TYPES OF ENVIRONMENTAL MODELS

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Summary

Environmental systems are generally characterized by four main features.

(i) Environmental systems generally depend on complex nonlinear interactions of different system components.
(ii) The main forcing variables or states of environmental systems, such as those related to climate, topography, soil types or population density are commonly extremely heterogeneous, varying over fairly small temporal and spatial scales. This means that data collected at larger scales is often insufficient to fully characterize the variability of the system.
(iii) The characteristic temporal and spatial scales of environmental system components are often incompatible, meaning that it presents challenges for combining models of different system components.
(iv) Many environmental systems are inaccessible, or their processes are unobservable, for example groundwater behavior cannot be observed directly; rather it must be inferred using sparse measurements. As well, observations are typically error-laden. This can limit human understanding of environmental processes and can impede the creation of accurate system models.

Three main types of models are used to model environmental systems: empirical, conceptual and process-based models. These model types differ in complexity, with empirical models generally being considered to be the most simple model type, used for describing aggregate processes, and process-based models being the most complex model type, generally containing a large number of spatially distributed parameters. Conceptual models are considered to have a complexity between these two model types. Different types of models are more commonly used with different environmental systems. For example, climate models tend to be very complex process (physics) models containing a very large number of parameters and modeling over very large distributed spatial scales. Empirical or stochastic models are more commonly used in areas such as ecological modeling, to model population or biodiversity.

1. Introduction

An environmental system is an arrangement of a number of separable biological, physical, or chemical components, as well as social and economic components, that interact with each other as a part of the Earth's environment. Examples of environmental systems include the atmosphere and oceans, populations of plants and animals and catchments. Many problems are currently being observed in environmental systems. These include the potential for global warming due to the effects of industrialization on the atmosphere, increasing salinization of land and water systems and the extinction of many species. Models of environmental systems have been developed for a broad range of applications and environmental issues. A discussion of the types of environmental models available first requires consideration of the types of environmental systems for which models have been developed. Different types of modeling approaches and distinct issues and problems are associated with particular environmental systems. Consideration of types of environmental models also requires an understanding of the purposes of modeling different environmental systems. There are a number of common features of environmental systems which affect the types of modeling approaches which are used and the problems encountered when modeling environmental systems.

2. Common Features of Environmental Systems

While the term "environmental system" covers a myriad of possible systems and processes, including land, ocean and atmospheric based systems, there are a number of features which are common to almost all environmental systems, regardless of whether they are physical, biological, or chemical in nature.

2.1. Complex Nonlinear Interactions

Environmental systems generally consist of complex nonlinear interactions between different system features. Environmental systems are driven by the interaction of physical, chemical, biological, social, and economic processes. For example, water quality in a stream relies upon land use and management in a catchment. However, decisions on land use will depend on land suitability, which is a function of rainfall, temperature, topography, and soils, as well as on economic, social and cultural features of the individual catchment. The interaction between these different processes is complex and often poorly understood. This complexity can mean that it may be difficult to capture many of the underlying causes and effects of environmental phenomena. Simplifying assumptions about the way in which these factors interact must generally be made when modeling, and important system components, such as social and economic drivers are often ignored. Fairly complex relationships that are only partially understood must often be represented in models by simplified relationships, limiting the accuracy of model results.

2.2. Heterogeneity of System Features

Important characteristics of environmental systems vary both spatially and temporally over a variety of scales. Characteristic scales of component processes of environmental systems may be extremely small, as is the case for some ecological systems where spatial scales may be less than one millimeter and temporal scales may be over seconds to hours, to very large systems, such as those found for some ocean or groundwater processes where spatial scales may be in the order of hundreds or thousands of kilometers and temporal scales may range over decades or centuries, or longer. In many cases these heterogeneous features are difficult or even impossible to characterize with the limited observational data that are available. Where data is available, it is often subject to a great deal of error and uncertainty. In addition the frequency with which data is sampled is often inadequate to capture the dynamics of the environmental system. This can mean that models are difficult to parameterize at appropriate scales. This can lead to a large number of parameter values being estimated through calibration against observed data, leading to problems of model identifiability, or may mean that measured data is used to represent a much larger area than is warranted by the heterogeneity of the system process, limiting the physical interpretability of parameters and raising questions about model accuracy.

2.3. Incompatible Scales

The characteristic temporal and spatial scales of different features of most environmental systems vary, making it difficult to create truly generic models of environmental systems. For example, the system response to a rainfall event in a surface water system such as a river or stream may occur over hours or days, whilst the response of the groundwater system to this recharge event may occur over a number of years, even though these two systems are linked. The characteristic temporal scales of these two systems are very different, so that a model linking these two systems will have to find a compromise between these two scales. To further complicate the modeling problem the climatic process which provided the rainfall event probably occurred on a different temporal and spatial scale from each of the hydrological systems. Thus an important consideration when modeling environmental systems is the scales at which to model the system components. This involves making decisions on what processes should (and shouldn't) be modeled in a system, and on what features need to be considered exogenous to the model. Boundaries on the different components which are represented in a model have to be set.

2.4. Inaccessible or Unobservable System Processes

Important processes or features of environmental systems are often inaccessible or unobservable. This may be because the scale of component processes is very large or very small, as is the case with many oceanic systems which may cover thousands of square kilometers, or may be because of other difficulties in obtaining measurements or physical observations of system processes, such as is the case with many groundwater systems. Knowledge or these systems is generally indirect, obtained through measurement of a limited number of characteristics which relate to system processes. The inaccessibility of these features limit human understanding of these processes, and the accuracy of models of these environmental systems. Processes for which there is limited knowledge are generally modeled using simplified empirical representations.

3. Types of Environmental Systems

Given these common features, individual systems vary in terms of key processes, characteristic scales and other important system features, which critically affect the type of models that will be required. Different systems tend to be modeled in different ways. The modeling problems that arise may differ between types of environmental systems, and are often overcome differently.

Environmental systems can be split broadly into at least three main categories of systems: hydrological, ecological and climatic. These systems are not entirely independent of one another, and may in many cases be subsets of one another. For example surface water hydrological systems are often a component of much larger climatic systems. However for the purposes of modeling, these systems are often treated separately.

3.1. Hydrological Systems

Hydrological systems consist of a number of individual systems including: surface water systems; subsurface systems; and coastal systems. These systems are not entirely independent of one another. Drainage from the surface water system contributes to recharge of the groundwater system. Discharge from the groundwater system contributes to lakes and rivers. Water and pollutants from the rivers and from runoff in coastal areas flow into the sea and contribute to coastal systems. These interactions can be seen in Figure 1, which is a diagram of the hydrological cycle.

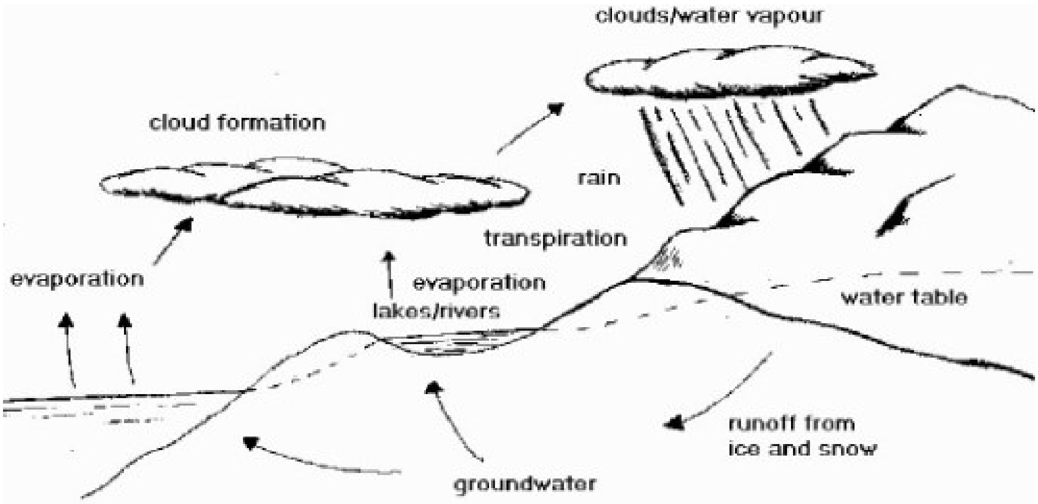

Figure 1. The hydrological cycle.

3.1.1. Surface Water Systems

Streamflow yields in a catchment system depend on a number of key climatic and landscape features. The amount of runoff that can be generated in a catchment depends on climatic features such as rainfall distribution and seasonal patterns, and evaporation. Streamflow and related contaminant, and pollutant loads, also depend on landscape factors such as topography, land use, soil type and land management. Different types of vegetation provide different densities of groundcover, affecting the amount of water that evaporates off the ground surface, the amount that forms recharge to the groundwater system, and the amount that runs off into the stream. Different land management options can also change the effect of land use on each of these factors and on the quality of water in streams through such changes as erosion rates and solute transport. The quality and quantity of water in the surface water system is important to human, animal and plant populations as a source of water for consumption and for the irrigation of crops and pastures for food production.

Catchments may vary in scale from tens to thousands of square kilometers. Response times to rainfall events may be from hours to days. Longer-term changes in landscape features such as land use and management may have impacts over much longer scales, such as from months to years.

3.1.2. Subsurface Water Systems

Subsurface water systems, or groundwater systems, are an important part of the hydrological cycle. Water and pollutants flow between the groundwater and surface water systems. In particular salt stores may reach the surface and affect agriculture and other ecology when the height of the water table changes. This can affect the quality of land and water for agriculture, as well as having impacts on urban infrastructure. Changes in groundwater quality and quantity can affect the surface water system, impacting on plants, animals and humans who use this water. The amount and quality of water in the groundwater system is dependent on factors that affect recharge and discharge. Rainfall and runoff will limit the amount of water that is available for recharge to the groundwater system. Land use and management as well as soils and topography will affect the amount and quality of rainfall that drains to the groundwater system. For instance, more water will drain through sandy soils than those that are clay based. Trees act as pumps on the groundwater system, reducing the amount of water in the groundwater system and the height of the water table. Management practices on agricultural land also affect the amount of water that drains to the groundwater system, and often the quality of that water. Groundwater is often pumped for human use, for agriculture or town water supplies. All of these features have a direct impact on the amount and quality of water that is stored in the groundwater system.

The characteristic temporal scales of the groundwater system tend to be much longer than those of the surface water system. Water may take years, or even thousands of years, to move through an aquifer. Aquifers can be small and fairly local, in the order of tens of square kilometers or may be much larger, covering hundreds or thousands of square kilometers.

3.1.3. Coastal Systems

The coastal system may be seen as the area in which the terrestrial environment and the marine environment interact. These systems are very complex, varying in size over time, with tidal levels. A coastal system may consist of several kilometers of land inwards from the beach, out to a width of sea just beyond the breaking waves. The coastal system is affected by climatic influences such as storms as well as by human influence, in terms of human constructions. The width of beach, and the amount of sand erosion that has taken place, will depend not only on recent storms but also on human built structures that impede or expedite erosion. Tidal influences also effect the beach environment and the amount of erosion that has taken place. Changes to rivers, in the form of dams have also effected the coastal systems by changing the amount of sediment discharged to the coast for distribution along the shore. Changes to the coastal system may impact on human communities and maritime structures as well as on plants and animals that inhabit the coastal and broader oceanic systems.

Temporal scales of coastal system vary. Littoral drift can cause erosion and movement of sand and sediment over long time scales of months and years. However relatively large amounts of sediment can be moved over very short periods of storm front, in the order of hours to days. Spatial length scales can be over tens to hundreds or even thousands of kilometers of coastline.

3.2. Ecological Systems

The term “ecological systems” is used here to refer to two major types of systems: agricultural systems and wildlife systems. These systems are not completely independent of one another, as changes in one system will often affect the other. For example, the introduction of crops will change the available food supply for various native populations, which may increase or decrease population numbers depending on the ability of different species to adapt their diet and habitat. Increased clearing of land for agricultural use will also impact on native populations. However, for modeling purposes these systems are different enough for them to be considered separately in most work.

3.2.1. Agricultural Systems

Agricultural systems consist of human developed systems of crop production and animal grazing. The impact of these systems on the environment depends largely on the type of crop that is grown or animal that is grazed, as well as on the practices which are used to manage this production. For example, the introduction of hard hoofed animals into Australian environments is believed to have increased soil erosion, and the replacement of native vegetation with shallow rooted crops and pastures has increased groundwater levels, causing problems with dry land salinity. Crop yields depend on characteristics of the landscape such as soils and topography as well as on climatic factors such as rainfall patterns and solar radiation. These yields can be further modified by the use of different land management techniques, such as the use of different tillage and rotation schemes and the application of pesticides, herbicides or fertilizers, which may have effects on local wildlife and hydrological systems. Important scales in crop production can be at the individual plant scale, looking at individual processes of photosynthesis and evapotranspiration, or at larger plot or field scales. Impacts of changes in crop production techniques can have impacts at much larger scales, such as at the catchment scale for water quality, if changes are widespread.

Changes in the management or distribution of pastoral systems can also have effects at a range of scales. The capacity of a landscape to carry livestock depends on factors like soils, topography, rainfall patterns and solar radiation. The rate at which animals are stocked on pastures and the rotation of animals between pastures will effect soil erosion and land degradation, as well as water quality and sedimentation of streams flowing through pastoral areas. Different management of these pastoral systems will also affect their productivity. Scales of pastoral systems are similar to those of crop systems with the main characteristic scales being the individual or the field scale. The effects of changes in land use and land management may be widespread and may occur over temporal scales of years to decades. Individual processes occurring within crop or pastoral systems can occur over very short time scales of days or weeks.

3.2.2. Wildlife Systems

Wildlife systems consist not just of the more visible vertebrate animals but also other animal species, plants and micro-organisms. The abundance of different forms of wildlife is dependent on the abundance and distribution of suitable habitats, food sources, predators and competition. Features of the landscape as well as the amount of human interference in an area will limit the amount of suitable habitat for different species. Certain species may be more tolerant to human influences than other species. Climatic impacts in terms of the pattern of rainfall, the persistence of drought and flood and the amount of sunshine will all affect wildlife populations. The interactions between these different factors, and between different species and individuals are complex and nonlinear. This means that predictions of the effects of changes in climate or habitat are difficult to make.

The scales of wildlife systems are very variable. On an individual basis, different species have very different life expectancies and population ranges. For whole populations, larger scales are generally important. In terms of evolution, ecological impacts may occur over a number of generations that may mean time scales of thousands of years, whereas populations may become extinct over a fairly brief period of time.

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Biographical Sketches

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