1 Overview of Environmental Systems

Chapter Objectives—
After you finish this chapter, you should be able to:

1. *Recognize many environmental phenomena as coming from dynamic systems.*
2. *Name the* ***four components of a system*** *and use those components to construct a simple model of a system.*
3. *Describe how* ***difference equations*** *are used to calculate the behavior of a dynamic system over time.*
4. *Distinguish between* ***systems thinking*** *and other kinds of thinking.*
5. *Explain how dynamic systems models can be used to understand environmental problems.*
6. *Define* ***feedback*** *and* ***steady-state behavior*** *and explain why these features are important to environmental systems.*

1.1 Introduction

This book is about change. In particular, it is about how our environment changes. The purpose of this text is to teach you how to model, understand, and analyze the dynamic nature of many real-life environmental phenomena. In doing so, it is our hope that you will develop an intuitive feel for the extraordinary collection of systems that govern the behavior of the environment. It is also our hope that you will learn to use some important tools for evaluating how human beings can potentially upset those systems or significantly alter their behavior.

This book is also about modeling. Virtually all environmental problems are inherently dynamic systems problems: They all deal with environmental phenomena that change over time (i.e., they are ***dynamic***) and involve numerous interrelated components (i.e., they are ***systems***).

Scientists who study environmental issues now commonly employ computer-based models of environmental systems to help them understand how the environment changes and to make predictions on how it will evolve in the future. These models are not academic curiosities. Their predictions help shape public policy, which in turn has significant impacts on the environment and the economy.

This is where you and this text come in. This book will help you more effectively participate in the scientific and political discussions of the environment by equipping you to describe and study environmental problems within a ***systems analysis*** framework. You will learn how to evaluate computer-based models of environmental phenomena, and then how to use those models to better understand the underlying systems and to predict future outcomes. You will also learn some of the underlying principles and thinking skills that are used to build these models.

In order to accomplish these goals, you must first learn to use some tools associated with systems thinking. This chapter introduces some of the basic systems modeling tools and concepts that we will use throughout the text.

1.2 An Example of a Simple System

We all use the word *system* in a variety of contexts in everyday conversation. In dynamic systems modeling, however, the concept of a system has a very specific meaning. We will use the term ***system*** in this text to refer to any collection of entities that includes the four components discussed in the following.

1.2.1 Reservoirs

A *reservoir* can be thought of as a repository where something is accumulated, stored, and potentially passed to other elements in the system. For example, suppose we wish to model the growth of a population of deer in a particular ecosystem. This model would possibly include a *vegetation reservoir* that represents the food supply of the deer. The system would also have one or more *predator reservoirs* representing the populations of predators that kill the deer. We would also include a *deer reservoir* to represent the population of deer. It is important to note that a reservoir does *not* represent a geographical location. Our deer reservoir should not be thought of as a location in which all the deer reside; rather, it is an accounting mechanism that enables us to keep track of how many deer live in the system at any point in time.

1.2.2 Processes

A *process* is an ongoing activity in the system that determines the contents of the reservoirs over time. Examples of processes in our deer population model might be:

- Birth process (process by which the deer reservoir increases in size)
- Death process (process by which the deer reservoir decreases in size)
- Predation process (process by which the predator stalks and kills the deer)

1.2.3 Converters

Converters are system variables that can play several different roles within a system. Their most important role is to dictate the rates at which the processes operate and therefore the rates at which reservoir contents change. An example of a converter is the ***birth rate*** of the deer population. This constant will clearly dictate the rate at which the ***birth process*** generates new deer. It will also affect the size of the deer reservoir over time.

1.2.4 Interrelationships

Interrelationships represent the intricate connections among all components of the system. These relationships are usually expressed in terms of mathematical relationships. For example, we can define a simple mathematical expression that describes the interrelationship among the birth process (i.e., the number of new deer born in a year), the birth rate, and the size of the deer reservoir. Suppose that the birth rate is equal to 0.2 deer born per capita per year. If we let $D(t)$ stand for the size of the deer reservoir in year t, then we can calculate the number of births in year t as follows:

$$\#\ \text{births} = 0.2 \cdot D(t)$$

The specific manifestation of the four system components listed previously depends on the context. Different combinations of these components will be used to model different systems. In addition, any given problem can involve one or more systems, each of which is interrelated with the others.

We will now further illustrate these concepts by constructing a simple model involving an imaginary group of 20 tourists (10 males, 10 females, and no children) who have been shipwrecked on an uninhabited and uncharted, but lush, tropical island. This group is hopelessly lost with no chance of rescue in the foreseeable future; hence, they will have to make the best of it. Let us suppose that they build a small village of huts and settle in for a new life of tropical living. Further suppose that one of these villagers is a systems modeler who has a laptop computer (solar powered, of course) along with the latest version of a systems modeling software package. This villager has decided to model the growth of this population of shipwrecked tourists to better understand how its future might unfold on this isolated island. In particular, the modeler wishes to determine:

- The conditions under which the population will survive and flourish, and the conditions under which it will die off
- The time frame over which the population would likely die off, if it should not survive
- The number of people that can be realistically sustained on the island.

Based on this description, the system with which the modeler is interested is the island ecosystem as it relates to the survival (or demise) of the population of shipwrecked tourists. Note that there are many "systems" that the modeler could study. For example, the modeler could model the ecosystem of the barrier reef around the island, or the weather system in the regions around the island. The list could go on and on. Whenever we focus our attention on the modeler's three goals as stated earlier, however, these other systems end up playing at most a secondary role. This assumption admittedly limits the scope of the model (after all, perhaps the ecosystem of the barrier reef will have some impact on the human population). We will err on the side of simplicity (an important principle of systems modeling), however, and then add more detail as needed. We will now discuss examples of the four components for this imaginary system.

1. The reservoirs. In order to identify the reservoirs in this system, we should always answer the following simple question: ***Are there important objects or entities in the system that will accumulate and (possibly) diminish over time?***

The modeler is clearly most interested in tracking the number of people that live on the island. In addition, the growth (or death) of the population is dependent on the long-term viability of the island's resource base. Both of these collections of entities can be expected to accumulate or deplete over time; hence, two important reservoirs for this example are:

- *First reservoir*: The human population on the island (measured as the number of individuals)
- *Second reservoir*: The island resources available for sustaining the human population (measured in generic resource units)

2. The ongoing processes. The processes are those activities (either natural or otherwise) that determine the size of the reservoir contents over time. In our island community, there are two basic processes that will dictate the size of the population of humans. There is a "birth" process, which increases the size of the population, and there is a "death" process, which decreases the population. These processes and the population reservoir can be represented graphically as shown in Figure 1.1.

Figure 1.1 illustrates some modeling conventions that we will use throughout this text. The reservoirs (e.g., *People on the Island*) are represented with rectangles (which we will also call ***stocks***). The processes (e.g., *Birth* and *Death*) are represented with directed double-line arrows and attached bubbles (which we will call ***flows***) that flow either into or out of the reser-

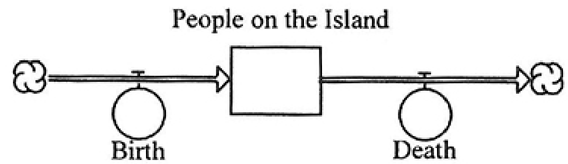


FIGURE 1.1. Population reservoir, with Birth and Death process.

voir. Flows into a reservoir will increase its contents. Flows out of a reservoir will decrease its contents. The reservoirs (stocks) represent stored quantities. The flows represent the processes by which those stored quantities are accumulated or diminished.

The value of each flow (or, equivalently, each process) is expressed as the amount of change it causes in the reservoir in one full-time unit. If time is measured in years, then the *Birth* flow will be expressed in units that correspond to the number of people born in 1 year. The *Death* flow will likewise, be expressed as the number of people that die in a single year.

This interpretation of the units of the flow processes and Figure 1.1 imply an important set of equations that dictate how our model will calculate (and hence predict) future contents of the *People on the Island* reservoir. In particular, the simulation model will calculate the contents of the reservoir at each point in time in the following way.

$$\text{Future contents} = \text{previous contents} + \text{all inflows} - \text{all outflows}$$

We can rewrite this using some simple mathematical variables. Let $R(t)$ stand for the contents of a reservoir at time t. Because the flow processes are expressed as the change in the reservoir contents in a full-time unit, we can calculate the future contents of the reservoir one unit ahead in time as follows:

$$R(t+1) = R(t) + \{\text{sum of all inflows} - \text{sum of all outflows}\}$$

If we wanted to predict the contents of R only one-half unit ahead in time, we would use the expression

$$R\left(t+\frac{1}{2}\right) = R(t) + \{\text{sum of all inflows} - \text{sum of all outflows}\}\cdot\frac{1}{2}$$

In general, if we wanted to predict the contents of R at a point in time that is Δt time units in the future, we would use the expression

$$R(t+\Delta t) = R(t) + \{\text{sum of all inflows} - \text{sum of all outflows}\}\Delta t \qquad (1.1)$$

Equation (1.1) is called the ***difference equation*** for the reservoir $R(t)$. A difference equation of a reservoir is an equation for calculating future values of the reservoir from past values.

For our island population model, the difference equation for the *People on the Island* is

$$\textit{People on the Island}\ (t+\Delta t) =$$
$$\textit{People on the Island}\ (t) + \{\textit{Birth}\ \text{flow} - \textit{Death}\ \text{flow}\}\Delta t \qquad (1.2)$$

There are two similar processes that will dictate the size of the *Island Resources* reservoir. To aid in clarity, we will give the inflow process the name *Renewal* and give the outflow process the name *Depletion*. Figure 1.2 presents a diagram representing these two processes and their associated reservoir.

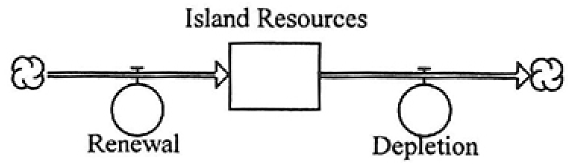


FIGURE 1.2. Island Resource reservoir, with Renewal and Depletion processes.

The choice of units for expressing the elements in Figure 1.2 is not as evident as it is in the case of the *People on the Island* reservoir and the *Birth* and *Death* processes in Figure 1.1. In fact, it is often the case that a natural choice of units is not obvious. In such a case, the model builder can arbitrarily create a new unit and define its meaning. For example, let the *Island Resources* reservoir be measured in a generic unit called a resource unit, where a resource unit stands for the amount of resources needed to sustain one person for a single month. If time is measured in years, then the *Renewal* and *Depletion* processes are expressed, respectively, as the number of resource units created or lost in 1 year. A single person would need 12 of these "resource units" to survive for 1 year.

In accordance with Equation (1.1), the underlying difference equation for calculating the contents of the *Island Resources* reservoir at any point in time is

$$\textit{Island Resources}\ (t + \Delta t) = \textit{Island Resources}(t) + \{\textit{Renewal}\ \text{flow} - \textit{Depletion}\ \text{flow}\}\Delta t \qquad (1.3)$$

3. Converters or system constants. The two sets of reservoirs and associated processes in Figures 1.1 and 1.2 comprise the "backbone" of our system. All other elements in our system will regulate the rates at which the processes in this backbone operate. These additional system elements are the converters. The converters will dictate, for example, that rate at which the *Renewal* process adds new resource units to the *Island Resources*, or the rate at which the *Depletion* process removes resource units. In order to identify the converters to include in our system, consider the following question: ***What additional quantities or system characteristics regulate the rates at which the processes run (thereby dictating the rates at which the reservoir contents change over time)?***

Consider the *Birth* process in Figure 1.1. This process dictates how many births occur in a given time interval. What determines the number of births? There are clearly complex biological processes involved; however, for our purposes, a way of calculating the average number of births that will occur in a given time interval is all that is needed. Some common sense suggests that the number of births in a given time interval ought to be proportional to the number of people in the population. If the population size were doubled, then we would expect the number of births also to double (all else being equal). We can write this relationship mathematically as:

$$\text{\# births} = b \cdot (\text{\# people in the pupulation}) \qquad (1.4)$$

This equation includes a constant, *b*, which will serve to regulate the number of births that are generated. The constant *b* represents the number of people born per person in the population each year. Hence, *b* is a birth rate, expressed in births per capita per year. We will add a converter to our model to represent the quantity *b* and give it the name *Birth Rate*.

Using similar reasoning, we can also determine that we need a converter in the system to represent the death rate, which is expressed in deaths per capita per year. Call this converter the *Death Rate*. Another converter (call it the *Renewal Rate*) regulates the rate at which the *Island Resources* are renewed. The second converter (the *Depletion Rate*) regulates the rate at which the *Island Resources* are consumed or lost. We will express the *Depletion Rate* as the number of resource units consumed by a single person per year. We can add these converters to our system by augmenting Figures 1.1 and 1.2, as shown in Figure 1.3. Table 1.1 summarizes the information in Figure 1.3 by listing each entity, along with its units.

4. Interrelationships between the reservoirs, processes, and converters. Now that we have formulated a first-draft schematic of the major components in our system (Figure 1.3), we need to specify how these components are interrelated. We will graphically display these relationships by using single-line arrows to show what we understand to be the cause-effect relationships among the components of the system.

You may have noticed that some relationships are already implied by Figure 1.3. For example, we have already pointed out that there is a relationship between each reservoir (stock) and its associated processes (flows).

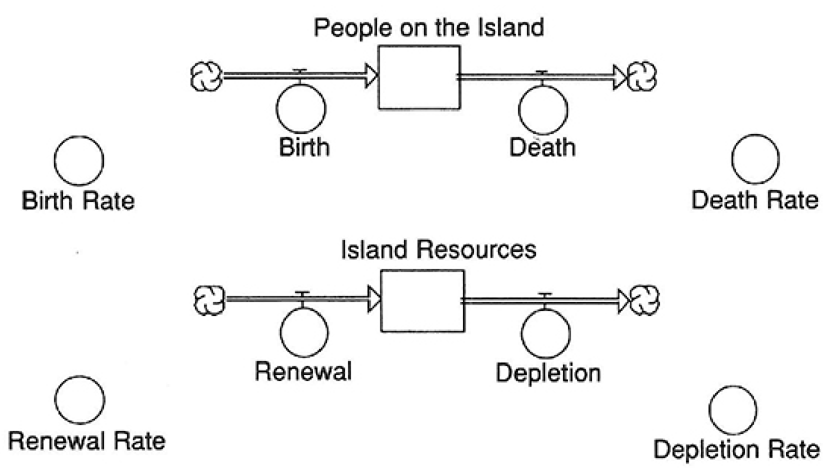


FIGURE 1.3. Island Community reservoirs, processes, and converters.

TABLE 1.1. Reservoirs, processes, and converters in the island system.

System entity	Type of entity	Units
People on the island	Reservoir (stock)	# people
Birth	Process (flow)	# people born per year
Death	Process (flow)	# people dying per year
Island resources	Reservoir (stock)	# resource units (1 unit = amount needed to sustain one person for 1 month)
Renewal	Process (flow)	# resource units added per year
Depletion	Process (flow)	# resource units lost or consumed per year
Birth rate	Converter	# people born per capita per year
Death rate	Converter	# people dying per capita per year
Renewal rate	Converter	# resource units added for each existing resource unit per year
Depletion rate	Converter	# resource units lost or consumed by each person per year

In fact, ***in every system model that we develop, we will always assume that the only system entities that can directly affect the values of the reservoirs are the inflows and outflows associated with that reservoir.*** It is important to note that other entities that are not flow processes can influence a reservoir's contents. The preceding assumption, however, requires that the only way other nonflow entities can affect a reservoir is by affecting the processes that flow into or out of it.

This assumption closely matches what you would expect in real life. Consider the *Birth* and *Death* processes that affect the population reservoir (see Figure 1.1). One could argue that something like the food supply (i.e., the *Island Resources* reservoir) will also affect the population of humans. The only way this will happen, however, is by affecting the *Birth* or *Death* processes into and out of the *People on the Island* reservoir (i.e., the only way to impact the size of a population is by affecting the number of births and deaths in that population). We have assumed, of course, that there are no emigration or immigration processes in this model: No one can leave the island, and no one can migrate onto the island.

Let us now see if we can specify which system entities are related to which. Remember that we will use a single-line arrow to show the direction of the relationship. The arrow will run from the entity that is the "cause" toward the entity that is "affected." We will refer to these single-line arrows as ***connectors***. The ***connectors*** are used to display the cause–effect relationships between the various entities in the system. Figure 1.4 gives a first cut at specifying these relationships. The numbers on the arrows are provided so that we can briefly discuss the rationale for each. In general, our system diagram would not include these numeric identifiers.

Explanation of the Connectors in Figure 1.4

- *Connectors 1 and 2* indicate that the number of births in the island community is a function of the *Birth Rate* and the number of people in

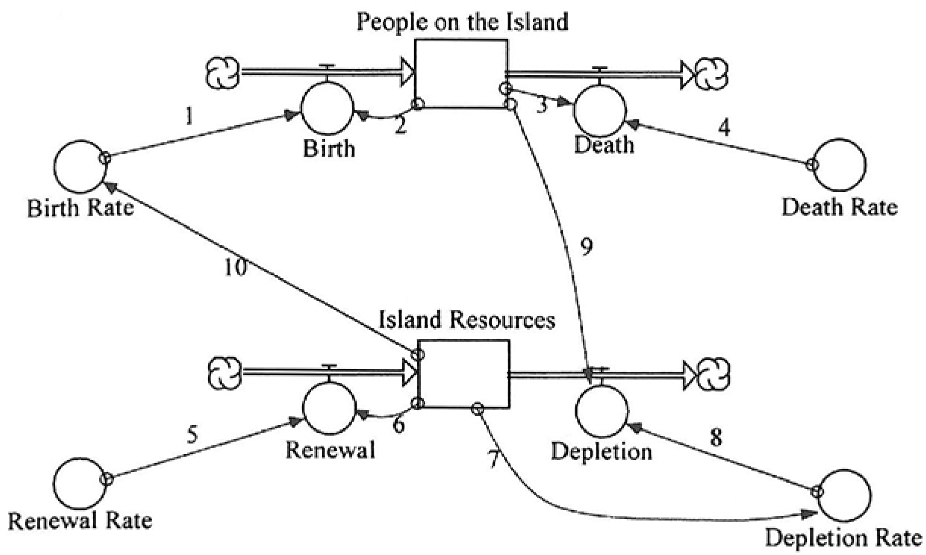


FIGURE 1.4. Island Community system diagram with connectors to show relationships between reservoirs, flows, and converters.

the population. This follows from the discussion leading up to Equation (1.4).

- *Connectors 3 and 4* are justified with the same rationale as connectors 1 and 2 [see the discussion following Equation (1.4)].
- *Connectors 5 and 6* imply that the number of resources that are added to the *Island Resources* reservoir is a function of only the *Renewal Rate* and the number of existing resources. This association makes sense if we consider the *Island Resources* essentially to be a renewable food supply. The growth of that supply will occur through natural processes that are analogous to a birth process in the human population (i.e., the more edible plants—or animals—on the island, the more "offspring" they will have over the year).
- *Connector 7* runs from the *Island Resource* reservoir to the *Depletion Rate* converter to indicate that the rate at which resources are consumed or lost depends on the size of the existing resource base. For example, it is likely that individuals in the island community will consume more resources per person whenever there is an abundant resource base than whenever the resource base is more scarce.
- *Connectors 8 and 9* signify that the number of resource units that are consumed or lost over any time interval is a function of the *Depletion Rate* and the number of *People on the Island*.
- *Connector 10* indicates that the *Birth Rate* in the human population is affected by the size of the existing resource base. This effect could come about because of conscious decisions by the island community to reduce the number of births in the face of limited resources. It could also come about because of the fact that limited resources may impact the overall

health of individuals in the population, thereby reducing their ability to bear children.

Once the connectors are drawn, our modeling friend must formulate mathematical expressions to explain how each quantity in the model is to be calculated at each point in time. The equations that dictate the size of each reservoir will have the general form that was given in Equation (1.1). If any other entity does not have any connectors or flows entering into it, then its value will typically be ***exogenous*** (i.e., not determined within the model, but defined by the model builder at the outset). If an entity has connectors running into it, then the modeler must specify how the inputs are to be used to calculate that entity's value.

For example, consider the *Birth* process in Figure 1.4. The diagram indicates that the number of births is a function of the number of *People on the Island* and the *Birth Rate*. That is,

$$\textit{Birth}\ \text{flow} = f(\textit{People on the Island, Birth Rate}) \tag{1.5}$$

We can determine the exact form of the function *f( )* in Equation (1.5) by considering the discussion leading up to Equation (1.4). Hence, the expression for the right-hand side of Equation (1.5) is

$$\textit{Birth}\ \text{flow} = \textit{Birth Rate} \cdot \textit{People on the Island} \tag{1.6}$$

Using similar reasoning, we can derive many of the mathematical expressions for the other system entities.

It is important to use mathematical expressions that are very simple and which match our common-sense understanding of how things work. It will often be the case that simple addition, multiplication, or division operations will do the job.

Figure 1.5 provides another version of Figure 1.4 with several of the mathematical relationships superimposed on the diagram. Some of the chapter exercises will require that you carefully examine Figure 1.5 and understand the mathematical expressions given. In addition, you will be asked to develop mathematical expressions for those entities for which equations are not given.

You may have noticed that the mathematical expression for two of the converters in our system in Figure 1.5 (the Birth Rate and the Depletion Rate) are not defined with mathematical expressions. Their numeric values are instead "provided by a graph." In some cases, the exact form of the mathematical relationship that defines a system entity may not be obvious; however, we can often describe the *shape* of the relationship between an entity and the quantities that determine it. For example, our system diagram indicates that the *Birth Rate* is determined by the value of the *Island Resources* reservoir. We cannot (at this point) credibly define a mathematical relationship in which the *Island Resources* value is used to calculate the *Birth Rate* value; however, the *Birth Rate* should decrease as the size of the *Island Resources* reservoir decreases. We could therefore construct a graph

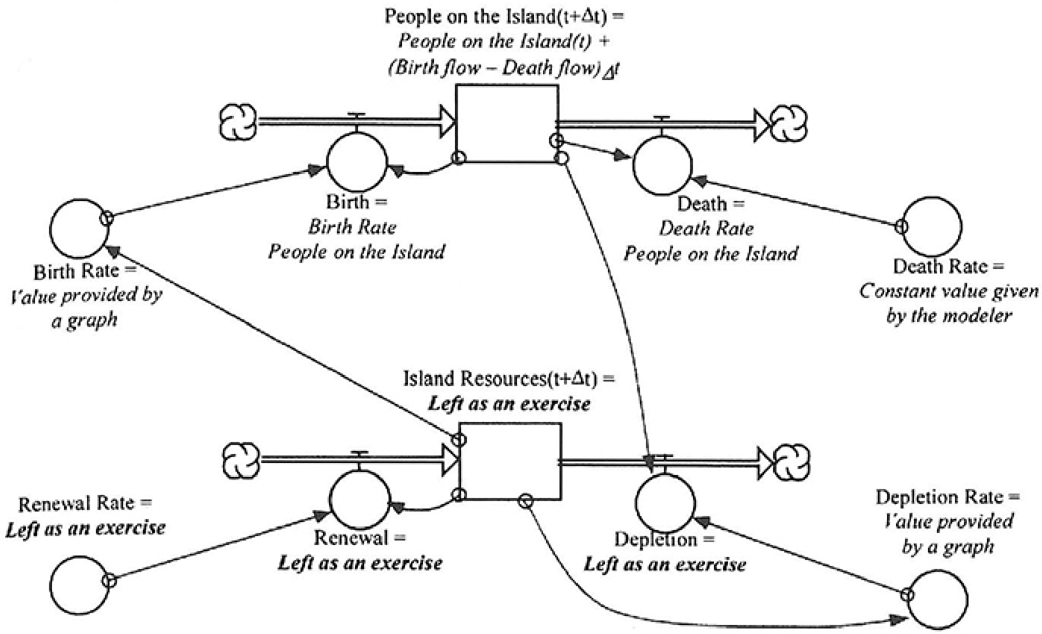


FIGURE 1.5. Island Community system diagram with some mathematical relationships defined.

in which the size of the *Island Resources* is on the *X*-axis and the ***Birth Rate*** is on the *Y*-axis. This graph should show an overall upward trend as the *Island Resources* reservoir increases. We would also expect that the ***Birth Rate*** would never drop below zero (a physical impossibility!) and that it would never increase beyond some theoretically maximum value (can you explain why?). Hence, the relationship between the ***Birth Rate*** and the *Island Resources* reservoir would probably look something like the graph in Figure 1.6. The scales on the *X* and *Y* axes in this graph must be specified

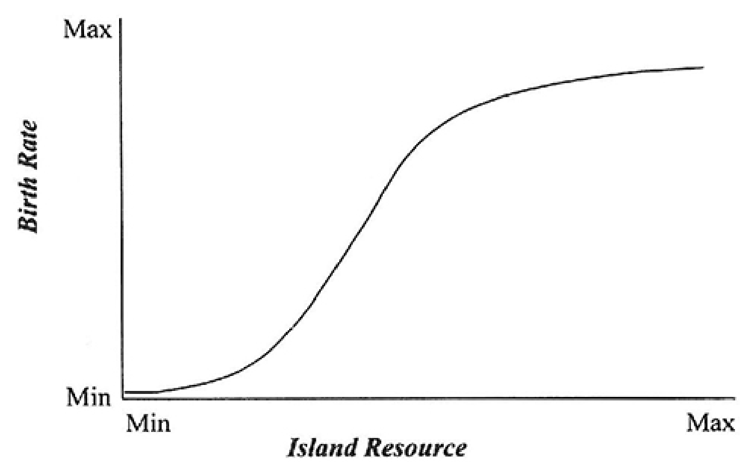


FIGURE 1.6. Suggested graphical relationship between Birth Rate and Island Resources.

by the modeler, based on an understanding of the *Island Resources* as well as an understanding of the reproductive capabilities and tendencies of the shipwrecked tourists.

1.3 Uses of Systems Models

The example model described in the previous section is a rather simple one. We hope, however, that you can see that the shipwrecked tourists on our imaginary island could find many practical uses for a valid and accurate model of their community. In fact, it is often the case that even simple models like the one discussed earlier can yield many useful insights that can in turn guide decision making and policy. To be sure, there are many simple and also some very complex models that are used by researchers and policymakers. How are these models used? Two important uses of these types of models are:

1. To understand the underlying mechanisms dictating how a system works
   - Describe the underlying processes and converters
   - Identify possible mechanisms behind observed cycles and long-term trends
   - Determine how the system maintains stability or identify mechanisms by which its stability is jeopardized
2. To predict future performance of an existing system
   - Project cycles and trends
   - Evaluate the impact of policy options
   - Identify scenarios by which system stability will be jeopardized or restored

1.4 A Systems Approach to Environmental Problems

1.4.1 A Definition of Systems Thinking

We now turn our attention to describing what we mean by ***systems thinking***. Our intent is to show how systems thinking differs from other approaches to studying environmental problems. We will then describe a conceptual framework for applying systems thinking to environmental problems in such a way as to integrate scientific principles with the impacts of technology and policy.

A simple example will serve to illustrate some of the distinguishing characteristics of systems thinking. One word of caution: By defining systems thinking we are not implying that you are either a "systems thinker" or that you are an imbecile. The truth is that most of us have already used some sort of systems thinking. For example, if you have ever had to coordinate a large project involving several components and possibly several different people (like building a house), then you have had to employ some systems thinking.

Suppose that you decided to build a house and that you hired a general contractor named Roger OneStep.You contracted Roger because he was a great finishing carpenter. You had seen some of his work and were particularly impressed with his kitchen cabinets; however, problems soon appeared. Roger did not seem to know where to begin. He was great with cabinets, but he did not understand how all the elements of a new home (e.g., floor plan, materials, heating/cooling systems, etc.) were supposed to fit together. You quickly negotiated a new contract, in which Roger would build and install only your kitchen cabinets.You also identified a new general contractor,Wally WholePlan. Wally made it clear to you that he was not an accomplished finishing carpenter (like Roger), however, he did understand all the components of a successful home construction project. He knew how all the parts of a house fit together to make a dwelling with which you would be pleased.

Wally WholePlan represents the systems thinker in this story. Roger OneStep represents the individual who does not use systems thinking, but who has a thorough understanding of one component of the system of house construction. It is clear from the story that both types of thinking are necessary. It is also clear that these two types of thinking are indeed different from one another. Our emphasis in this text is on developing your systems thinking skills, particularly in the context of environmental modeling and policy analysis.You should keep in mind, however that our focus on systems thinking should not be taken as a de-emphasis on the more specialized type of thinking embodied by Roger OneStep.

We will now discuss six viewpoints and assumptions that characterize systems thinking. Many of these characteristics are not unique to systems thinking; however, all six taken together comprise a powerful approach to analyzing and understanding environmental issues.The six characteristics are:

1. Systems thinking begins with a global description and moves toward the specific. For instance, consider the depleting ozone layer in the upper stratosphere. This ozone layer protects us from ultraviolet radiation, yet some chemicals produced by humans have been causing this protective layer to decrease for decades. The systems thinker might first characterize changes in stratospheric ozone in terms of general processes like "atmospheric convection," "ozone formation," and "ozone depletion," and then move toward a more specific description of each process, as needed. A chemist, on the other hand, might begin by describing in detail the photochemistry behind ozone formation. A meteorologist might begin by describing the atmospheric flows that affect ozone levels. To be a systems thinker, you must first grasp the BIG picture.

2. Systems thinking focuses on dynamic processes. The systems thinker interprets system behavior as the product of possibly numerous underlying processes that are always changing and moving. The systems thinker recognizes the dynamic processes of the system. For example, in our ozone depletion example, a systems thinker would consider both the present level of ozone concentrations as well as the factors affecting these concentrations and how these factors might change or have changed over time.

3. Systems thinking seeks a closed-loop explanation for how things work. The systems thinker attempts to define the system so that its behavior is dependent on only the elements within the system (i.e., system behavior is not dependent on things outside the system). The systems thinker tries to capture all the important factors in his/her systems model while avoiding unnecessary complexity. Factors that are truly outside the system, or which cause little if any effect on the system, are ignored and not considered.

4. Systems thinking identifies feedback loops. The systems thinker assumes that the flow from cause to effect is not in one direction. According to this thinking, changes at point A in the system will cause changes at point B (and possibly elsewhere), which then cause changes that eventually come back to influence point A again.

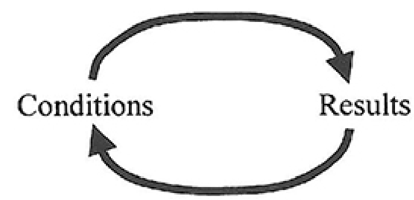
5. Systems thinking looks for checks, balances, and potential for runaway processes. Many systems involve some competing processes or feedback loops that tend to "compete" (e.g., *Birth* processes and *Death* processes). In such cases the system may eventually stabilize around a constant set of conditions. Other systems involve processes that can run "out of control." The systems thinker seeks to identify those competing or runaway processes, and to understand how they work to affect the overall system.

6. Systems thinking focuses on causal relationships. The systems thinker defines relationships among the elements of the system to reflect true cause–effect relationships. For example, a model that predicts the number of drowning deaths on a given day from the revenues of ice cream sales might give reasonably accurate predictions. This model, however, does not represent a causal relationship (buying ice cream does not cause one to drown!). Hence, the systems thinker would not incorporate such a relationship in his/her model.

An individual who studies environmental problems from a systems perspective is someone who describes what is observed in nature in terms of ever-changing, interdependent processes and conditions. This individual understands the behavior of the environment as coming from the ongoing, dynamic give-and-take between those underlying components. In addition, the systems thinker pays attention to identifying sources of feedback in the system and the conditions under the system will reach a steady state or run out of control.

This approach to understanding environmental problems is facilitated by using the simple modeling constructs of reservoirs, processes, converters, and connectors that were described earlier in this chapter. In addition, it is also clear that using a systems approach requires that we understand the concepts of feedback and steady-state behavior.

FIGURE 1.7. Feedback: A closed-loop circle of cause and effect.



1.4.2 Definition of Feedback

A ***feedback loop*** in a dynamic system can be defined as a closed-loop circle of cause and effect in which "conditions" in one part of the system cause "results" elsewhere in the system, which in turn act on the original "conditions" to change them. This is represented schematically in Figure 1.7.

Feedback is very common in dynamic systems. For example, consider the island population model introduced in Section 1.2 and reproduced in Figure 1.8. This system includes several feedback loops. One such loop is highlighted in the figure.

The size of the *Island Resources* (a "condition") affects the *Birth Rate*, which thereby affects the number of births in the *People on the Island* (a "result"). If this causes an increase in the size of the *People on the Island*, then more *Island Resources* will be consumed by the increased number of people on the island. This is shown in the model by the connector running from the *People on the Island* to the *Depletion* process flowing out of the *Island Resources* stock.

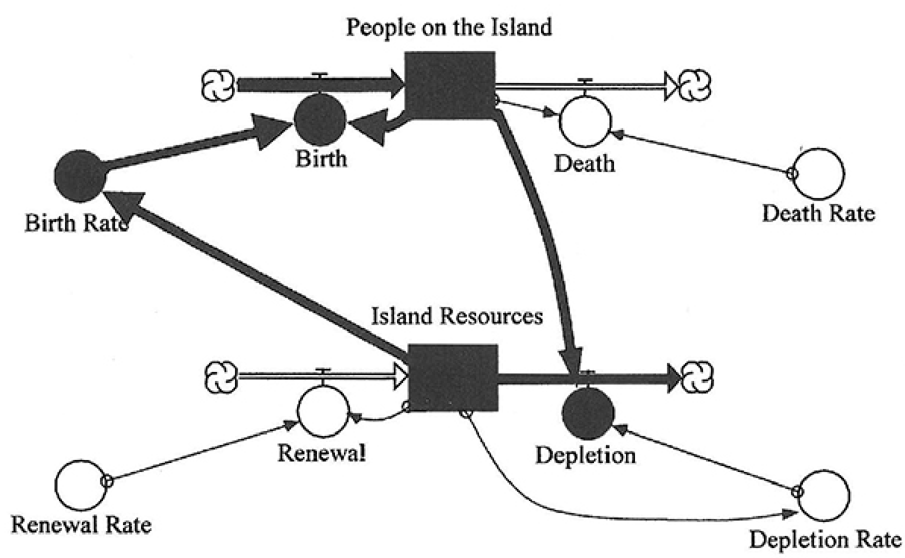


FIGURE 1.8. Island Community system diagram example of feedback highlighted in bold.

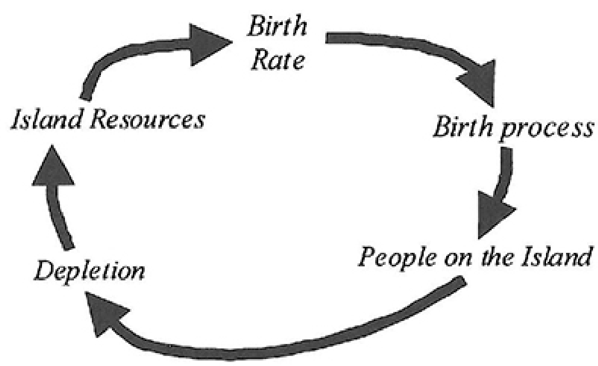


FIGURE 1.9. Example feedback loop in the Island model.

This feedback loop is also shown in a slightly different way in Figure 1.9. The designation of the "conditions" and the "results" in this loop is arbitrary. The important thing is that any node on this loop can be seen to "cause" results at the next node, which in turn eventually come back to affect the original node.

There are two types of feedback loops that can occur. These are (1) ***positive feedback*** (also called ***reinforcing feedback***) and (2) ***negative feedback*** (also called ***counteracting feedback***). Both types are common in the environment. In fact, being able to recognize and distinguish between these two types in a real-life environmental system can lead to significant understandings of how the system works.

1.4.3 Positive Feedback

Positive feedback (also called ***reinforcing feedback***) exists whenever changes at one point on a feedback loop eventually work their way back to reinforce or amplify the original change. Such systems tend to eventually run out of control. Many environmental problems are closely associated with naturally occurring positive feedback loops whose influence on the overall system has been accentuated by changes due to human activity.

One example of a positive feedback loop can be found in models of global climate change. It is hypothesized that increases in carbon dioxide (CO_2) emissions into our atmosphere will cause the earth's global temperature to rise (a phenomenon we will discuss in detail in a later chapter). This in turn will reduce the ability of the earth's oceans to hold gaseous CO_2, thereby causing the oceans to release additional CO_2 into the atmosphere. This additional increase in atmospheric CO_2 will lead to further warming, which will then lead to even more CO_2 released from the oceans, and so on. According to this theory, increased CO_2 levels (e.g., from the use of fossil fuels) could lead to a "runaway" accumulation of CO_2 in the atmosphere, thereby leading to increased global temperatures and eventual breakdown of the world's ecosystems. The diagram for this feedback loop is shown in Figure 1.10.

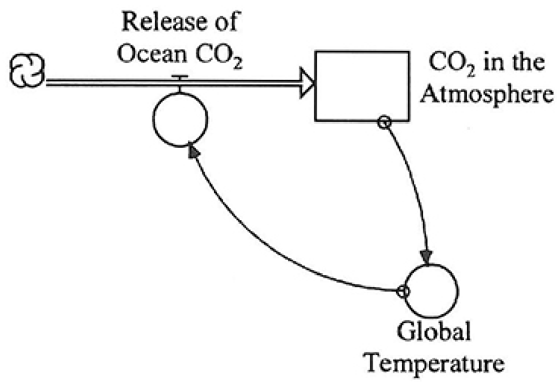


FIGURE 1.10. Global warming positive feedback loop.

1.4.4 Negative Feedback

Negative feedback (also called ***counteracting feedback***) exists whenever changes at one point on a feedback loop eventually work their way back through the system to counteract or "damp out" the original change.

Such systems tend to be self-regulating and are not as prone to run "out of control." Naturally occurring predator-prey ecosystems typically include negative feedback loops. Negative feedback loops help many environmental systems remain stable. In fact, some environmental problems can be attributed to the breakdown of naturally occurring negative feedback loops. Whenever these loops do break down, then the system can lose its stability and can begin to behave in ways that lead to an eventual collapse of the system. For example, take the feedback loop depicted in Figures 1.8 and 1.9. If the size of the *People on the Island* reservoir increases, then the *Island Resources* will be more rapidly consumed. This will in turn reduce the Birth Rate, slowing or even reversing the overall growth of the *People on the Island*. Hence, an initial change at one point the loop (i.e., an increase in the *People on the Island*) eventually works to counteract or "damp out" the original change (i.e., the Birth Rate is reduced and the *People on the Island* either increase more slowly or even decrease).

1.4.5 Steady-State Behavior

Another important type of behavior that occurs in many systems is referred to as ***steady-state behavior***. Systems that exhibit steady-state behavior eventually "level off" so that the system reservoirs either change very little or remain constant. When a system finally "levels off" in this fashion, it is said to have ***reached steady state***. A system has reached steady state whenever the rates at which its reservoirs change approach zero.

Most environmental systems operate at or near a steady state (i.e., the environment is relatively stable). The underlying systems in the environment often exhibit just the right mix of positive and negative feedback so that the system never runs "out of control." It is important to identify those conditions under which a system will exhibit steady-state behavior. In doing so, we can determine those conditions that must be maintained in order for the environment to maintain its remarkable resiliency. On the other hand, we also need to know conditions under which a system will not exhibit steady-state behavior or when it will "run out of control." In doing so, we can determine what impacts we can have through technology or policies to either upset or help maintain stability in the environment.[1]

A reservoir exhibits steady-state behavior whenever a graph of that reservoir's value versus time is a flat (horizontal) line. In other words, whenever a reservoir exhibits steady-state behavior, its rate of change with respect to time is equal to zero. We can use this fact to develop a simple strategy for analyzing the conditions under which a reservoir achieves steady-state behavior. This strategy depends on the use of elementary calculus.

Recall that if $R(t)$ is the value of a quantity at time t, then $\frac{dR(t)}{dt}$ stands for the instantaneous rate at which the quantity $R(t)$ is changing with respect to t. We refer to $\frac{dR(t)}{dt}$ as the ***derivative*** of $R(t)$ with respect to t. The derivative provides a powerful tool for analyzing the behavior of a reservoir over time. The sign of the derivative indicates whether $R(t)$ is increasing or decreasing over time. Moreover, the larger the magnitude of the derivative, the faster $R(t)$ is changing. For example, if $\frac{dR(t)}{dt} > 0$ at a particular time t, then we know that $R(t)$ is increasing at that point in time. If $\frac{dR(t)}{dt} < 0$, then $R(t)$ similarly is decreasing at that point in time. If $\frac{dR(t)}{dt} = 0$, then $R(t)$ is holding at constant value (at least for an instant). Hence, if $R(t)$ has achieved a steady state after some point in time, then we know that $\frac{dR(t)}{dt} = 0$ during that steady-state period.

This interpretation of the derivative of a reservoir leads to a simple strategy for identifying those conditions under which the reservoir achieves steady-state behavior. This strategy will briefly be described. We will illustrate its use in Chapter 2.

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[1] Note that we are using the terms *stability* and *steady state* somewhat interchangeably here. These concepts, however, are not equivalent. For example, many predator–prey populations exhibit oscillatory behavior through time. This behavior is stable (i.e., it does not "run out of control"), but it is not the same as steady-state behavior (i.e., the populations do not hold at constant, unchanging levels). For the purposes of this present discussion, however, this distinction is not important.

1. Develop the systems diagram
2. Use the systems diagram to develop the difference equation for the reservoir of interest
3. Use the difference equation to develop an expression for the derivative of the reservoir with respect to time.
4. Determine conditions under which the derivative is equal to zero.

These four steps require that we develop a mathematical expression for the derivative of each reservoir in the system in order to determine the conditions under which that system will reach steady state. This mathematical expression will be an equation that we will refer to in this text as the ***rate equation*** for the reservoir. The ***rate equation*** of reservoir $R(t)$ is a mathematical equation for determining the derivative of $R(t)$. That is, the rate equation will have the general form

$$\frac{dR(t)}{dt} = \ldots$$

where the right hand side is some sort of mathematical expression. We find the steady state conditions by finding the expression for the right hand side of the above equation. Then we use basic algebra and common sense to find conditions under which that expression evaluates to zero. This is the process referred to in the four steps given above.

How do we find the rate equation for a reservoir? This is done rather simply by beginning with the difference equation for the reservoir. Recall that the difference equation for a reservoir $R(t)$ is given by Equation (1.1). This equation is reproduced here for clarity.

$$R(t+\Delta t) = R(t) + \{\text{sum of all inflows-sum of all outflows}\}\Delta t$$

Recall from elementary calculus that the derivative of $R(t)$ is defined by

$$\frac{dR(t)}{dt} = \lim_{\Delta t \to 0} \frac{R(t+\Delta t) - R(t)}{\Delta t}$$

By subtracting $R(t)$ from both sides of the difference equation given earlier and then dividing by Δt, the difference equation is transformed into the equation

$$\frac{R(t+\Delta t) - R(t)}{\Delta t} = \{\text{sum of all inflows-sum of all outflows}\}$$

By taking the limit of both sides as Δt approaches zero, we find the following expression for the derivative of $R(t)$.

$$\begin{aligned} \frac{dR(t)}{dt} &= \lim_{\Delta t \to 0} \frac{R(t+\Delta t) - R(t)}{\Delta t} \\ &= \lim_{\Delta t \to 0} \{\text{sum of all inflows-sum of all outflows}\} \\ &= \{\text{sum of all inflows-sum of all outflows}\} \end{aligned}$$

Hence, the rate equation for any reservoir $R(t)$ is given by

$$\frac{dR(t)}{dt} = \{\text{sum of all inflows-sum of all outflows}\}$$

It is often the case that the right hand side of this equation involves fairly complicated expressions. Nonetheless, regardless of the type of system studied, the derivation of the rate equation for any reservoir in the system will have this general form. We will use this approach throughout the text to derive the rate equations and steady state conditions for the systems covered in this text.