted from overexploitation of water resources or releasing contaminated water into the nature, availability of fresh water and overall water supply increases, but at the same time more energy is required to treat and pump the waste water (Skaggs and Rice, 2012). Water availability influences energy and food sector positively, while higher energy demand exerts higher pressure on energy sector which, in turn, may increase water demand in energy sector (depending on the technology mix in energy sector), as well as energy price due to increased overall energy demand. Water price is likely to increase as a result of increased energy intensity of water service. Food sector will be negatively influenced from increased water price, increased energy price and decreased energy availability, while it benefits only from higher water availability. At the end, the extra benefit from higher share of waste water reuse for water sector may be more than offset by unintended consequences as resulting from altered state of the system. Identifying the channels of influence and properly quantifying them is a key step towards building an integrated system dynamics Water-Energy-Food model.

Limit to Success archetype; cost and availability

Limit to Success is a situation in which improvement of performance gradually faces a constraint inhibiting further improvement (Figure 4). This archetype can effectively explain many bottlenecks in WEF system. Limited availability of water which inhibits growth in energy and agriculture sector and limited availability of energy which inhibits growth in water and agriculture sector are directly noticeable.

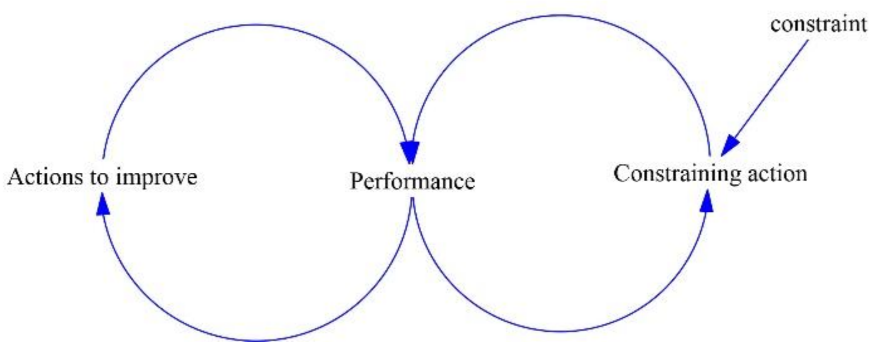

Figure 4: Limit to Success archetype

Figure 5 illustrates extended Limit to Success archetype applied to WEF system. Reinforcing loop (R1) aims to improve performance of energy sector (i.e. increase total energy produced) through investment. Improved performance gradually activates balancing loop (B1) by increasing water demand which leads to limited water availability, which in turn, decreases energy production potential and total energy produced. The same structure limits the success of water sector by decreasing energy availability (R2 & B2). Reinforcing loop for growth in agriculture (R3) is bounded by two balancing loops, B3 and B4, representing limited water availability and limited energy availability, respectively. For simplicity, bioenergy production is not shown.

Figure 5 includes traces of Accidental Adversaries as well, even if it may not be evident at the first glance. Three reinforcing loops (R1, R2 and R3) resemble actions to narrow the performance gap (investment), to increase success (increase total energy produced) in Figure 3. Total energy produced reversely affects total agriculture production through decreasing water availability, which resembles “energy’s unintended consequences affecting agriculture”. It also affects water production cost through chain of cause and effects. Figure 5 is a special case of a more generic structure of Accidental Adversaries including some of the most widely discussed channels of influence and observed behaviors in the literature.

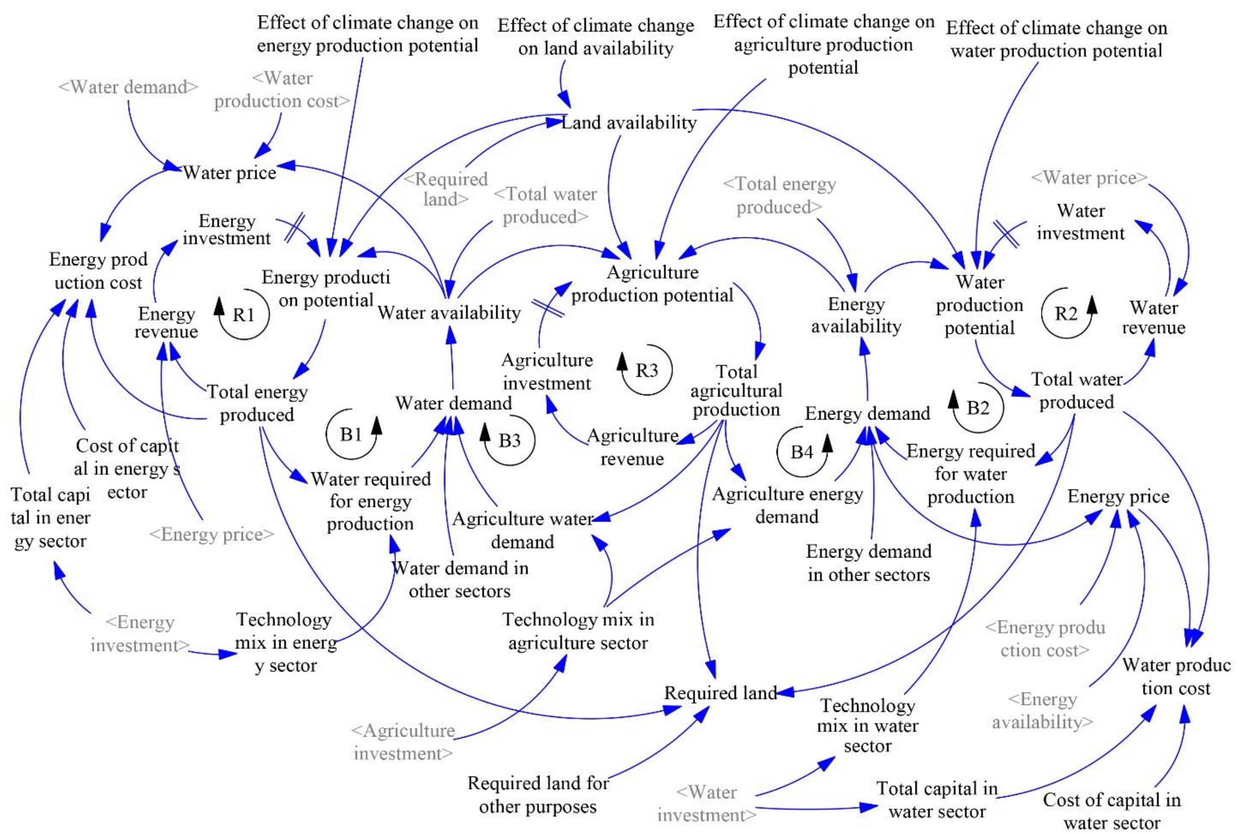

Figure 5: Extended Limit to Success diagram. Reinforcing loop R1, R2 and R3 are sectoral efforts for improvement, resembling the “actions to narrow the performance gap” in Figure 3. Balancing loop B1 and B3 delimit the growth in agriculture and energy sector as a result of limited water availability. Balancing loop B2 and B4 delimit the growth in agriculture and water sector as a result of limited energy availability.

Previously discussed channels of influence are all present in Figure 5: first channel of influence, adjusted demand for the final products of the other sectors, results from technology mix and total production of each sector and affects production potential of sectors. Second channel of influence, competition over the shared resources, is shown by required land and land availability which can possibly delimit further growth in each sector or cause tragedy of the commons in extreme cases. Third channel of influence is represented as exogenous effect of climate change.

In the literature, there is particular emphasis on availability (input-output method) and cost, while there are also other issues involved, e.g. reliability of service which can become decisive factor in some cases. Extensively discussed effects of environmental pressures and climate change have particular relevance for WEF system, but they are out of the scope of this study and thus, only minimally represented in the model.

Policy recommendation

WEF nexus approach is relatively new, therefore the quality and reliability of models, and as a result the validity of policy recommendations is limited to the current level of understanding of dynamics within WEF system.

Additionally, analytical quality of policy insights from system archetypes are low, because robustness of insights to parameter or structural changes cannot be tested. Available insights are not grounded in simulation and the real links in a system are not developed in a rigorous way (Lane, 1998). While the model of WEF system elaborated in this study resolved some of this issues (e.g. more precise representation of real links in the system), most of above mentioned critics are valid, thus, any policy derived from the qualitative models in this study should be treated with caution. Nevertheless, the following general policy recommendations can be deduced from the model:

- **Investment; a key driver of long term availability**
  Investment plays a critical role in the long term dynamics of the system. It determines technology mix in each sector, which in turn, affect the availability of water and energy. Dominance of balancing loops B1, B2, B3 and B4 in Figure 5, responsible for availability, are significantly affected by investment decisions. Investment decisions affect the prices indirectly through availability and also directly through capital intensity.
- **Necessity of harmonized development**
  Water availability is determined by total water produced and water demand. If water sector for any reason is not able to produce enough water, energy production will be limited to available water. Likewise, water production is limited to available energy. If one sector lags behind, other sectors will suffer. This mutual dependency calls for harmonized development.
- **Necessity of transparency and effective communication**
  Organizational boundaries are important to understand WEF system. While ‘‘most water, energy and land-use planning, decision and policy making occurs in separate and disconnected institutional entities (Bazilian *et al.*, 2011)’’, the behavior and evolution of WEF system which place a limit to the success of each organization, is first and foremost determined by interaction of those decisions, not

the decisions themselves. Investment decisions, for instance, should be informed by both the current conditions and future plans in other sectors. This requires effective communication and cross-sectoral collaboration.

Conclusion

The models of WEF system presented in this study are constructed based on the knowledge accumulated in the scientific literature. We employed two system archetypes –Accidental Adversaries and Limit to Success- in conceptualization phase of building WEF model in order to structure the existing knowledge and to build the dynamic hypothesis for long term evolution of WEF system based on several case studies, examples, evidences and identified channels of influences. System archetypes proved to be effective tools in structuring the fragmented knowledge of causalities and relationships which is evident in WEF nexus literature. The result serves as a framework for WEF system analysis and a starting point for quantitative system dynamics model.

The notion of trade-offs and synergies and the need to made them explicit in decision making is one of the core concepts in the nexus approach. Accidental Adversaries proved to be an appropriate framework (a) to capture trade-offs and synergies, (b) to take into account multiplicity and simultaneity of numerous interacting and mutually dependent channels of influence, (c) to relate development strategies to sectoral goals and overall goal of the whole system in order to analyze long term evolution of the system as a result of these strategies, and (d) to provide a basis for collaborative and cross-sectoral policy making. The extended Limit to Success CLD diagram has developed as a special case of the more generic structure of accidental adversaries. It depicts the effect of cost and availability of energy, water and land, which are the most widely discussed channels of influence in the literature, and explains the effect of investment on both availability and cost.

The models presented in this study, despite their ability to represent the internal structure of WEF system, has limited analytical precision, therefore any policy recommendation derived from these models should be treated with caution. Nevertheless, this study does not intend to formulate policies, rather, it aims to provide a framework for quantitative WEF model. Future efforts should be directed towards constructing and validating a quantitative SD model. The authors welcome feedbacks and dialogues in this regards.

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