1
Introduction

Chapter goals:

1. Introduce the concept of geocomputing and how it applies to water resources science and engineering.
2. Understand the role of Geographic Information Systems (GIS) in geocomputing for water resources science and engineering.
3. Motivate water resources scientists and engineers to learn GIS.

1.1 What is geocomputation?

The word "Geocomputation" in the title of this textbook has probably piqued your curiosity and you cannot wait to learn more about it and how it is used in water resources engineering and science. Searching the word "Geocomputation" on Google, as we come close to completing this book, yielded roughly 80,600 results (in 0.28 s). By Google search standards, this represents a very small presence. As a comparison, searching the phrase "GIS" yielded 82,800,000 results (in 0.29 s), a whopping three orders of magnitude difference. Even spelling out "Geographic Information Systems" resulted in 35,200,000 results (in 0.25 s). Based on these results, we can surmise that while people have begun to study, research, and discuss "geocomputation," the field is still burgeoning and not as mature as geographic information sciences (Google search of this word yielded 9,540,000 results in 0.50 s).

There is however a geocomputational community consisting of researchers and scholars (see www.geocomputation.org) who have organized annual conferences in this area since 1996. They adopt a broad definition and define "Geocomputation" as the Art and Science of Solving Complex Spatial Problems with Computers. The field of "Geocomputation" represents a commitment to using geographical concepts in analysis and modeling applications. This commitment not only extends to the use of existing methods to solve new problems but also to identify areas where our current geographical understanding is limited and to develop new theories to enhance geographical knowledge. By the same token, the field also includes exploring ways to include our geographic knowledge into computer programs by developing new algorithms and frameworks. Geocomputation seeks to take a doubly informed perspective of geography and computer science. Geocomputation represents a true enabling technology for geographers, environmental scientists, and engineers while offering a rich source of computational and representational challenges for computer scientists (Gahegan 2014).

Openshaw and Abrahart (1998) provide an early historical account of geocomputation. Early computers were capable of performing many of the algebraic number crunching operations that we routinely use today. However, these computers were not readily accessible nor did they come with user-friendly programs that helped process the data. Therefore, programming skills were essential to use the computers. A small group of researchers in water resources engineering, as well as quantitatively inclined geographers and other environmental scientists, sought ways to exploit the powers of the computer to solve their problems. These problems ranged from characterizing how landscapes changed and evolved over time to evaluating how these spatial changes in conjunction with natural variability in climate impacted the flow of water across the entire hydrologic cycle. In particular, geographers were interested in understanding geographic space (both physical and human dimensions of the space and their interrelationships including human alterations of the geographic space), environmental scientists sought to understand how these changes in geographic space affected the ecosystems (and the environmental quality), and civil engineers were concerned with how to develop new ways to manage water resources in the context of geographic space to ensure that they are available for the progress of human race. Understanding the interrelationships and dynamics of processes was not a trivial task but required extensive datasets and computational resources.

The advent of databases and development of relational database concepts in the 1970s revolutionized the way we stored data and provided faster algorithms and techniques to retrieve and process large amounts of data. However, the computers in those days were not good at helping us visualize how information was scattered in the real-world geographic space. Early GIS software were very similar to packages of modern-day graphics and did little more than visualize data using keyboard characters like *, –, or #. They were largely developed by computer scientists with limited interaction from geographers or other end users such as water resources engineers. As computers

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became more powerful and started permeating our society, more and more geographers and engineers started using computers and demanded better visualization tools. They expressed their frustration at existing software; some geographers even felt that early GIS software were too simple and a step backward in the progress of the field. Over the course of time, scientists and engineers helped develop new algorithms for processing information and better ways to visualize spatial information. The modern-day GIS software embody hundreds of thousands of human hours of effort that went into improving the software and making it what it is today. Nowadays, geographically based data visualization is a key component of most, if not all, water resources applications. This is not to say we have reached the limit of what the software can do and the progress to make things bigger and better continues on.

1.2 Geocomputation and water resources science and engineering

Water resources engineers and scientists, as well as resource managers, focus on providing safe and sufficient amount of water to humans and ecosystems alike. They undertake analyses to understand how water and associated physical, chemical, and biological constituents enter a system of interest and move through and out of it. The conservation of mass, momentum, and energy forms the basis for defining the hydrologic cycle, which describes how water is cycled on the earth and defines various inflow–outflow processes including rainfall, snowmelt evapotranspiration, infiltration, runoff, and base flow. A watershed is a fundamental system or entity for managing surface water resources, whereas an aquifer is the fundamental entity for managing groundwater systems. The watershed is a parcel of land bounded by ridge lines (also known as water divides), which drains water (or associated pollutants) to a point known as "drainage point." The drainage point is a "collection point" of water and pollutants within the watershed and also serves as a discharge point for continued downhill flow. The aquifer is an underground water-bearing reservoir from which sufficient quantities of groundwater can be extracted and represents a fundamental unit for managing groundwater resources. The vadose zone is the system that lies between the land surface and the aquifer. The vadose zone plays a critical role in partitioning rainfall between runoff and infiltration, two processes that ultimately control water and chemical fluxes to surface and groundwater systems, respectively.

Water resource engineers and scientists make use of these hydrologic concepts to identify new water supply sources and find ways to reduce pollution and to manage flow rates and wastewater discharges. They design water storage structures such as dams and reservoirs and also play a major role in shaping public policies, zoning laws, and regulatory statutes to manage water resources. They also study how best to allocate water among various competing users (of which the ecosystem is also one) and plan for future development as well as unforeseen and unwanted natural events such as droughts and floods. **To summarize, water resources engineers and scientists seek to understand what happens to water quantity and quality in space and over time and use this information to develop engineering structures and administrative guidelines to manage water in a sustainable manner.**

The field of water resources science and engineering is highly quantitative in nature. Water resources engineers and scientists need to quantify how the actions they recommend at one location (say allowing someone to discharge wastewater into a river) will affect others at some point downstream. By the same token, how does an action taken today (e.g., allowing a farmer to pump water for irrigation) affect the supplies in the region at some later point in time. The quantitative nature of water resources engineering is well established today and owes its development to some early pioneering work by scientists and engineers in the early part of the 20th century. The unit hydrograph theory (Sherman 1932) and the solution to radial flow in an aquifer to a pumping well (Theis 1935) are some examples of pioneering work that is still widely used today. The use of mathematical techniques in hydrology has spiraled tremendously since the 1970s. Water resources engineers and scientists have tried to harness computational resources available to them to develop quantitative tools and models that simulate the flow of water and the transport of pollutants. The Stanford Watershed Model (Crawford & Linsley 1966) and the Prickett Lonnquist Aquifer Simulation Model (PLASM) groundwater model (Prickett & Lonnquist 1971) represent some early attempts on mainframe computers. Water resources modeling has kept pace with computational advancements, and recent versions of the Modular Groundwater Flow Model (MODFLOW) (Harbaugh 2005) and the Soil Water Assessment Tool (SWAT) model (Arnold *et al*. 2012) now allow practicing engineers and scientists to simulate fairly complex and heterogeneous water resources systems on desktop computers. The use of computers in water resources engineering practice will clearly continue to grow in years to come.

Water resources engineers and scientists characterize and model flow of water and pollutants in watersheds and aquifers, which are geographic entities. **Although not explicitly acknowledged, all calculations and computations performed by water resources engineers and scientists can be viewed as geocomputation by the very nature of the task, as geographic information is central to defining the system being modeled.** Water resources modeling (be it for water quantity or water quality) broadly entails three steps:

1. **Development of the conceptual model:** Here, the boundaries of the system of interest are defined, and the constituents of concern (water and pollutants) are identified. Possible pathways of entry of these constituents into the system and out of the system, along with transformations (additions and subtractions) within the system, are defined using physical, chemical, and biological processes that control the movement of water and pollutants. The data necessary to delineate the system and define the controlling processes are also compiled as part of the conceptual model development. In summary, the conceptual model provides a qualitative summary related to how water and pollutants are likely to behave in the geographic system (watershed or aquifer) of interest to us.
2. **Development and application of the mathematical model:** In this step, the qualitative conceptual model is translated into a set of mathematical equations that characterize the movement of water and/or pollutants through the system (called as governing equations). The interaction of the system with the universe surrounding it is mathematically defined (boundary conditions), and the initial state of the system at the beginning of the simulation (initial condition) is also

specified. The data compiled as part of the conceptual model development are then fed into a computer program, which then solves the equations and obtains results. Numerical methods are often used as these techniques require the system of interest be broken down into a set of interconnected subsystems (grid cells). In a similar manner, computations are carried out at discrete time intervals. The results obtained from these models represent the behavior of a property of interest, which is also referred to as the state variable (such as pressure or concentration) in space and time.

3. **Processing and visualization of results:** In this final step, the output generated by the computer program is processed using contouring and charting tools to understand the system response or how certain stresses on the system affect the response of the state variable in space and time.

Many models and computer programs used by water resources professionals (some of which are still used today) were developed in the 1970s and the 1980s used the FORTRAN (Formula Translation) programming language. While FORTRAN is a powerful high-level language and offered several computational advantages, it also required the input files to be formatted in a specific format. A significant portion of the overall modeling effort focused on getting information to these programs in the proper order. As water resources models were generally based on finite difference or finite element codes, the data inputs for the models involved matrices whose dimensions depended on the level of discretization that was used to translate the underlying ordinary and partial differential equations into algebraic expressions. In other words, once the spatial domain of interest to be modeled was identified, the first step of the modeling process was to develop a grid (or a mesh in the case of finite elements) that covered the area of interest with a sufficient degree of accuracy. Spatial information, with regard to various hydrological properties and sources and sink terms such as recharge, was then assigned to each cell of the grid by overlaying the grid (drawn on an acetate or tracing paper) on geologic and hydrologic maps. It was extremely cumbersome and an arduous exercise to change the grid dimensions. All the data from various maps did not fit perfectly with the selected grid, and, therefore, the development of model input files entailed considerable subjectivity (or more euphemistically, professional judgments). Asking a modeler to resize the mesh size or re-orient the grid was tantamount to discarding months of hard work and a significant escalation of costs and added delays to modeling projects. Similarly, the visualization tools were rather primitive, and although the outputs obtained from the model described changes in space and time, there was no easy way to see what was going on. Contour plots depicting changes in space were often hand-drawn, which was not only time consuming but also prone to significant errors and subjective judgments made by the drafters of the plot.

1.3 GIS-enabled geocomputation in water resources science and engineering

The three basic modeling steps described in the previous section have not changed over time. However, the ease with which we can perform these steps has changed considerably over the last few decades. In particular, advancements in GIS, satellite, and aerial remote sensing have put vast amounts of geographic data into the hands of water resources engineers and scientists. Advances in GIS software have greatly enabled processing and visualization of results. There is a growing push to integrate mathematical models and software with GIS to develop efficient processors that facilitate easy data input and to provide rich sets of tools for visualization. The importance of GIS in water resources engineering and science has been recognized for a while (e.g., Tim *et al*. 1992), and the influence of GIS on water resources engineering and science will continue to expand in years to come as evidenced from the growing number of journal articles being published on the topic as well as the use of GIS in the water resources industry. GIS technology has matured considerably in recent years. The industry-standard software, ArcGIS (ESRI Inc., Redlands, CA), now offers thousands of geoprocessing tools. Even several free GIS software (e.g., GRASS, Quantum GIS (QGIS)) now offer considerable functionality and user-friendly interfaces, which greatly blunts the learning curve and makes the technology accessible even to people in underdeveloped nations where remote sensing and GIS resources can help reduce the data collection burden. Given the maturity of GIS, its usefulness in water resources analysis and modeling, we feel it is important that water resources engineers and scientists jump on the GIS bandwagon at the earliest and make learning GIS tools and techniques a lifelong learning goal and exploit its utility to the fullest. **Based on this thinking, we define geocomputation in water resources engineering and science as GIS-enabled analysis, synthesis, and design of water resources systems.** At a basic level, GIS provides several geoprocessing tools and techniques such as overlay, buffering, and interpolation that can be used directly in certain water resources applications. **However, more importantly, we feel the true power of GIS is harnessed when traditional and modern computational methods used in water resources science and engineering are coupled with GIS to develop innovative decision support systems** that help solve challenging problems of water supply and quality facing the world today. **Our definition of geocomputation, while broad, seeks to focus on this aspect of the integration of geoprocessing and computational algorithms.** As GIS forms the basis for our definition of geocomputation and is required for geoprocessing, we start by motivating water resources engineers and scientists to learn GIS.

1.4 Why should water resources engineers and scientists study GIS

The advent of GIS and advances in geospatial technologies has not only considerably simplified hydrologic modeling but actually revolutionized the way we do things.

1. Large amounts of geospatial data required by models is now digitally available (and usually for free), and modeling preprocessors makes it easy to import them and make them ready for use with hydrologic models.
2. GIS allows for data reuse as data collected for one project may be used in another seamlessly, thereby leading to considerable cost savings. In a similar vein, GIS also allows seamless data transfer between different operating systems, which eases up issues related to data formatting and archival.

3. GIS removes the constraints of scale, and the overlay functionality of GIS helps professionals understand the relationships between various inputs, and when direct information is not available, GIS provides surrogate information that can be used to estimate inputs. For example, aquifer recharge is difficult to measure yet an important input for groundwater flow models. Surrogate information such as soil texture, precipitation, and land use/land cover (LULC) spatial datasets can be integrated within GIS and used to develop estimates for recharge and represent variability.
4. GIS-based spatial decision support systems (SDSS) provide an integrative framework wherein both **hard data** from sensors and models can be coupled with **soft information** (namely, stakeholder preferences and expert knowledge), which can be very useful in participatory management and policy formulation applications.
5. A suite of powerful geocomputational techniques are built into GIS software. Advanced interpolation techniques such as Kriging can be used to fill-in information from a finite set of measurements in an objective manner, thus minimizing the need for subjective judgment calls on the part of the modeler.
6. Conceptual model development is no longer tied to the numerical discretization of the hydrologic model. A conceptual model can be built within GIS by integrating required hydrologic data and using geoprocessing routines. A grid of any size can then be overlaid on this conceptual model, and required inputs corresponding to each cell can be read for use with the hydrologic model. Grid sizes can be changed virtually on the fly if the hydrologic modeling needs to be carried out at another spatial resolution. **GIS has truly enabled hydrologic modelers to move from a "model-centric" approach to a "system-centric" approach**. One can now focus on collecting high-quality spatial data and objectively decide how the data can be assigned to model cells. If the trends were to continue, the advances in computational and geospatial technologies will make GIS and hydrologic models more tightly integrated in years to come. Therefore, having a basic understanding of GIS concepts and principles and familiarity with GIS software is no longer preferred but is quickly becoming a requisite skill for hydrologic modelers.
7. GIS software is available over a wide range of platforms including as "apps" for smartphones. Therefore, wide-scale dissemination of data, particularly about hydrologic disasters, has become easier.

1.5 Motivation and organization of this book

As we have stated earlier, GIS is a mature technology. Most universities offer courses in GIS both at the undergraduate and graduate levels. There are several books written on the subject ranging from practical hands-on introductions to those that cover the advanced theory of geographic information science. Typically, GIS courses are offered in geography programs, and the introductory courses are open to all majors. Therefore, most introductory GIS courses tend to be subject neutral, and the applications presented tend to focus on broad social issues such as crime and accidents that students from all disciplines can relate to. Civil engineering students are typically required to take at least one course in hydrology and environmental engineering at the undergraduate level. Depending on their interest and availability, they take additional courses in water resources engineering or seek to obtain a specialization in water resources engineering at the graduate level. An introductory GIS course is typically an elective that not all students can fit into their degree plan. As GIS coursework is not formally required, there are no expectations for students to use GIS in their hydrology and water resources classes. Ad hoc training on GIS is sometimes provided in these classes to facilitate the use of a modeling software, which results in students not fully comprehending the advantages of GIS and the benefits it can offer. While a course in GIS is often required by most graduate programs in water resources engineering, the offerings in geography programs help to expose students to the rudiments of GIS but typically do not show them how they can be used in water resources engineering applications. While environmental science and geography majors are often required to take one or more courses in GIS and remote sensing, their curricula are somewhat limited in scope with regard to computationally intensive water resources courses at both undergraduate and graduate levels. In particular, there is often limited emphasis on the quantitative aspects and modeling, which leaves students having a fairly good understanding with regard to the functioning of GIS but with limited training in the computational aspects of water resources disciplines.

Our motivation with this book is twofold. First, we seek to introduce students in water resources engineering and science to the fundamental concepts and geoprocessing tools and techniques of GIS. As we have discussed earlier, GIS forms the backbone of modern-day geocomputing for water resources science and engineering. To motivate students, we use examples from water resources disciplines in our discussions of GIS and make explicit demonstrations of how GIS can be useful to water resources engineering and science. We believe that the integration of GIS and water resources not only helps students to realize the usefulness of GIS in water resources engineering and science but also helps them develop a more visual and intuitive feel for the subject matter.

Our second goal is to introduce students to modern geocomputational techniques and how they are enhanced through the use of GIS. The utility of soft computing methods such as artificial neural networks (ANN), fuzzy arithmetic, and artificial neuro-fuzzy information systems (ANFIS) for analyzing water resources systems has been explored in the literature related to water resources (Tayfur 2011). However, a significant amount of material is found in archival journals, conference proceedings, and advanced research monographs, which are generally hard to read and follow for many undergraduate and early graduate students.

Although developing journal article reading and synthesis skills is a useful tool not only to be successful in graduate school but also to embark on lifelong learning well beyond the confines of academia, an introduction to these topics in a textbook such as this one can facilitate effective learning. The case studies in this textbook illustrate how different modeling techniques can be integrated within a GIS framework to solve water resources problems. Our goal with these case studies is to develop material that is similar to what would be found in peer-reviewed archival journal articles, but to introduce them in a gentler manner with the hope that these case studies will provide a launching pad to tackle advanced materials found in archival journals.

It is hoped that this book will motivate the development of senior and early graduate level courses that emphasize the use of GIS and geocomputation in water resources science and engineering. We seek this book to be as comprehensive as possible with regard to the coverage of GIS and geocomputation techniques and assume no experience on these topics from the reader. However, some familiarity with hydrologic and water resources concepts such as those covered in an introductory hydrology class in civil engineering, geography, and environmental science curricula is assumed on the part of the reader. Several computer programs such as the SWAT for watershed flow and transport modeling (Arnold *et al*. 2012) and MODFLOW for groundwater flow modeling (Harbaugh 2005) have become industry standards in recent years. Many of these computer codes have either public-domain or commercial processors that utilize spatial concepts to perform input data entry and visualize results. Many faculty are starting to use these software in their classes (namely, water resources engineering, environmental modeling and applications with GIS, advanced GIS applications, water resources planning). To the extent possible, we have tried to refrain from using standard modeling codes for the following reasons:

1. These programs tend to be rather involved and any attempt to introduce them in a GIS or geocomputation course would simply distract from the subject matter at hand and take the course off on a tangent.
2. As there are several processors and models, our selection would simply reflect our biases toward the value of the theoretical concepts that we seek to emphasize.
3. Most processors in the market mask the underlying spatial calculations in order to make programs user-friendly. While this approach is beneficial in practical applications, using such processors add limited pedagogic value. We therefore emphasize the application of fundamental geospatial analysis using simple intuitive examples and subject matter that the students would have seen in their introductory classes. We do believe that understanding GIS and geocomputation methods presented in this book will help students understand the inner functioning of the model processors, which in turn will help them better evaluate the results generated by them.

This book has sufficient material to cover a semester-long class focused on "GIS and geocomputation" at either undergraduate or early graduate levels in civil engineering, geography, and environmental science programs. We hope to motivate application-oriented civil engineers to understand the theory behind geoprocessing and computation and in the same vein encourage geographers and environmental scientists to develop an appreciation for the rich set of applications that GIS can be used in the broad field of water resources science and engineering. Undergraduate courses would emphasize the material presented in Modules (Parts) 1–3, briefly discuss the subject matter in Module (Part) 4, and discuss a few case studies in a classroom setting. However, Modules (Parts) 1–3 can be covered more quickly in a graduate-level class (possibly in the first half to two-thirds of a semester), and the remaining time be used to discuss application challenges and more involved hands-on exploration of the case studies. We believe that having a historical perspective of the field and understanding the potential challenges and unsolved problems in GIS and geocomputation upfront helps the student place their learning in proper perspective and enables them think creatively to find innovative solutions or, at the very least, pragmatic workarounds to some of the limitations that GIS has at this point in time. We therefore start our exploration of GIS with a short historical perspective in the next chapter.

1.6 Concluding remarks

The goal of this chapter was to define geocomputation and demonstrate why the use of GIS is beneficial to water resources engineering and science practice. Using systems thinking as the basis, we defined "geocomputation" in water resources science and engineering as the coupling of GIS with traditional and innovative computation techniques such as physically based models and soft computing strategies to develop decision support systems that effectively integrate and mine data from disparate sources and generate information whose value is greater than the sum of the individual parts.

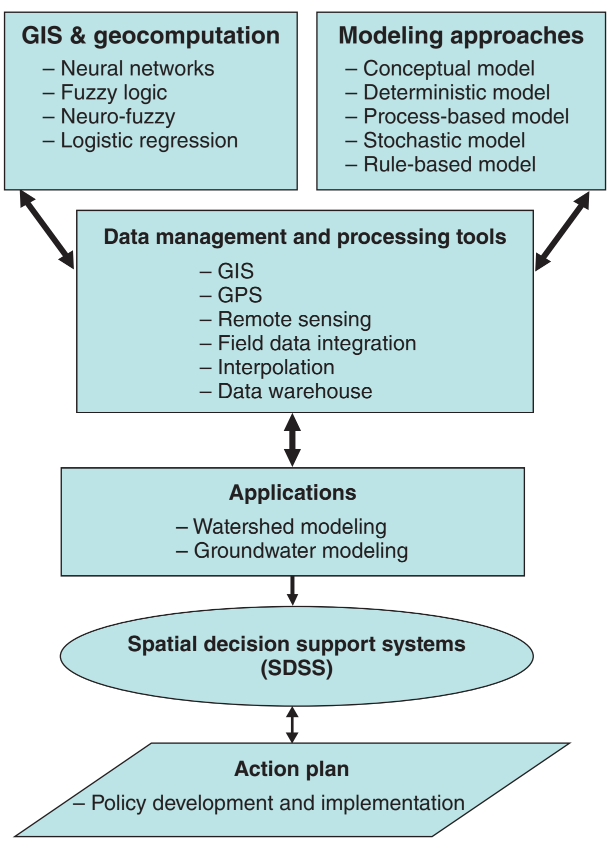
Conceptual questions

1. Discuss the importance of the application of GIS, geospatial technologies, and geocomputation for water resources modeling management.
2. Why should students acquire cross-disciplinary training to learn the theoretical foundations of GIS and geocomputation as well as various water resources modeling approaches?
3. What are the opportunities and benefits of using GIS and geospatially integrated approaches?
4. Can you think of a hydrologic or water resources application that you came across in your introductory class that would not benefit from using GIS? Explain your reasoning.

Spatial decision support systems (SDSS)

GIS is an integrated system of hardware and software that allows us to capture, manage, analyze, and visualize data that has some geographic reference. GIS data are stored in special file systems, which are generally composed of multiple files. At a minimum, GIS files contain spatial information about the various "real-world" geographic entities within a domain of interest. This spatial information includes information such as latitudes and longitudes as well as the relative locations of one geographic object in context to another. In addition to spatial information, GIS files also store attributes (or properties) associated with different spatial objects. For example, we could have a GIS file containing data on Texas reservoirs. This file would not only store the relative locations as well as the extent of each reservoir but also contain attributes associated with these geographic entities (reservoirs). For example, we could store the drainage area corresponding to each reservoir, average reservoir depths, prevailing wind speeds, and water quality characteristics, such as dissolved oxygen levels and chlorophyll-a concentration. Therefore, GIS can be thought of as an intelligent map or

GIS = MAP + DATABASE.



Although GIS can be useful to visualize locations of various entities, its real power lies in processing the attribute information to develop insights that can guide policy planning and development. Water resources policy planning is inherently a complex process involving several different trade-offs. For example, a reservoir can be used for both recreation and water supply purposes. From a recreational standpoint, people may want water levels to be high for boating and the reservoir stocked well with fish. Having a lot of fish in the reservoir could lead to increased oxygen demand and water quality deterioration, which is not good from a water supply standpoint. From a policy planning perspective, one could develop a mathematical model that relates biological oxygen demand (BOD) loadings and fish stock to see the effects of stocking fish on water quality levels of the reservoir or lake. Clearly, the fish stock and water quality relationship could change based on lake characteristics, particularly how oxygen is added to and assimilated within the lake. GIS attributes such as wind speeds and reservoir water levels come in extremely handy when developing water quality models. The water quality levels in the lake depend not only on what is happening in the lake (due to fish stock) but also on the natural and anthropogenic influences around the lake. GIS presents tools to delineate watersheds (catchment areas) of reservoirs. Land use/land cover (LULC) maps can be overlaid to see how runoff from cities and agricultural areas contributes to water quality loadings in reservoirs. All these data can be input into a watershed model to assess the relative contributions of internal sources of pollution (fish stocks), sinks (lake aeration), and nonpoint source loadings (urban and agricultural runoff), as well as the interactions between these competing processes. This type of model can be used to identify the amount of fish that can be stocked in the lake and how reductions in point and nonpoint sources of contamination affect lake water quality. We can use a model of this kind to see what happens when a new process is added to an existing wastewater treatment plant upstream of the lake or stream. We can also use the model to facilitate a "policy dialogue" pertaining to how land use changes (i.e., reductions in nonpoint source loadings) can enhance the recreational value of a lake. GIS can be used to develop new land cover maps, which in turn can be used to estimate future nonpoint source loadings and allow people to realize the trade-offs of wanting recreational benefits and the associated changes in waste management practices. People are more likely to make changes if they value recreational use of a lake, and this is very likely if there are no other lakes nearby. GIS can be used to make proximity calculations and estimate travel costs, which can be useful when people are deciding what course of action to take.

Decision support systems (DSS) are computer programs and software that help to support decision-making process required during engineering design and public policy development and implementation. DSS for water and environmental policy making are intrinsically complex and require decision makers to consider diverse and disjointed pieces of information arising from the engineering, physical, and natural sciences, as well as the social science arenas. Water resources engineering and policy always have a spatial dimension as we are dealing with rivers, lakes, aquifers, and watersheds. The role of GIS in engineering design and public policy should be clear, given the integrative nature of these tasks and the inherent spatial dimension. DSS developed using a GIS framework are often referred to as SDSS. The early pioneers of GIS were driven by the dream of building such SDSS. Advances in computing technology have now made it possible to build SDSS on a routine basis, which has truly revolutionized water resources policy planning and design.

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