Chapter 7
System Dynamics Approach for Water Resources Systems Analysis

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Abstract The world is currently facing extremely high water scarcity, due to the limitation of available water resources, droughts, and increasing water demand follows population growth and changing consumption patterns. In such circumstances, it is necessary to determine the optimal and sustainable operational policies of this vital source. In addition, considering the role of simulation and optimization approaches as one of the management tools, the existence of a comprehensive, integrated, and dynamic notify system is necessary regarding the type and combination of the costs. This tool helps experts and users to compare different scenarios in specific time periods, and to be able to adopt measures to manage water consumption. In this regard, system dynamics approach is one of powerful management and simulation tool in solving, supporting, and decision-making complex issues. This approach refers to the computer simulation method for simulating a dynamic and complex system with feedback process inclusion and make system users a better understanding of the dynamic behavior of systems during time. This method has been successfully applied in a wide variety of business and socio-economic fields. Furthermore, in recent years, this method has been used in water resources research, such as flood management, operation of reservoirs, management of catchment basin, planning management, and analyzing the decision-making policies of water resources management, and the results have been very significant. Considering the importance of this issue and the benefits of using System Dynamics analysis approaches in solving problems, in addition to introducing this method, examples of different studies conducted in the simulation of water systems using system dynamics analysis technique are presented, in this chapter.

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7.1 Introduction

Population growth, urban development, agricultural development, and the rapid growth of various industries, and on the other hand, increasing water demand and water resources limitations have made serious problems for supplying water. These crises in alignment with its subsequent problems can only be decreased through correct management and planning. However, the existence of multiple decision-makers and consumers with different preferences and priorities in water resources management and planning issues raise considerable disagreements and concerns about the allocation of water resources, which will be of utmost concern for managers and planners in this segment. Therefore, water resources management is interdisciplinary and multi-component management and requires comprehensive decision making, which is now one of the most important challenges. Nowadays, with the rapid development of computational tools and the appearance of new optimization and simulation models, the application of systematic approaches in planning and management of water resources systems has been expanded, making it possible to make complex systems more accurate by identifying components and analyzing the relationships between them. One of these approaches is the System Dynamic (SD) approach. This method is one of the most effective methods available for a comprehensive evaluation of system performance. System dynamics was first devised by Forrster (1961) to better understand strategy issues in complex dynamic systems. Models written in this way, with insights into the feedback processes, help system users to better understand the dynamic behavior of systems over time. The application of this method is widespread, which is more emphasized in socio-economic issues.

The application of this method in water research, such as the planning of river basin, management, and planning of water resources systems, management of reservoirs, urban water systems, flood, irrigation, and drainage have been developed and had excellent results. Over the years, several System Dynamics models have been developed for various water (Chen et al. 2017; Ahmad 2016) and environmental management (Amoueyan et al. 2017; Rusuli et al. 2015) applications. A comprehensive review of system dynamics applications has been provided by Winz et al. 2009; Mirchi et al. 2012). System Dynamic has been used for the management and planning of river basins and water resources in several studies such as integrated analyses of water resources in Canada (Simonovic and Rajasekaram 2004), SD analysis for Zayandeh-rud river basin management (Madani and Mariño 2009), water management in complex systems (Hassanzadeh et al. 2014), SD simulation model for sustainable water resources management and agricultural development (Kotir et al. 2016), SD application in integrated water resources modeling (Zomorodian et al. 2018), hybrid SD and optimization approach for sustainable water resources planning (Li et al. 2018), analysis of water management scenarios using coupled hydrological model and SD (Qin et al. 2019), dynamic management of a water resources-socioeconomic-environmental system (Dong et al. 2019).

There are other applications of SD in hydropower studies, which were mentioned in hydropower generation assessment using SD (Sharifi et al. 2013) and power generation simulation of a hydropower reservoir (Jahandideh-Tehrani et al. 2014). SD has also been used to investigate the impact of water demand priorities on downstream by Qashqai et al. (2014). In the last three studies, SD has been used in research involving a reservoir or a set of reservoirs.

SD is also used in studies of irrigation and drainage networks and studies of irrigation water management. Vaez Tehrani et al. (2013) used SD to model irrigation network rehabilitation. Nozari and Liaghat (2014) used SD to simulate drainage water quantity and quality and showed that the SD model can be used to manage and control drainage salinity to prevent environmental damage. Nozari et al. (2014) simulate irrigation network and crop pattern by using SD, and the results showed that SD is suitable for simulation. Matinzadeh et al. (2017a, b) used SD to simulate nitrogen dynamics in agricultural fields with drainage systems. Pluchinotta et al. (2018) used SD to manage irrigation water in southern Italy.

SD also has been used for flood management (Ahmad and Simonovic 2000, 2001, 2004, 2006), water security studies (Chen and Wei 2014) and water security assessment in Rafsanjan, Iran (Bagheri and Babaeian 2020), Urban water system management (Karimlou et al. 2019), groundwater modeling (Bates et al. 2019), surface water quality management (Elshorbagy and Ormsbee 2006), integrated system dynamics model (Liu et al. 2015), the impact of global climate change on water quantity and quality (Duran-Encalada et al. 2017), water quality modeling (Amoueyan et al. 2019 a and b; Venkatesan et al. 2011a, b; Nazari-Sharabian et al. 2019), water allocations (Wu et al. 2015; Qaiser et al. 2011, 2013; Kandissounon et al. 2018), climate change impact on water resources (Dawadi and Ahmad 2012, 2013; Zhang et al. 2016), carbon footprint of water projects (Shrestha et al. 2011a, b, 2012; Bukhary et al. 2018), water conservation (Ahmad and Prashar 2010; Dow et al. 2019), rainwater harvesting (Tamaddun et al. 2018), and energy planning (Moumouni et al. 2014). Models have also been developed (Stave 2003; Nussbaum et al. 2015) for Lake Mead and the Las Vegas water supply system to educate public about water conservation.

7.2 Basics and Logic of the Subject

Issues in a system have both dynamic characters and feedback structure. Based on the dynamic characteristics, the quantity and quality dimensions of the system change over time, and according to the system's feedback structure, different elements of the system are influenced by each other at any time. The system dynamics method is based on feedback control theory and nonlinear dynamic theory which enables the construction of a real-world model for a better understanding of phenomena (Sterman 2000). This method can be used when the human mind is incapable of analyzing the structure, relationships, and behavior of a phenomenon (Bala et al. 2017). In fact, system dynamics is a method based on systematic thinking which can provide the possibility to describe complex systems based on reality, and also user participation in model development in addition to the description.

7.3 Definitions and Terms

In this part, common expressions in creating and using SD is going to be described.

7.3.1 System

System is a set of elements and components interacting with each other for a specific purpose. Systems may be classified as (a) open systems and (b) feedback systems. In open systems, the output is defined by input, and the output has no impact on the input. However, feedback systems are closed-loop systems in which the inputs are influenced and changed by outputs. Figure 7.1a shows an open system and Fig. 7.1b shows a feedback system.

A feedback system is classified as a positive feedback system or a negative feedback system. Positive feedback systems have brought growth and increase, while negative feedback systems will bring a reduction (Bala et al. 2017; Sterman 2000). Connector signs describe the structure of the system and are unable to determine variables' behavior which defines how changes in the cause will lead to changes in effect (Table 7.1).

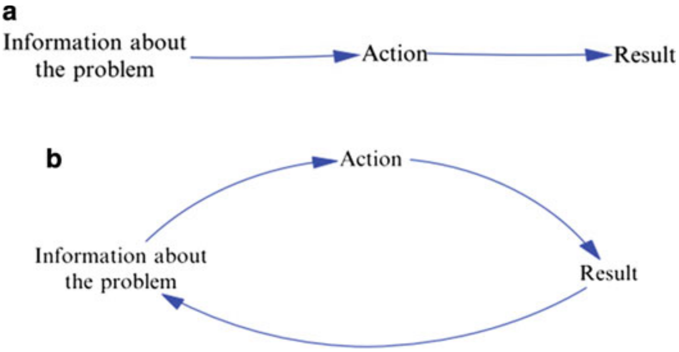


Fig. 7.1 **a** Open system (Bala et al. 2017). **b** Feedback system or closed-loop system (Bala et al. 2017)

Table 7.1 Positive and negative feedbacks definition

Figure	Describe	Computational equations
	If x increase (decrease), than y will increase (decrease)	$\frac{\partial y}{\partial x} > 0$
	If x increase (decrease), than y will decrease (increase)	$\frac{\partial y}{\partial x} < 0$

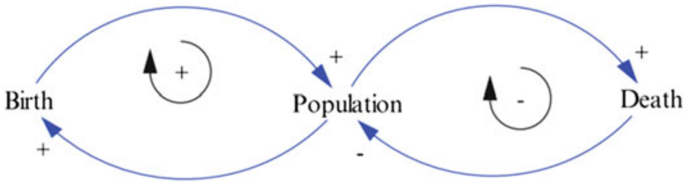


Fig. 7.2 Schematics of positive and negative feedback loops (Bala et al. 2017)

7.3.2 *Causal Loop Diagram*

All dynamic systems are created by a positive and negative loop. In other words, positive loops help the system to improve and grow, and negative loops play neutralizing and balancing roles in the system (Bala et al. 2017). In general, the feedback process consists of negative and positive loops. These loops illustrate the causal relations of a system, which, in fact, are the main structure of a dynamic system. The primary purpose of these diagrams is to represent causal hypotheses during modeling to express the entire structure interconnectedly. These diagrams help the creator to communicate quickly with feedback structure and basic defaults. Figure 7.2 shows an example of positive and negative feedback loops.

As it represents, with population growth, the birth rate increases, which leads to population growth again creating a positive feedback loop. On the other hand, population growth leads to an increase in the death rate, which causes population reduction, creating a negative feedback loop. Thus, birth in positive feedback leads to an increase in population, and death, in negative feedback, leads to a decrease.

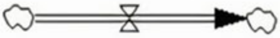
7.3.3 *Stock and Flow Diagram*

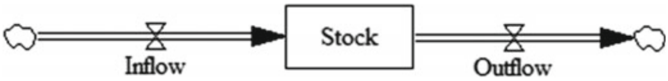
Stocks are systems accumulations and represent system statuses, and system decisions and activities are governed by them. Flows indicate changing rates which means they demonstrate the processes which increase or decrease stocks. It can be said that in a system, decisions are made based on the stock variable, and through flow variables, those changes are implemented.

To draw stock and flow diagrams, four essential elements of stocks, flows, connections, and converters are used (Table 7.2). Stock is displayed as a block in the model to indicates the status or conditions of the model at any given time. Flows are divided into inflows and outflows; inflows are shown by arrows in towards stock variable, and outflows are also shown by arrows in the opposite direction going out of stock variable. Connections are used to show the relationships among model variables. In fact, connections carry information from one part to another part of the model which is shown by arrows. In the end, converters connect the input to output which can be manifested as mathematical equations or diagrams and tables. shows elements to be used in stock and flow diagram.

The mathematical structure of stock and flow diagram with one stock variable with an input and an output can be seen in Fig. 7.3.

Table 7.2 Elements for creating stock and flow diagrams

	Stocks
	Flows
	Connections



$$Stock(t) = \int_{t_0}^{t} (Inflow(s) - Outflow(s))ds + Stock(t_0)$$

$$ds/dt = Inflow(t) - Outflow(t)$$

Fig. 7.3 Mathematical structure of stock and flow diagram

7.4 Importance and Necessity

The ever-increasing demand for water every day is the result of agricultural development, overpopulation, and the rapid growth of industries. At the same time, the limitation of controllable water, as well as continuous demand growth, requires accurate planning for better water management and operation regarding this limited source. The existence of comprehensive understanding and the ability to predict circumstances help planners use these water resources more appropriately and achieve an optimal sustainable operation based on seasonal and climate conditions. However, multiple decision-makers and consumers with different priorities and interests in water resource planning and management issues create considerable disagreement and tensions over water resources allocation, which will be of much concern for managers and planners of this section. Today with the rapid development of computing tools along with the emergence of new optimization and simulation models, the application of systemic views has expanded in water resource planning and management and it has been made possible for complex systems to be analyzed better by recognizing and analyzing components and their connections. One of these methods is the System Dynamic (SD) approach. This method has been developed for the simplification of interaction between managers' models and analysts' official models. The main feature of this tool is to recognize and to show the feedback processes of consumers, flow structures, and time delays and considering nonlinear relationships to show system dynamics.

7.5 Materials and Methods

In the process of using system dynamics, there are five steps for each problem: 1. Statement of the problem; 2. development of a dynamic hypothesis; 3. mathematical expression of the simulation model; 4. testing the simulation model; and 5. policy or strategy of designer, experimentation, and analysis (Sterman 2000). This section describes these five steps.

7.5.1 Statement of the Problem

In order to have successful modeling first, problems must be identified and desired objectives must be specified. That is, the following should be specified in this stage.

- What is the problem? What is to be investigated, and why is it important?
- What are the essential variables and main concepts of the system?
- What is the time specifications for the implementation of the current study?
- How the system and essential variables behaved in the past and how is it predicted to behave in the future?

It can be seen that to recognize the problem; a complete description must be provided based on available reports, previous and current studies, expert opinions, historical and statistical records, and past behavior of the system. A thorough description of the problem provides a proper understanding by showing important and effective components for the researcher.

7.5.2 Development of a Dynamic Hypothesis

After identifying the problem, the next step is to develop a dynamic hypothesis based on the basic and initial behavior of the problem over time. The dynamic hypothesis is a conceptual model consisting of causal loop diagrams and state-flow diagrams or their combination. Therefore, at this step, policy structure diagrams, causal loop diagrams, and stock-flow diagrams should be defined.

7.5.3 The Mathematical Expression of the Simulation Model

At this step, the initial structure of the model is created by the above-mentioned tools. In other words, at this step, the relationship between these important and effective components is recognized and related parameters are formulated. Also, in this part, the initial value of variables and their possible estimation are determined, and the simulation model is ready to be implemented.

7.5.4 Testing the Simulation Model

After the simulation, it is necessary to check whether the model structure complies with the rules and decision-making processes of the system or not. Are the dimensions of equations used in the model compatible with each other? With changing in parameters, boundaries and, time intervals, will there be significant changes in numerical values, behavior, and policies?

One of the important tests is the comparison with historical data. In this test, the accuracy of the model in the simulation of a historical event can be determined. System dynamic modelers have prepared a variety of specific tests that help users to achieve a better understanding of the model. In following these tests, and their tool will be introduced.

7.5.4.1 Boundary Adequacy

This test examines model behavior change by stabilizing boundary assumptions and policy changing duo to model boundaries extension. This test also determines whether the basic and essential concepts can address the endogenous problems of the model or not. Using model charts, diagrams, model equations, use reports, expert opinions, archived documents, direct inspection or participation in system processes along with modifying the model to add appropriate additional structures and change constants and exogenous variables endogenous will help users in this test.

7.5.4.2 Structure Assessment

The purposes of this assessment are to examine the compatibility of model structure with descriptive principles and concepts of the system, level of aggregation, conformity of model to the physical laws, and the ability of decision rules to capture the behavior of system components. For this assessment, tools such as model charts (policy structure diagrams, causal diagrams, stock, and flow diagrams), model equations, reports, expert opinions, archived documents, and direct inspection or participation in system processes can be used. By conducting partial model tests and laboratory experiments, the rationality of decision rules can be evaluated, and the mental models and decision rules of system participants can be elicited. The development of disaggregate models for comparing with aggregate formulations and disaggregation of suspicious structures are the remaining tools and procedures of this assessment.

7.5.4.3 Dimensional Consistency

The purpose of this test is to evaluate the dimensional consistency of model equations without the using parameters which have no real-world meaning. For this test, dimensional analysis software and model equations investigation for finding suspect parameters can be used.

7.5.4.4 Parameter Assessment

The purposes of this assessment are to examine the compatibility of parameter values with descriptive and numerical concepts and principles of the system and inspect real-world counterparts of all parameters. For this assessment, statistical methods for parameters estimation, partial model tests for calibrations, judgemental methods, and development of disaggregate submodels are the primary tools.

7.5.4.5 Extreme Conditions

In this test, model equations will be tested by extreme values as input in order to evaluate their response to extreme conditions like extreme policies, shocks, and parameters. In this test, each equation must be investigated, and their response to extreme values of inputs, alone and in combination, must be analyzed. By subjecting model to large shocks and extreme conditions and implementing tests for examining model conformance to basic principles, model and system response to extreme conditions will be evaluated.

7.5.4.6 Integration Error

This test examines results sensitivity to time step choices or numerical integration methods. By changing the time steps and using different numerical integration methods, model behavior will be tested.

7.5.4.7 Behavior Reproduction

In this test, the model ability to reproduce favorite behavior of the system in terms of quantity and quality and generating different modes of observed behavior in the real system will be evaluated. Another purpose of this is to figure out the accordance between variables and data. Computing statistical measures between model outputs and observed data such as descriptive statistics, time-domain methods, frequency-domain methods, comparing model output and data qualitatively, and examing model response to test inputs, shocks and noises are the essential tools for this test.

7.5.4.8 Behavior Anomaly

In this test, the possibility of the model for resulting in abnormal behavior due to changing or deleting assumptions will be examined. By loop knockout analysis and replacing equilibrium assumptions with disequilibrium structures, this test can be implemented.

7.5.4.9 Family Member

In this test, the model ability to generate observed behavior in other instances of the same system will be evaluated by calibrating the model to a wide range of related systems.

7.5.4.10 Surprise Behavior

In this test, the ability of the model for generating previous unobserved or recognized behavior, and success anticipate of the system response to novel conditions will be tested. For this test, the user must keep accurate, complete, and comprehensive simulations records and also use the model to simulate the future behavior of the system. For better results, all disagreements between model behavior and user understanding of the real system must be resolved, also documenting components mental model prior to starting modeling.

7.5.4.11 Sensitivity Analysis

Numerical, behavioral, and policy sensitivity analysis are the main ones for dynamic models. Univariate and multivariate sensitivity analysis, analytic methods, model boundary and aggregation tests, and optimizations approaches are practical methods for performing these analyses.

7.5.4.12 System Improvement

The purpose of this test is to evaluate the modeling process effect on system improvement and designing, developing and creating instruments and appropriate controlling tests for modeling process evaluation, monitoring, and treatment are the essential tools in this test.

The mentioned tests were adopted and extended from Sterman (2000).

7.5.5 Policy or Strategy Designer, Experimentation, and Analysis

After validating the model, different scenarios are defined and implemented by the model for solving the problem. The purpose of these scenarios is to analyze different situations to achieve the best solution for the problem. In this point, the sensitivity of each parameter and the impact of policies on important variables are evaluated by investigating the connections between policies and different decisions.

7.6 Practical Examples

7.6.1 *Simulation of Drainage Water Quantity and Quality*

Nozari and Liaghat (2014) used SD to simulate water movement in soil and solute transport in saturated and unsaturated conditions in the presence of a drainage system. The predictive variables were water table fluctuations, drain discharge, drain water salinity, and groundwater salinity. In this study, the conceptual model which was defined for saturated and unsaturated zones and boundary conditions consists of infiltration and evapotranspiration from the soil surface, lateral seepage and, deep seepage. The results from this model can be used to manage and control drain water salinity and also to prevent environmental damage. Figure 7.4 represents the flowchart of the above-mentioned system.

The causal loop diagrams in this study are shown in Figs. 7.5, 7.6 and 7.7.

In the stock and flow structure of this model, important variables are layer, water table, and groundwater.

Figure 7.8 shows the stock and flow structure of the related problem.

In order to validate the model results, in addition to boundery condition testing and sensitivity analysis, a case study was conducted on ARC1-18, 25 ha research site,

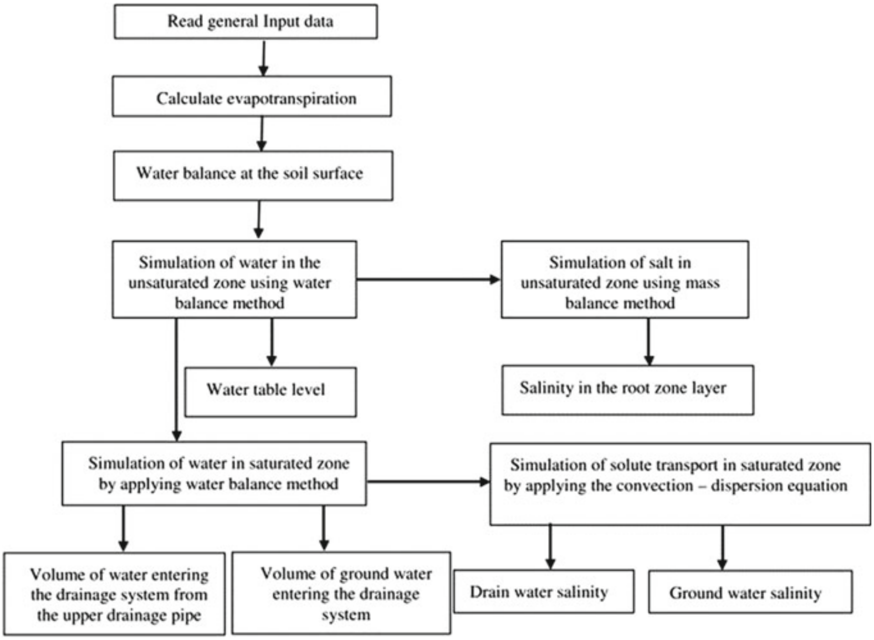


Fig. 7.4 Flowchart for the water table depth, drained volume, salinity of drain water and salinity of groundwater calculations

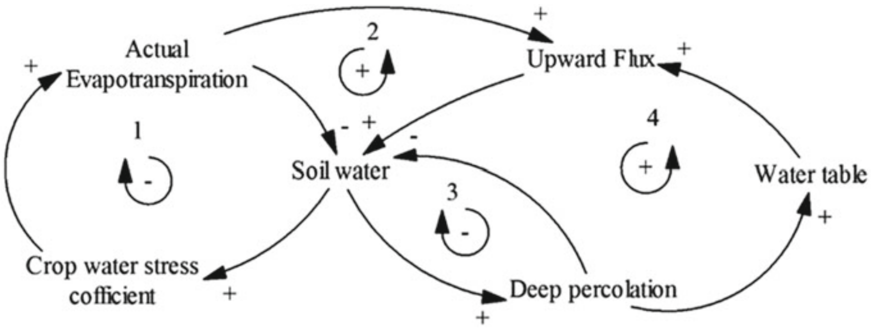


Fig. 7.5 Unsaturated zone causal loop diagram

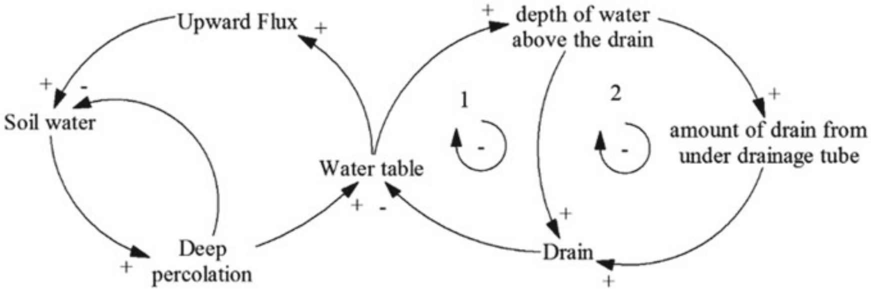


Fig. 7.6 Drainage performance causal loop diagram

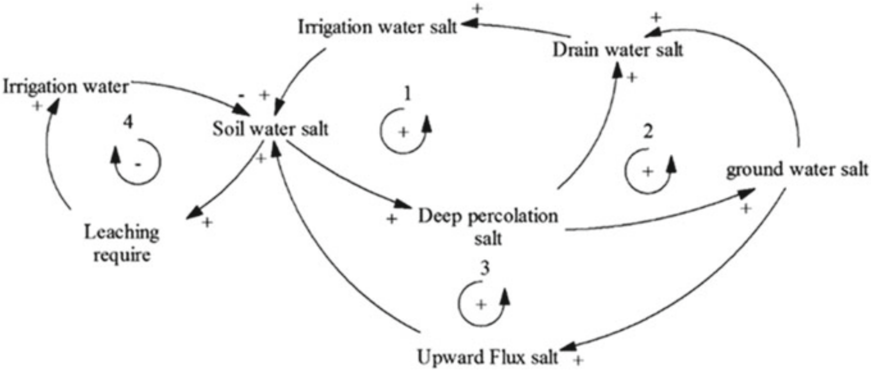


Fig. 7.7 Causal loop diagram for dynamic salinization model

located on Amirkabir Sugarcane Research Center, which is one of the seven units of the sugarcane development plan in Khuzestan, Iran. To evaluate water table fluctuations and groundwater salinity, three rows of piezometers were installed at distances of 100, 250, and 375 m from the collector. In every row, there were three piezometers

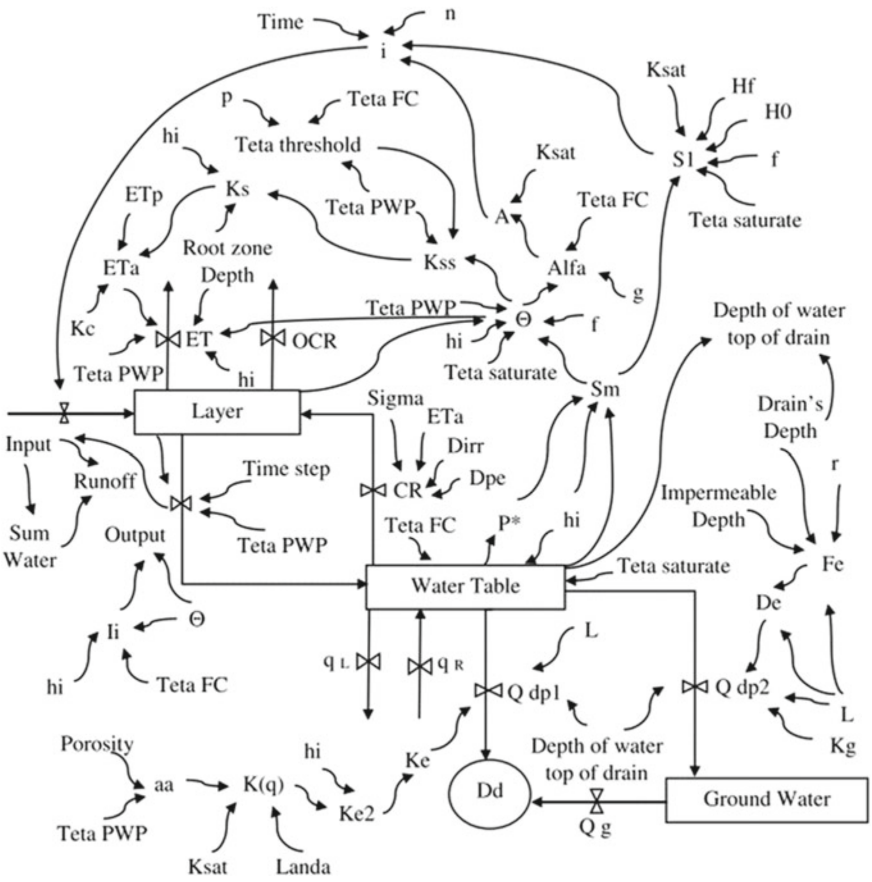


Fig. 7.8 Stock and flow structure

at depths of 0.2, 0.6 and, 1 m below the drain tube for collecting samples. During the irrigation period (April to September), parameters such as daily water table fluctuations, drain discharge, irrigation water salinity, piezometers water salinity, and drain water salinity have been recorded. In Table 7.3, the statistical indices show the comparison of the model results with the observed data. The results show an effective

Table 7.3 Standard error and relative standard error for different variables

Variable	Water table depth (cm)	Drainage flux (L/s)	Drain water salinity (dS/m)	Ground water salinity (dS/rn)		
				220 cm	260 cm	300 cm
SE	14.4	0.43	2.8	0.49	0.29	0.36
RSE	8	20	19	12.9	7.5	8.2
R^2	0.7	0.76	0.2	0.63	0.7	0.64

and acceptable performance of the model in simulating water table level, drainage discharge, and groundwater salinity.

7.6.2 Power Generation Simulation of a Hydropower Reservoir System: Case Study of Karoon Reservoir System

Jahandideh-Tehrani et al. (2014) used SD for calculating energy production in a hydropower reservoir system in several operational scenarios. Complex and nonlinear relationships characterize hydropower reservoirs, and variables such as storage volume, release, power production, and reservoir water level depend on each other. Therefore, the use of trial-and-error simulation or other methods based on a repeating loop is needed. This research has studied a three-reservoir system consisting of Khersan 1, Karoon 3, and Karoon 4 in Karoon river basin in Khuzestan, Iran. This system consists of a storage reservoir under study called Khersan 1 and two storage reservoirs under operation called Karoon 3 and Karoon 4. Figure 7.9. shows the location of these reservoirs.

The water released from the upstream reservoirs goes directly into the downstream reservoir and affects its energy production. Therefore, this study focused on hydropower reservoir systems and the effects of upstream reservoirs on the power generation of downstream reservoirs. Eight operational scenarios that involve different combinations of reservoirs are defined to calculate average values of power generation over a 44-year operational period. From eight defined scenarios, six scenarios are considered for an individual reservoir, and upstream reservoirs impact on downstream reservoirs and the other two scenarios are considered for multi-reservoir systems. These scenarios are as follows:

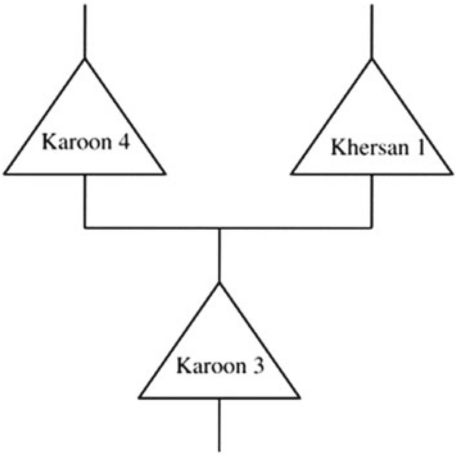


Fig. 7.9 Location of studied reservoirs Results

- Operational scenario 1 considers Khersan 1 individually with the condition that there are no other upstream or downstream reservoirs,
- Operational scenario 2 considers Karoon 4 individually with the condition that there are no other upstream or downstream reservoirs,
- Operational scenario 3 considers Karoon 3 individually with the condition that there are no other upstream reservoirs,
- Operational scenario 4 considers Karoon 3 individually with the condition that both Khersan 1 and Karoon 4 are located upstream,
- Operational scenario 5 considers Karoon 3 individually with the condition that only Khersan 1 is located upstream,
- Operational scenario 6 considers Karoon 3 individually with the condition that only Karoon 4 is located upstream,
- Operational scenario 7 considers power generation of the two reservoirs Karoon 4 and Karoon 3.
- Operational scenario 8 considers power generation of the three reservoirs Khersan 1, Karoon 4, and Karoon 3.

In this study, performance criteria such as reliability, vulnerability, and resiliency for each scenario are defined at three performance thresholds (100, 90, and 70%).

Figure 7.10 represents the stock-flow model diagram of a reservoir and the effect of variables on each other, and Fig. 7.11. represents the stock-flow model diagram of a reservoir at downstream.

Table 7.4 shows the results of performance criteria and average annual energy production of each operational scenario.

The results illustrate that scenario 8 has more average energy production in comparison with other scenarios. Although Khersan 1 is under study, comparison of

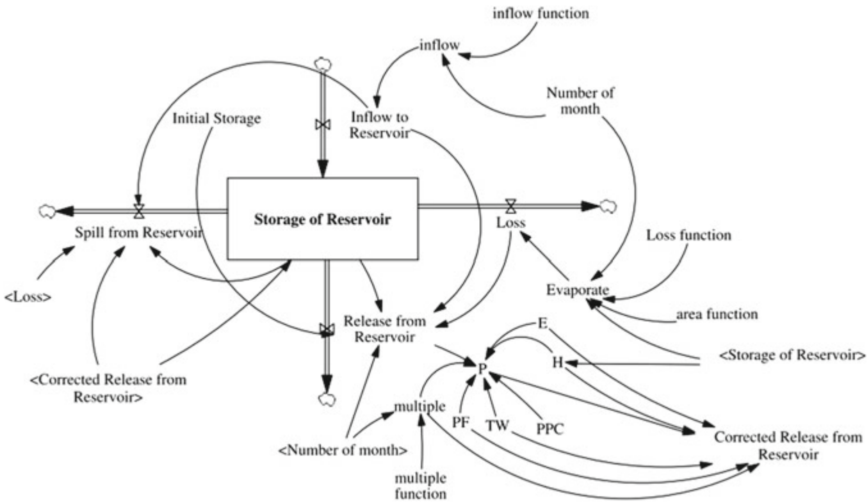


Fig. 7.10 Model of each single reservoir

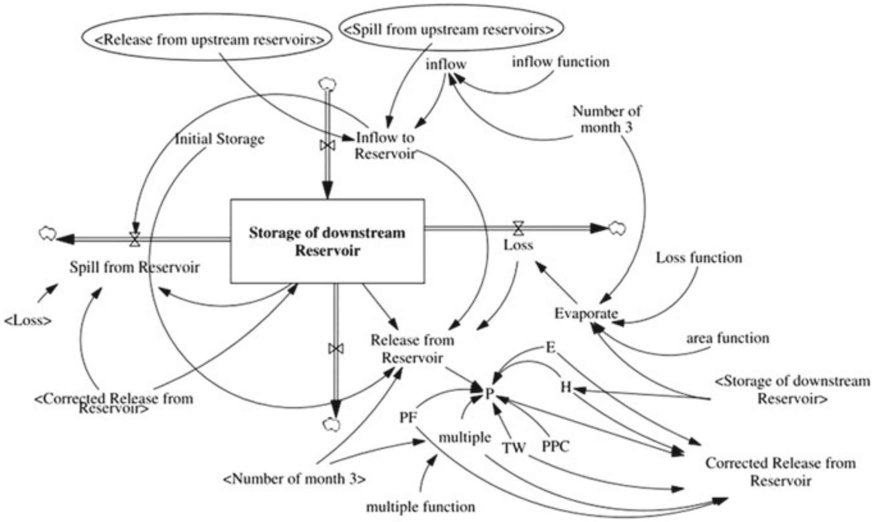


Fig. 7.11 Model of downstream reservoir in reservoir system model

Table 7.4 Performance criteria and average annual energy production of each operational scenario

Operational scenario number								
Performance criteria (%) and average annual energy production (109 W • h)	1	2	3	4	5	6	7	8
Time-based reliability 100%	41	87	36	32	36	31	31	19
Time-based reliability 90%	44	88	44	39	43	38	46	45
Time-based reliability 70%	53	90	56	51	56	51	61	63
Volumetric reliability 100%	72	94	70	70	70	69	78	77
Volumetric reliability 90%	75	95	73	73	74	73	82	82
Volumetric reliability 70%	83	96	79	81	79	81	91	90
Vulnerability 100%	28	6	30	30	30	31	22	23
Vulnerability 90%	25	5	27	26	26	27	18	18
Vulnerability 70%	18	4	21	19	21	19	9	10
Resiliency 100%	12	28	9	7	9	7	7	6
Resiliency 90%	15	28	14	10	13	11	12	12
Resiliency 70%	19	31	18	14	17	14	20	20
Average annual energy production	921	1,651	3,069	3,062	3,082	3,052	4,703	5,635

scenarios 7 and 8 show the importance of Khersan 1 construction. In other words, the addition of Khersan 1 to Karoon 4 and Karoon 3 reservoir system leads to higher average energy production and relative stability of performance criteria. Results of Table 7.3 shows that the average energy production in scenario 4 is less than that in scenario 3 because of water regulation and evaporation from upstream reservoirs, which reduce the average energy production in scenario 4 compared to that of scenario 3. Due to the presence of Khersan 1 in upstream of Karoon 3 in scenario 5, the average energy production of this scenario has increased compared to scenario 3. The presence of Khersan 1 in upstream of scenario 5, which stores water in the wet season and releases it during the dry season, has caused an increase in power generation and water storage in Karoon 3. In the wet season, due to the limitation of reservoir volume, scenario 3 loses more water by spillage than scenario 5.

The results of this study indicate that system dynamic has the ability for using in hydropower systems. It can also be highlighted that construction and addition of the Khersan 1 to Karoon 3 and Karoon 4 reservoir system increases energy generation by 20% during the 44-year simulation period, and regardless of construction costs, Khersan 1 can help to meet more energy needs during peak consumption periods.

7.6.3 Modeling of Reservoir Operations for Flood Management

(Ahmad and Simonovic 2000) prepared a general framework for modeling reservoir operations using the SD approach. Prepared model, developed for a single multipurpose reservoir with a focus on flood management role of the reservoir in order to develop a reservoir policy for high-flow years for minimizing flooding. Also, this model can be used as a tool for studying the impacts of changing reservoir storage allocation and temporal distribution of reservoir levels and outflows. This approach has been used for modeling reservoir operations of Shellmouth reservoir, located on the Assiniboine River, close to the Manitoba/Saskatchewan border in Canada. The flooding in the Assiniboine River, mainly caused by heavy spring runoff, has resulted in extensive damage to residential, agricultural, and industrial property. The Shellmouth reservoir was developed primarily to protect the cities of Brandon and Winnipeg from floods on the Assiniboine River, and supplementary benefits of the project include flood control to agricultural land. Release from the reservoir, which exceed the channel capacity, causes flooding at several locations along the river downstream of the reservoir. Due to the lack of existence of control structure on spillway for regulating reservoir outflow, the objectives of the simulation modeling study were defined as:

- Developing a reservoir operational policy for high flow years to minimize flooding.
- Exploring the impacts on the reservoir flood management capacity by installing gates on an existing unregulated spillway.

- Developing a tool for evaluating alternative operating rules by changing the reservoir storage allocation, the reservoir levels at the start of the flood season, and the reservoir outflow.

Figure 7.12 represent the schematic location of the Shellmouth reservoir, Assiniboine River and, cities at downstream of the reservoir.

Two causal loop diagrams were implemented in the structure of the reservoir dynamic model Fig. 7.13. Figure 7.13a illustrates the positive influence of inflow on the reservoir and an increase in reservoir storage causes an increase in the reservoir level, which causes flooding at the reservoir upstream. Figure 7.13b represent the storage reallocation, and by increasing flood storage zone in the reservoir, flooding will be reduced; however, it will also reduce the supply of water for other uses.

The implemented dynamic model for flood management can be divided into three main sectors: the reservoir, the upstream area, and the downstream area. A schematic diagram of the reservoir and its three sectors is shown in Fig. 7.14.

The results proved that system dynamics is a successful, user friendly, and effective approach for reservoir modeling. Alos researchers acknowledged that by revising

Fig. 7.12 Study Area

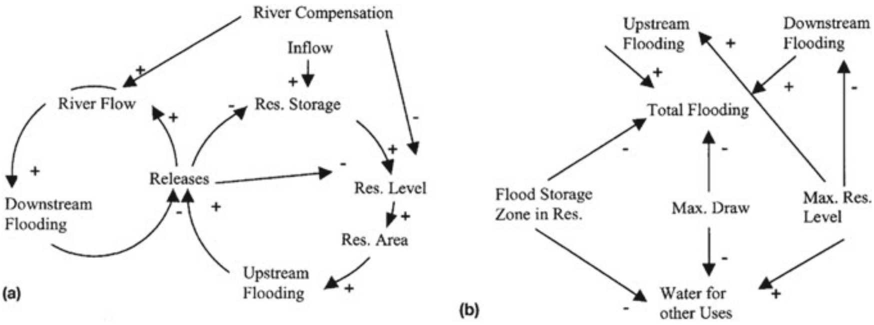


Fig. 7.13 Causal loop diagrams

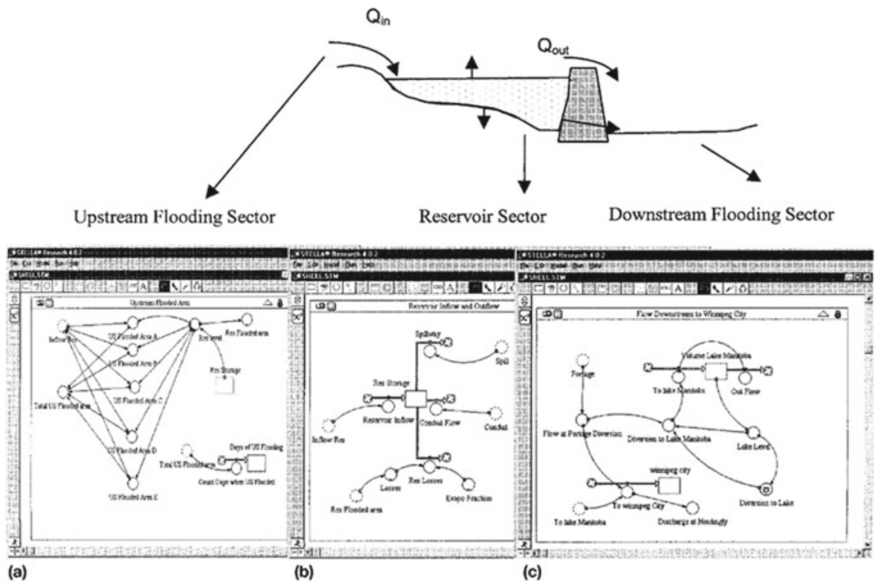


Fig. 7.14 Schematic diagram of reservoir with different sectors

operating rules, the capability of the Shellmouth reservoir for flood management can be improved. Due to the revision of the operating rules, the contribution of the Assiniboine River towards the flooding of Winnipeg City is negligible. At the end of this study and by considering the simulation of the shellmouth reservoir operation, it was recommended that the installation of gates on the spillway will improve reservoir flood management capacity, especially for large floods.

7.7 Summary

Water is one of the biggest challenges of this century, which can be sources of many positive and negative changes in the world. Due to the limitation of water resources as well as the development of industrial and agricultural projects along with population growth, which has made this vital resource unsustainable in many parts of the world. Thus, the optimal use and management of these resources have become particularly important. However, occasionally the adopted management solutions are not effective in improving the situation, and even our performance in solving the problem may lead to new problems after the implementation of the adopted policy. Because all possible feedbacks ranges are not considered in one system. In order to prevent adverse reactions to adopted policies and achieve the dynamic interrelationship between existing management systems, it is necessary to expand model boundaries by a comprehensive approach. For solving such problems, an analytical system with a decision-making system is required to model all involving processes in a complex system systematically. The characteristic of this approach is a system that can be divided into multiple subsystems to work together to achieve a specific goal. Also, by assuming the surrounding environment as a variable, the combination of solutions for solving the problem can be considered as variable, and with a systematic insight can solve such problems.

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