Using Remote Sensing and GIS to Teach Inquiry-Based Spatial Thinking Skills: An Example Using the GLOBE Program's Integrated Earth Systems Science

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Abstract

Earth systems science and technology are essential elements of a contemporary education. Remote sensing and GIS provide a valuable spatial framework for scientific inquiry, and are highly effective as a means to integrate Earth system science components. Drawing on the GLOBE Program's K-12 Earth science curriculum, we show how remote sensing and GIS can be used to integrate GLOBE's Land Cover-Biology and Hydrology investigations, emphasizing the Earth as a system. Our approach uses spatial thinking, geospatial technology, and the concept of watersheds to help students develop an understanding of the basic relationships between land cover and surface hydrology, two critically important and easily observed components of the Earth's surface. By starting with very simple exercises and analyses, students build upon a conceptual framework for understanding how land use pattern can influence the quantity and quality of one of the most critically important Earth resources, local fresh water. Ultimately, by understanding how terrestrial and aquatic systems interact, students begin to understand the link between science and land use policy.

Introduction

This paper presents a new approach to structuring the GLOBE Program's Earth science curriculum through an integrated study of watersheds using remote sensing and Geographic Information Systems (GIS). GLOBE (Global Learning and Observations to Benefit the Environment) is "hands-on", inquiry-based K-12 Earth science initiated in 1994 by the National Science Foundation (NSF), the National Aeronautic and Space Administration (NASA), and the U.S. State Department and currently involves over 1 million students in 10,000 schools world-wide (GLOBE 2003). GLOBE's core mission is to improve science education, increase environmental awareness, and contribute to the understanding of Earth as a system. Since its inception, GLOBE has focused on five discrete Earth science thematic areas, called "Investigations": Soils, Atmosphere, Hydrology, Land Cover-Biology, and Earth as a System (Table 1). While students are engaged in a series of coordinated Learning Activities and associated hands-on field study Protocols that focus on individual components of the Earth system, the GLOBE curriculum connects students with cutting-edge Earth systems scientists by sharing data and supporting data analyses, interpretation, and inquiry across a global network of students, teachers, and scientists.

GLOBE is not the only formal academic-scientific partnership focusing on K-12 Earth science education. "Mission Geography", for example, is a collaboration between NASA, the American Geography Education Implementation Project, and other educational stakeholders, that uses remote sensing to teach spatial organization and analysis, physical systems science, and human-environment

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Table 1 The Five GLOBE Investigations and their primary objectives (adapted from the GLOBE Teacher's Guide, 2003).

Investigation Area	Objectives
Atmosphere	understand atmospheric properties, characteristics, and conditions, and variability of weather and climate
Hydrology	understand the hydrologic cycle, and the importance of various water quality measurements
Soils	understand soil properties and characteristics, and soil function within the ecosystem
Land Cover-Biology	understand variability in land cover classes, and be able to identify and map common land cover types
Earth as a System (includes Phenology)	understand the interconnected nature of Earth processes, and be able to describe connections between Earth system components

interactions (Bednarz and Butler 1999). Whereas GLOBE applies an inquiry-based model dependant on gathering and analyzing 'local', indigenous data centered around and shared between GLOBE schools, Mission Geography uses a variety of NASA satellite and ancillary data from around the world to teach Earth science and geography. NSF's Digital Library for Earth Science Education (DLESE) hosts a wide range of Earth science curricula and associated data, spanning K-12 and undergraduate levels, including tools for evaluation and assessment and support materials for integrating research into geoscience education.

The Next Generation GLOBE (NGG) program is currently developing new ideas for implementing the GLOBE curriculum in the 21st century (GLOBE 2005), creating an opportunity to incorporate improved geospatial technology with a more comprehensive understanding of Earth systems science. We argue that, for students to gain an understanding of the Earth as a system, it is necessary to study the spatial, process-based relationships that exist between the five GLOBE Investigation areas. Remote sensing and GIS are tools to facilitate an understanding of these relationships while simultaneously teaching important technical skills, thus playing a key role in understanding Earth as a dynamic system. It is essential that students become aware of the interrelated nature of the Earth system because humans are having a profound negative and potentially long-lasting impact on soils and land cover, biodiversity, atmosphere, climate, fresh water, and ocean resources. Students who posses both an awareness of the connections between Earth system components and knowledge of the technology used to study Earth systems will be in a position to further their education and ultimately address these challenges (NRC 2002; Scotchmoor *et al.* 2005). By developing a series of Learning Activities and Protocols that build on the existing curriculum by integrating Investigation areas, GLOBE will more effectively meet its goals of:

- Enhancing environmental awareness throughout the world
- Contributing to scientific understanding of the Earth; and
- Helping students reach higher levels of achievement in science and mathematics

This paper is structured in five sections. The first section outlines the importance of an integrated approach to Earth systems science and technology education using remote sensing and GIS. The second section introduces the existing GLOBE Land Cover-Biology and Hydrology Investigations. The third section describes why watersheds are an effective spatial framework for studying land cover – hydrology interactions using remote sensing and GIS. The fourth section introduces the Integrated Land Cover Hydrology Investigation and provides a hypothetical example lesson and exercises that link land cover to local hydrology. The final section summarizes and concludes with a proposal for adoption of integrated Learning Activities and Protocols within the NGG program.

The Importance of Integrated Earth Systems Science and Technology in Education

Earth systems science is an interdisciplinary domain defined as the formal scientific study of the Earth as a single integrated system that cycles energy and matter through a set of reservoirs, including atmosphere, hydrosphere, biosphere and geosphere (AGU 1996). It is distinguished from the single disciplinary Earth sciences of geology, hydrology, meteorology, and oceanography by its emphasis on open subsystems, and particularly by its emphasis on interactions between subsystems, for example between terrestrial and aquatic freshwater environments or between land and atmosphere. According to the America Geophysical Union (AGU 1996), "Earth system science conveys the complexities, ambiguities, and uncertainties of the processes that control and shape the planet. The world is viewed as a multivariate... system. Studies in this field range from interactions among small components of the system to a holistic view of the Earth system and its place in space. At some levels, the system's behavior is predictable, while at others it is not and may never be. The Earth system approach allows students to understand... the interconnected nature of the system..."

Technology has always played an important role in Earth science, and Earth science and technology have been fundamental components of a formal education since the scientific revolution. Throughout the intervening centuries, those who understood Earth science and technology held a significant advantage in exploration, engineering, agriculture, medicine, and many other important scientific and technical disciplines. This situation has not changed; indeed, a broad understanding of these two closely related fields is just as necessary today as in the past, perhaps even more so given the tremendous recent changes in global communication, global trade, and the global biophysical environment (Friedman 2005; Meehl *et al*. 2004).

Contemporary Earth science and technology make it possible to understand, at least in part, various aspects of our dynamic global environment, from natural and anthropogenic changes in climate and atmosphere, to changes in land cover and sea level, to socio-demographic change driven by immigration and disease. Using remotely sensed data and computer models, we now have a better understanding of the vast and complex challenges involved in sustainably managing the global "commons" - air, water, soil, and biodiversity upon which we all depend for economic and physical health, wellness, and security (Worldwatch Institute 2005). Given the impact Earth science and technology have on contemporary society, and given the role that they will ultimately play in global sustainability, it is essential that students understand basic Earth systems principles and are able to use geospatial technology. Today's K-12 students face a contemporary version of an historical challenge - become proficient in Earth systems science and technology, or rapidly fall behind.

Although the breadth, depth, and focus of Earth systems science education differs between curricula, most modern non-sectarian K-12 educational systems and undergraduate liberal arts institutions teach Earth systems sciences in one form or another (AAAS 1993; NRC 1996). GLOBE is well suited to teaching integrated Earth system science because it focuses on the primary, essential components of Earth systems, including water, air, land, and via phenology, the seasonal dynamics that in part link physical and biological systems to each other. The individual components already exist and are supported by a wealth of high quality Learning Activities and scientifically valid data collection Protocols (GLOBE 2003).

However, as currently implemented, the GLOBE Investigations are taught in isolation from one another. In contrast, we believe that to be most effective, the Next Generation GLOBE program should adapt to meet three closely related conditions. First, the Earth systems sciences should be taught as an integrated subject with a focus on interactions, not as a domain comprised of separate, independent subdisciplines. By interactions, we mean the biophysical processes and dynamic feedbacks that link components of the Earth system, for example those that link atmospheric and terrestrial environments, and those that link terrestrial and aquatic environments. It is the need to study and understand these between-component interactions that defines integrated Earth systems science as a discipline in its own right (Chi *et al*. 1994; Lawton 2001).

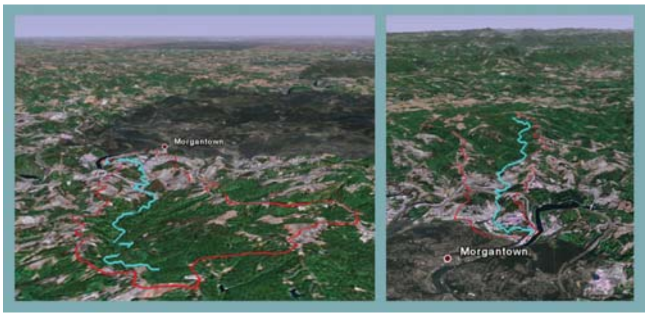
Secondly, Earth systems science education should use exciting, contemporary technology that facilitates student exploration of and inquiry into Earth system components and their interactions. While GLOBE promotes Earth system science, the tools to enable students to visualize the relationships between data are underutilized, unavailable, or simply not understood. Although some interactions can be subtle and a challenge to student understanding, many can be explored using the very technology that has driven many of the advances in our understanding of how the Earth system operates (Johnson *et al*. 2000). GPS units, freely available remotely sensed digital imagery and vector data, as well as the increasingly conspicuous and user-friendly web-based and desktop geographic visualization and exploration products such as Google Earth and NASA's World Wind, are developing very rapidly. Similarly, educational GIS packages including ESRI's Arc Explorer Java Edition for Education and the GEODE Initiative's MyWorld improve regularly. Technology that was not imagined by most science teachers ten years ago is now inexpensive or freely available, easily accessible, powerful, and remarkably user-friendly. Supplemented by a wealth of digital data, this new software will undoubtedly change the way Earth systems sciences are taught (Linn and Hsi 2000; Malone *et al*. 2002).

Thirdly, we believe that to be fully successful, Earth science education will require an appropriate organizational framework to explore relationships and study interactions. The most productive lesson plans are organized within a meaningful spatial context that facilitates the framing of issues and questions at the appropriate scale (NRC 2006). These lessons use space, and in some cases both space and time, as the conceptual and analytical framework within which data can be integrated, related, structured, and analyzed. By placing each topic or question into the appropriate spatial context, it becomes relevant to the student's own geographic framework and perspective (Bednarz 2000). By linking the topic to progressively larger spatial and temporal scales, students begin to understand the local and regional environment as nested phenomena, ultimately linking to the global scale where the Earth is perceived as a complex entity of open, interacting biophysical systems composed of biological resources, land, water, and atmosphere.

The GLOBE Land Cover-Biology and Hydrology Investigations

We have selected the GLOBE Land Cover and Hydrology Investigations as an example of the type of Earth system science curriculum integration that we are advocating because the thematic areas are already logically related within the GLOBE curriculum. Firstly, the connections between land cover and hydrology are easily explored using remote sensing and GIS tools. Secondly, these two Earth system components are directly connected through a series of observable, spatially quantifiable processes. Examples of such processes include major and minor types of overland flow, such as flooding and various types of erosion, point source and area source discharge, and an array of other common, spatially explicit interactions that link land use to water quality at a range of spatial and temporal scales.

For each Investigation, GLOBE provides a set of coordinated Learning Activities and associated sampling Protocols that guide students through various lessons and related data collection and analyses steps. In the Land Cover-Biology Investigation (Table 2), students use manual image interpretation, manual mapping, and automated classification of Landsat imagery using MultiSpec software to generate a set of land cover maps, followed by a map accuracy assessment. In the Hydrology Investigation (Table 3), students map their site and sample a range of water quality variables. As with the remaining three Investigations, students upload their data to a web site where it is displayed, shared, and utilized by Earth scientists and GLOBE schools around the world. The difficulty for teachers, however, is explicitly relating land cover to water quality. Because the GLOBE-provided Landsat imagery is not georeferenced, each domain is treated as an aspatial dataset and not explicitly referenced to the GLOBE study site imagery even though each specific study site has GPS coordinates. Fortunately Land Cover and Hydrology can be linked without fundamentally changing the GLOBE curriculum, by introducing a series of integrated Learning Activities and Protocols using the requisite geospatial tools of remote sensing and GIS. Using concepts of spatial thinking within a "watershed" framework, the links become clearly identifiable. Before undertaking the Integrated Land Cover-Biology Investigation, we recommend that students complete introductory sections of all five GLOBE Investigations as a foundation for studying the processes that connect them.



a) b)

Figure 1 A 3-dimensional perspective of the Cobun Creek watershed, Monongalia County, West Virginia outlined in red, using Google Earth Pro[1] with the terrain layer vertical exaggeration set at 3x (3 times the actual vertical displacement). By showing the terrain, students can more easily identify watershed boundaries. The view in 1 a is from the southeast looking northwest. Figure lb shows the same watershed from the northwest, and shows the Allegheny Mountains and Appalachian Plateau to the southeast. The darker areas in both scenes indicate areas covered by high resolution satellite imagery.

[1] Google offers several versions of Google Earth. The free version does not allow path and polygon creation. The Plus and Pro versions do. Google offers the Pro version free to qualified K-12 teachers.

Table 2 Selected GLOBE Land Cover - Biology Protocols. Protocols are measurements associated with each classroom or field-based Learning Activity. Learning Activities place each protocol into context. Adapted from the GLOBE Teachers Guide (2003).

	Recommended Measurement		
Protocol	Frequency Range	Location	Measurement / Data
Study Site Selection	once per site	pre-determined, centered on school	15 km x 15 km area, subset of recent Landsat image
Land Cover Site Sampling†	once per site	field-based	90 m x 90 m site, latitude, longitude, elevation, photographs, land cover classification
Biometry‡	semi-annually	field-based	canopy and ground cover, tree ht. and diam., herb-layer ht. and biomass
Manual Cover Mapping‡	once per site	classroom	manual image interpretation of Landsat image
MultiSpec Cover Mapping†	once per site	classroom	unsupervised classification of 15 krn x 15 km Study Site

† Requires using the GPS protocol
‡ Ongoing activities until study site is completely mapped

The Watershed - an ideal context for teaching spatial thinking skills

Catchment basins, commonly referred to as "watersheds", are the ideal spatial framework within which to initiate student exploration of terrestrial and hydrologic sciences, and are particularly appropriate when the focus is on land - water interactions. As discrete, nested, objectively defined areas, watersheds provide the relevant spatial framework and environmental and political context necessary for studying spatial and process-driven relationships between land cover and hydrology (Black 1996) (Figure 1). Because of their hierarchical nature, watersheds provide a multi-scale context for inquiry, beginning at the 'local' watershed scale where students have a familiarity with the environment and where hands-on teaching resources are accessible.

For example, water quality characteristics of the nearest stream can be assessed by students in the field, while supplementary data can be generated in the classroom or lab using digital imagery and GIS tools. Students can integrate the 'field' and 'lab' components using GPS technology to map water sampling locations and stormwater overflow points which are then visualized in the context of the stream network and base imagery displayed and queried within a GIS environment. Similarly, information on local land cover is accessible both on the ground via field trips and on the desktop through aerial or satellite image exploration. In a GIS, students begin to see the relationships between their field data and digital land cover type, size, shape, juxtaposition, elevation, slope, aspect, and other spatial and environmental characteristics. By beginning with land cover class, location, adjacency, and other relevant spatial relationships that link land cover to streams, students begin to see and understand some of the basic processes and interactions that operate within the watershed. These processes need not be understood in all of their technical complexity, but should be introduced at a simple level and developed in complexity as students master basic spatial relationships.

The preceding example demonstrates the initial process of "spatial thinking". Spatial thinking is a method whereby spatial relationships are used to frame, investigate, and resolve issues, and is based on three elements: concepts of space, tools of representation, and processes of reasoning (NRC 2006). In essence, spatial thinking:

> "depends on... using the properties of space ... for structuring problems, for finding answers, and for expressing solutions. By visualizing relationships... we can perceive, remember, and analyze the static, and, via transformations, the dynamic properties of objects and the relationships between objects. We can use representations in a variety of modes... to describe, explain, and communicate structure, operation, and function of those objects and their relationships" (NRC 2006).

Students gain a considerable educational advantage when they learn to think spatially, particularly when they simultaneously learn to use technology to address and resolve spatial questions (Kerski 2003). Although the GLOBE program has used GPS and remote sensing since 1994, it has not adopted GIS as a teaching and integration tool beyond the mapping tools located on the GLOBE web site that do not permit multiple data layers to be represented together (Figure 2). However the utility of GIS to individual Earth science domains is well established and the tools are exceptionally well suited to use in multidisciplinary fields where they facilitate an understanding of spatial relationships. The interest in global change issues provides a timely opportunity to expand the application of remote sensing, GPS, and GIS as tools for interdisciplinary Earth systems science education, to use geospatial technology as a means to integrate what were recently distinct domains of science education.

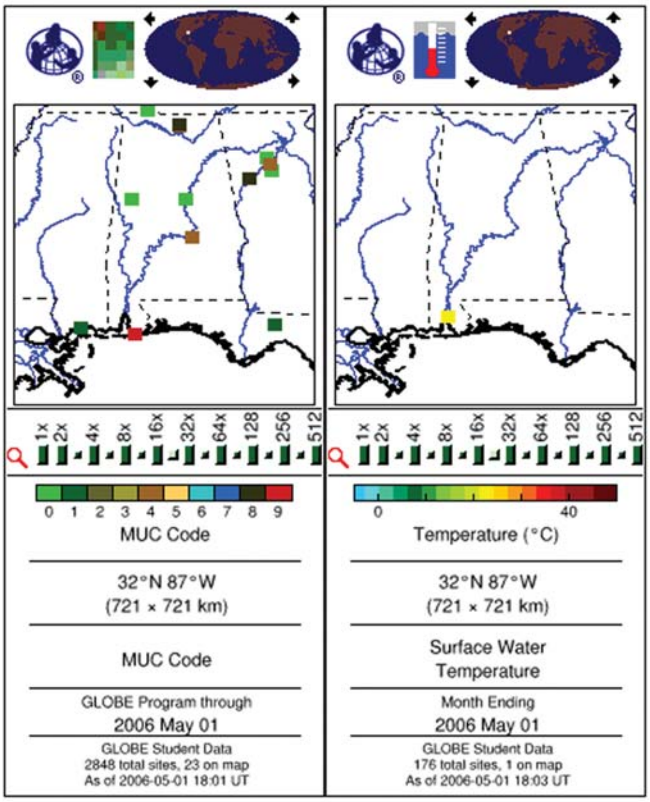


Figure 2 The GLOBE Program uses maps to display a wide variety of Earth science data. The map and panel on the left show locations where Land Cover sample sites have been sampled and classified using GLOBE's Modified UNESCO Classification (MUC) system. The map and panel on the right show a surface temperature sample location and associated temperature data.

An Integrated Land Cover and Hydrology Investigation - Investigating Cause and Effect

Exploration is only the first stage in developing an understanding of Earth systems sciences. The key for GLOBE teachers will involve exploration that is inquiry-based and guided toward a specific question or set of questions that

Figure 3 A hypothetical example of a student-developed digital land use map of the Mountaineer Mall and surrounding area created using the Google Earth Pro polygon" tool. Cobun Creek, in blue, has been digitized as a "path" feature. A map like this can be created in a short time and acts as an introduction to more skill-demanding and detailed digitization in an educational GIS package such as MyWorld.

require identifying relationships and making connections. Herein lie three challenges for GLOBE teachers that utilize remote sensing and GIS: to explore and understand basic principles within each domain, to identify fundamental links between the two domains, and, using student inquiry-based techniques (Audet and Ludwig 2000; NRC 2006), to develop interesting, challenging, class level-appropriate questions that investigate and assess the interactions.

In the Earth system sciences, the process of interactions can be thought of as cause and effect. Thus, to successfully link land cover to hydrology, it is necessary to identify the "causal" agent, for example a particular land use class, and an "effect", the impact that the particular land use class has on water quality. The most obvious approach to identifying a cause and effect relationship in this context requires identifying potential changes in water quality as water moves across a given land cover class. Land cover is the medium, the biophysical feature, upon which precipitation in the form of rain or snow falls, is collected, and is transformed in various ways as it moves through the landscape and into the nearest stream, river, or lake. Using land cover as the causal element, students are challenged to identify the processes that effect water quality within the watershed.

Table 3 Selected GLOBE Hydrology Protocols. Protocols are measurements associated with each classroom or field-based Learning Activity. Learning Activities place each protocol into context. Adapted from the GLOBE Teachers Guide (2003).

Protocol	Recommended Measurement Frequency Range	Measurement / Data
Study Site		
Documentation†	once per site	latitude, longitude, elevation, photographs, description of site attributes and details of location
Mapping	as needed	50 m transect showing shoreline, stream / lake characteristics, flow direction, opposite bank
Water Quality		
Transparency	weekly	Secchi disk depth or transparency tube reading depending on water body type (still vs. flowing)
Temperature	weekly	average of 3 samples, in degrees Celsius
Dissolved Oxygen	weekly	average of 3 samples DO in mg/L, taken concurrent with temperature and corrected for elevation / pressure
Conductivity	weekly	average of 3 samples in mS/cm, taken concurrent with temperature
Salinity	weekly	average of 3 samples of specific gravity, using a hydrometer, concurrent with temperature
pH	weekly	average of 3 samples using pH paper or pH meter depending on conductivity
Alkalinity	weekly	average of 3 samples in mg/L using LaMotte, Hach, or student-created test kits
Nitrate	weekly	average of 3 samples in ppm using nitrate test kits

† IRequires using the GPS protocol

The first step in this process is to develop an accurate land cover map. Thus, the Integrated Land Cover - Hydrology Investigation should begin where the original Land Cover Investigation leaves off, after manual mapping and automated classification using MultiSpec software. Because students will need digital land cover data in both raster and vector formats, they will need to digitize land cover using GLOBE's existing Modified UNESCO Classification (MUC) system. We take the next step in the land cover mapping process by developing a digital, vector-based land cover map using high resolution aerial imagery supplemented by the classified Landsat-based map, thus building on the existing GLOBE manual mapping exercise Protocols by extending manual mapping to the digital format where both qualitative and quantitative analysis is possible. By developing a digital data set of land cover polygons (Figure 3), students will be able to explore the quantitative and spatial relationships between cover classes and the stream network.

What follows is a hypothetical example of how a middle school Earth science class might accomplish the Integrated Land Cover-Hydrology Investigation in the humid eastern U.S., but it could be easily adapted to other regions with different climatic conditions. We have selected a shopping mall as a land cover type that could have an affect on local water quality. Other land cover types could also be studied depending on the physical and cultural geography, such as interactions between an industrial complex and a river in an urban area, or between high production agricultural land and a local stream in a rural area. We follow our hypothetical example through the next section to illustrate implementation. The authors are currently training K-12 science teachers to apply the Integrated Investigation in urban, suburban, and rural areas in West Virginia, USA.

Step 1. Scientific inquiry and hypothesis development

Questions are the key component to inquiry, and inquiry should be student-driven rather than teacher-driven (GLOBE 2003; NRC 2006). As a result of the experiences and knowledge gained, supplemented by the data acquired during the individual Land Cover and Hydrology Investigations, student inquiry into the effects of land use on water quality will likely develop. At this stage, questions do not need to be clearly formulated or framed in such a way as to identify the specific land cover type or specific water quality variable; questions are adequate assuming they have a spatial component and link land cover to hydrology. It is enough to inquire about possible spatial, process-based relationships, as long as the student is genuinely interested in the topic. When the student is directing his or her own educational experience, interest and motivation increase dramatically (NRC 2000).

To emphasize spatial thinking, questions should be framed in terms of geographic cause and effect relationships. For example, while mapping land cover, students in our hypothetical Integrated GLOBE Land Cover-Hydrology Investigation have identified the local shopping mall and assign a GLOBE MUC land cover class. They then observe that the mall forms an extensive impervious surface, and as such is capable of collecting a large volume of water during a precipitation event. Their most basic question, and a place to initiate formal hypothesis development, is “Does the mall affect water quality?” With assistance from the teacher, the

Table 4 Digital data required for the Integrated Land Cover-Biology Hydrology Investigation. Using this freely available data, students can create their own digital land cover vector data using Google Earth and various educational GIS packages.

Protocol	Dataset	Providing Agency	URL
<u>HYDROLOGY</u>			
Study site Documentation	Landsat image	GLOBE	www.globe.gov
Study Site Mapping	Aerial photography	NRCS	www.nrcs.gov
Watershed Boundary	NRCS HUC	NRCS	www.nrcs.gov
<u>LAND COVER - BIOLOGY</u>			
Manual Land Cover Map	Landsat image	GLOBE	www.globe.gov
Classified Land Cover map	Landsat image	GLOBE	www.globe.gov
Digital Land Cover Map	Landsat and aerial image	GLOBE, NRCS	www.globe.gov www.nrcs.gov

question can be further refined to address a specific water quality variable or set of variables, such as water temperature, turbidity, salinity, or another GLOBE measure that the students believe to be influenced by the mail. Using the visualization capabilities of GIS, students can phrase their question in a geographic framework in such a way as to explore the possible relationships between mall size, location, topography, proximity, and the water treatment and stream networks. The 3-D capabilities of geovisualization software are particularly well suited to developing and refining such basic geospatial questions; for the first time, students can see the mall and the surrounding land, including the stormwater overflow locations and stream network, from a new perspective.

Step 2. The data selection protocol

Although the existing Land Cover-Biology Investigation uses 30 m Landsat data, it will be necessary to supplement Landsat images with high spatial resolution datasets, which are available in many areas in the U.S. The high resolution data is necessary to more fully explore, describe, and document land cover and hydrologic systems (Figure 3). Exploration and description require first identifying the type, spatial resolution, date, and extent of data necessary to address the hypotheses developed in step 1. Thus, identifying, accessing, and exploring the necessary data are important steps that will determine the type and level of detail of questions in the preceding stages.

In our example, we assume that students are interested in measuring the size of the mall to determine the extent of impermeable surface area, and the extent of the road network and other impervious surfaces within a 100 m buffer of the mall. They select features within their buffer zone specifically to include development that they feel is directly related to the mall, such as feeder roads and associated transportation corridor cut banks that may influence water quality. They intend to use this information to estimate the quantity and quality of runoff generated by the mall during summer and winter rain events of approximately 3 cm of precipitation per hour, an amount that they have observed in the GLOBE Atmosphere-Climate Investigation occurs several times per year in their area. They plan to measure water temperature, turbidity, salinity, conductivity, and pH once in early June and once again in late January. They hypothesize that during June the runoff water temperature and pH are higher, while turbidity, conductivity, and salinity are lower. At the same time, they will sample the water in the nearby stream and determine if the differences in the selected water quality measures show the same patterns in stream water as they do for the mall runoff, or whether the patterns are different. They then select and map the specific sampling locations at the mall and along the stream using the high resolution imagery and the GLOBE GPS protocol. They decide to average the samples from three mall-site sampling locations. At the stream, they will acquire three samples immediately upstream of where the mall runoff enters the stream, and 100 m downstream of where the mall runoff enters the stream, again averaging the three samples at each location. They now have a digital, attributed land cover map, a set of hypotheses that spatially link a common suburban cover type to the watershed, and a sampling protocol. This process is an example of the "5 E" learning cycle where students are guided in the steps of engagement, exploration, and elaboration (Trowbridge *et al.* 2000). Through the development of student-based projects, these budding scientists will use their own data and GIS to explain their interpretation to one another and to critically evaluate their own and one another's assumptions (Bybee 1997; Linn and Hsi 2000).

Step 3. Map accuracy assessment

Digital raster and vector data may contain various spatial, spectral, or attribute errors depending on acquisition, development, and processing (Heuvelink 1998; Congalton and Green 1999). In most cases, some degree of additional processing and accuracy assessment is required before the data can be used for its intended purpose, even if that purpose is a simple qualitative or quantitative analysis. The type and degree of both processing and accuracy assessment should be minimal in these exercises, given the goal of exploring and utilizing digital data to address multidisciplinary Earth system science questions, and not to learn data processing and accuracy assessment per se. However, without becoming burdened with an unnecessarily complex accuracy assessment, students should be introduced to some of the basic approaches that are useful for determining map accuracy. GLOBE provides an effective map accuracy assessment Learning Activity and Protocol that is easily adapted to determining the accuracy of the digital land cover map. A matrix is developed using the student's reference data gathered in the field and the student-developed MUC classification cover classes developed using the aerial imagery. One significant advantage of using high resolution imagery as an alternative to Landsat images to map land cover classes is that the amount of information in aerial imagery permits a much more accurate initial cover class determination, thus reducing error significantly (Myeong *et al*. 2001). To keep the exercise within a reasonable time frame, we suggest limiting the assessment to those cover class assignments that the students are primarily interested in linking to stream water sample parameters. In this case, they would focus on assessing the accuracy of impervious land cover classes, and could expand this assessment to other cover classes, such as Forest, Grassland, or other natural or semi-natural ecosystem type, if they decide to study the affect of riparian buffer zones on stream conditions, for example. The point here is to maintain a focus on those cover classes that the students are interested in investigating, keeping in mind that stream conditions are a function of all land cover types within the watershed and that data accuracy is an important consideration in all remote sensing and GIS applications.

Step 4. Data analysis and interpretation

Student-lead inquiry in Earth systems science is an open-ended process where students determine the nature of the analysis. In our simple example, the students have identified a broad question, refined the question to a set of hypotheses that are testable, and devised a methodology to test the hypotheses. Without addressing complex, multidimensional questions, the data analysis and interpretation steps will determine whether stream water conditions are influenced to some extent by runoff from the mall and associated development. The known area of the mall, the amount of precipitation, and the temperature, turbidity, salinity, conductivity, and pH of the runoff allow students to estimate the amount and characteristics of water that flows from the mall into the storm water system and, during times of heavy runoff, directly into the local stream.

Taking our hypothetical example further, assume the students take samples in June during a substantial rainfall event of approximately 3 cm per hour. The three samples from the mall parking lot demonstrate a reasonable amount of variability in all measures except turbidity and temperature, both of which vary dramatically. Two have very high temperatures and relatively low turbidity, while the other is cooler and very turbid. At the stream location below the mall outflow zone, sample variability is low. Compared to samples taken upstream of the outflow, the mall-influenced samples are warmer, have a higher salinity and conductivity, show no difference in turbidity, and appear to have a higher pH. With the teacher's assistance and using a common spreadsheet package, they determine that the differences in averaged measures between upstream and downstream are significant for all variables except turbidity and pH. Although their initial question is not aimed specifically at understanding the relationship between water quality above and below the mall outflow, they have used a simple yet powerful spatial sampling approach to estimate the effect of mall runoff on the stream. By understanding the spatial and hydrologic relationship between upstream and downstream samples, they have taken a meaningful step toward documenting the effect of the mail on important measures of stream water quality that would not be possible from simply sampling water quality below the mall outflow.

Returning in the winter after a mixed rain and snow event, they repeat their sampling protocol at the same three locations and once again find differences in salinity and conductivity, but not temperature, turbidity or pH. Because of the extremely high salinity and conductivity values, this dataset raises a number of interesting questions that can be pursued in chemistry and biology class, linking salt concentrations to aquatic insects, fish, and reptiles that live in the stream. Are there larger populations, or more diverse populations, of insects above the mall outflow compared to below the outflow zone? Does the fish community differ too, or is it the same? Simply by asking these questions the students have used their geospatial thinking skills to seek valuable information about the health and productivity of their local watershed. They have connected physical and biologic domains in a fairly simple yet powerful way, demonstrating a series of fundamental connections between humans and the environment. Along the way they have learned the basic principles necessary to use geospatial technology to identify questions, to gather and develop the digital data necessary to address the questions, and to interpret the data in a powerful way that would not have been possible without applying a geographic perspective. They have used their reasoning skills in conjunction with geospatial technology to resolve a technically challenging set of spatial questions. In doing so, their environmental awareness has been raised.

Step 5. Reporting and submitting findings

After searching the library and Internet, and despite the obvious potential connections that the class has identified, the students agree that few studies have investigated the empirical relationships between impervious surface cover and stream hydrology (Snyder *et al*. 2005). They decide that a map of impervious surfaces within their local watershed would be a useful context for reporting their findings because it will show not only the spatial configuration and extent of their study area, but also because it will clearly show the extent of similar areas in the watershed. In fact, a two panel map showing a large scale, detailed view of the mall and stream sampling locations, next to a small scale map of impervious surfaces and the stream network, seems to be the most effective way of demonstrating the larger issue of watershed health and sustainability. A graphic and table adjacent to the detailed study area map clearly shows water quality variables at each sampling location. A narrative report describing their idea, methods, analysis, and conclusions accompanies the map. In their conclusions, they identify several other questions involving mitigation of runoff from development using riparian buffer zones and parking lot “tree islands”. Finally, they decide to put their map and report on the school's web site and link it to the GLOBE site so that other schools can contact them and ask questions, provide alternative interpretations, and describe their own integrated Earth system science and geospatial resource projects.

Conclusion

Integrated Earth systems science is leading to a much better understanding of the affects of land cover change on the global environment, including land cover change impacts on aquatic, atmospheric, and biological resources. Our improved understanding is in large part due to advances made in computational and geospatial technologies including remote sensing and GIS. At the same time, as we develop a better understanding of the complexities of the Earth system, we adopt an important responsibility; we become responsible to pass our understanding of our impact on the Earth system on to the current generation of K-12 students, to raise the environmental awareness of those who will soon be in decision-making positions.

One way to do this is to introduce students to integrated Earth systems sciences at an age-appropriate level of complexity, early in their formal education, through exposure to the local environment within the context of a safe, enjoyable, and relevant learning experience. Adapting the curriculum to the appropriate level will be key to the success of any integrated Earth system science education program and posses numerous challenges. An effective introduction is then followed at subsequent levels using an integrated approach, while maintaining a focus on local, relevant, interesting, student-based inquiry. The GLOBE Program's existing Earth as a System Investigation is an excellent introduction, but it is not an approach in and of itself. Integration of Earth components should be the conceptual approach, not a stand-alone unit, distinct from the single disciplinary domains of geosphere, atmosphere, hydrosphere, and biosphere. GLOBE's recently initiated "GLOBE at Night" project is an example of using internet-based GIS services to facilitate data viewing and exploration (GLOBE 2006), and focuses on the relationship between air pollution and star visibility around the world. In this way, spatial patterns can be explored and students can develop their own set of studies linking air quality to other Earth system components. For example, do areas with poor star visibility also have lower pH in precipitation? Students could use existing GLOBE data to link visibility with pH, and map pH and visibility across their region to explore a possible correlation. Advanced students could explore links between visibility, pH, ozone, and respiratory disease, linking Earth science to human health and wellness. Although somewhat nebulous, there are content standards addressing what we have termed "environmental awareness". For instance, at the K-4 level, science content standard F includes an understanding of "changes in environments". It says, in part, that:

> "Changes in environments can be natural or influenced by humans. Some changes are good, some are bad, and some are neither good nor bad. Pollution is a change in the environment that can influence the health, survival, or activities of organisms, including humans" (NRC 1996).

There are similar scientific concepts of pollution and environmental impact and degradation addressed at the grades 5-8 and 9-12 levels, and to understand these concepts is to have some level of environmental awareness. To actually acquire, record, graph, and discuss local air or water quality data is to gain highly relevant environmental awareness. If these data are compared over time or across space, and assessed relative to a standard or reference level, is to understand local environmental conditions in a very powerful way.

The Next Generation GLOBE program provides a timely mechanism for implementing this new integrative approach. GLOBE already supports teachers with lesson plans, exercises, a powerful web-based data entry and graphing interface, and background materials necessary to implement hands-on, inquiry-based integrated Earth systems science. What is lacking is an explicit set of exercises that formally link the five Investigation Areas at a level of complexity appropriate for each grade level. By using remote sensing and GIS to build upon the existing outstanding individual Earth system science Protocols and Learning Activities, teachers can begin to link one investigation to another through a series of student-lead explorations. Remote sensing and GIS are ideal tools to facilitate these connections. By integrating these tools into the curriculum, students not only gain new perspectives on the world around them, including their own backyards, but also develop important technical skills that allow them to expand their horizons in other directions as well (Cunningham 2002). In a world where teachers and students are both expected to "do more with less", the GLOBE Program's integrated Earth systems science curriculum can help both students and teachers make significant, meaningful strides toward meeting their common goals of understanding the Earth as a system.

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