

Chapter 5 - Scale

5.1 Introduction

One of the most useful beginning steps for addressing a problem in Environmental Science is to determine the time and distance scales of the objects and processes. This helps you identify the main processes and provides an estimate of their magnitudes. The second level of inquiry is to make observations that deliberately span several scales. The third level, which is very challenging, is to study how the processes work across scales. Each of these levels builds on the information from previous level.

The three levels are described below with examples of how they can be applied to environmental problems. One important aspect of the scale viewer is that this approach sets up the use of other viewers; in particular the systems viewer depends on knowing the major processes, objects and boundaries of the system being investigated. So even though the viewers provide different information about the problem, information from one can compliment and support other perspectives.

5.2 Identifying scales of physical objects and processes

This level is both quantitative and descriptive. The goal is to identify the major objects and processes and then estimate a range of characteristic of time and space values. For example, if part of the study deals with the interaction between birds, trees, and insect damage, then the characteristic space scales for birds would be size/weight and foraging range. Similarly the trees size and distance to neighboring trees might be important. In both cases the range of size of birds, trees and insects could also be of interest if it is very broad. The processes of interest would probably be the

growth rate (time to reproduce), the insect spreading rate (distance that the infestation moves per day), and other weather processes or disturbances that might affect the health of the trees, birds or insects. These ranges should all be listed in consistent time and space units (such as days and meters). Some example values are given in Table 1 and these are visualized in the accompanying Figure 1. Note that log-log axes are used (log of time vs. log of distance) because there is a wide range of values that need to be represented on the graph.

Table 1. Example of scales in a small forest system. Sizes are given in cm and characteristic time constants are given for processes.

insect size - 0.5 to 4 cm
 bird size - 10 to 30 cm
 tree size - 5 to 30 m
 insect doubling time - 10 days
 bird doubling time - 40 to 80 days
 tree doubling time - 5 years (1500 days)
 drought frequency- 1 every 10 years
 (3650 days)

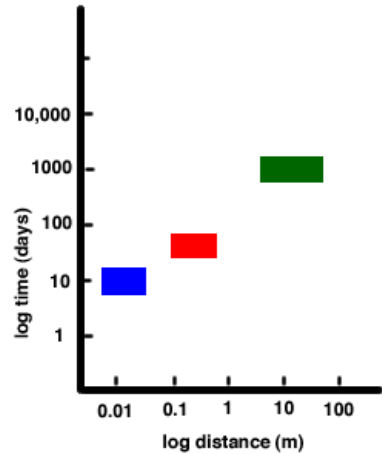


Figure 1. The green is trees, red is the birds, and blue is the insects.

Examine the texture of your surroundings.

Another way to interpret the effect of scale is to examine the "texture" of the study area. As you look around, what are the relative sizes of objects and how many are there. An easy example is looking into a stream pool that is about 1 x 1 meter. You may see a range of rock sizes from little pebbles to larger cobble. The texture of that system would be determined by the relative

distribution of different rock sizes. A comparison of the texture of two streambeds is shown in Figure 6.2.



Figure 6.2 a) Boulders in a stream in Candalaria, Spain. This stream receives heavy flows during the spring runoff from the Gredos Mountains. Strong stream flow can move very large boulders. Thus the "texture" of this stream has a large

number of larger boulders than would a small, slow flowing stream. b) By contrast a small stream in Yellowstone National Park that has a bed of small rocks in a sand bar. The forces that caused the texture of this feature are much less than above.

Or consider that you are doing a study in the middle of a pasture or meadow, there maybe very little texture that is obvious from your vantage point but if you do transects across the meadow you may see patterns of grasses that relates to the underlying soil types and moisture. Several 10 meter transects in different directions may help illuminate this structure. An aerial image of the Zumwalt Prairie in NE Oregon was analyzed for different types of ground cover (using by color). The percent of different vegetation/color types found is given in Figure 3.

a.



b.

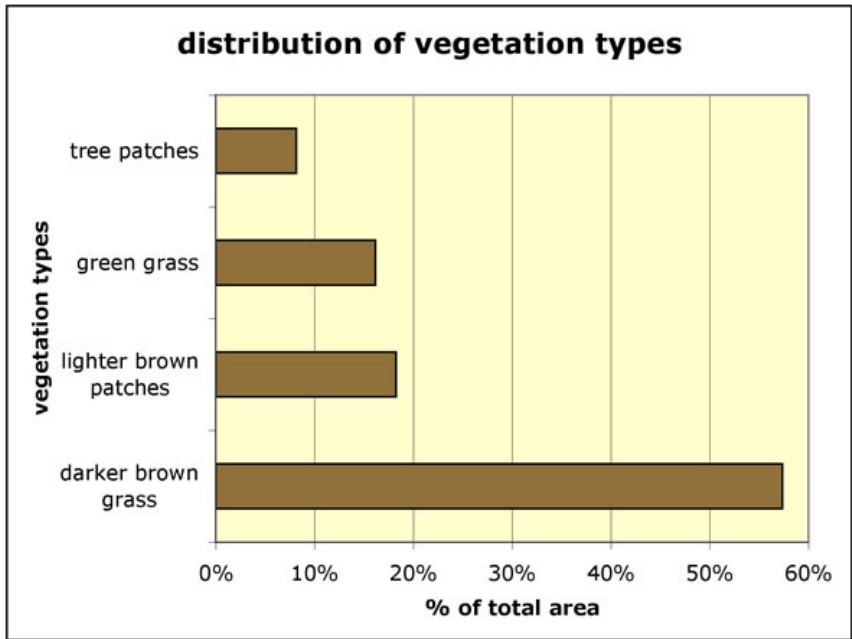


Figure 3 –Texture of a landscape. A) An image from maps.google.com This image is from Maps Google (Google - Imagery ©2010, USDA Farm Service Agency, GeoEye, State of Oregon, Map data ©2010 Google). The percent of the different colors was analyzed in the photo using Photoshop. B) Four categories of land cover as estimated from color and pattern.

The texture of these environments points to likely underlying processes and is very important for the organisms that exist at these scales. For example, in this little patch of the Zumwalt, small birds might have to flit from one stand or clump of trees to another to avoid the legendary number of birds of prey in this region. Please see the Nature Conservancy's description of this reserve at these two links:

- <http://www.nature.org/wherewework/northamerica/states/oregon/preserves/art6813.html>

- <http://www.nature.org/success/art17838.html>

Look for homogenizing processes

One of the major environmental impacts of humans is that we tend to homogenize small-scale landscape diversity and sometimes even across large scales. Much of this impact is from intentional projects that are designed to provide benefits to humans. Some of the most obvious effects are leveling of the ground, habitat destruction and construction of roads. The worry over "habitat fragmentation" is not that humans are breaking up homogeneous habitats, but rather that fragmentation allows the incursion of other forces into the middle of otherwise highly diverse and rich natural environments. Habitat simplification and the construction of corridors for human commerce are barriers for natural processes and are evident at all scales in the human/nature interface. For example, there are roads that range from only several meters across to super-highway complexes (especially the interchanges) that are several kilometers across. Roads and traffic often are a severe constraint to animal movement within their natural range. It has been claimed that there is nowhere in the continental United States that is more than 20 miles from a road (including gravel and other access roads). The automobile and truck traffic on roads is dangerous to animals and the transport of invasive and nuisance plant species is harmful to native vegetation. Road Ecology is emerging as an important sub-discipline to address the impacts and possible mitigation efforts.



Figure 4. Road impacts are so severe in some places that special highway overpasses or tunnels have to be built to allow safe passage of animals within their normal range. (Image from <http://www.huntingvt.com/wildlife-pictures.htm>: downloaded 9/13/2010)

Identify edge effects, dissipation zones and human energy intensity

These three concepts are related as they help describe the borders between human and natural areas and the coexistence of humans in a partially natural world. Consider a cleanly delineated human/nature border such as a road along a park. The edge effect is the distance from the road into the natural area for which the effect is felt. This effect depends on the target species or community, it may be only meters for grass because cars don't disturb grass unless they drive directly on it, but it may be tens or hundreds of meters for small mammals or amphibians because any little turtle trying to cross that road may suffer a disastrous fate. If the road is between upland and pond habitats for amphibians, the edge effect might include the entire habitat for that animal.

A dissipation zone is the region for which the stress is greater than the natural growth capacity of the community. The dissipation

zone deals with the direct release of energy from human activity. One example of a dissipation zone is along a roadside. In this case, it is similar to the idea of an edge effect. Other examples are the heat that is produced by a power plant warms the receiving water in a river or bay. In this case the dissipation zone is the region that has stress from the heat.

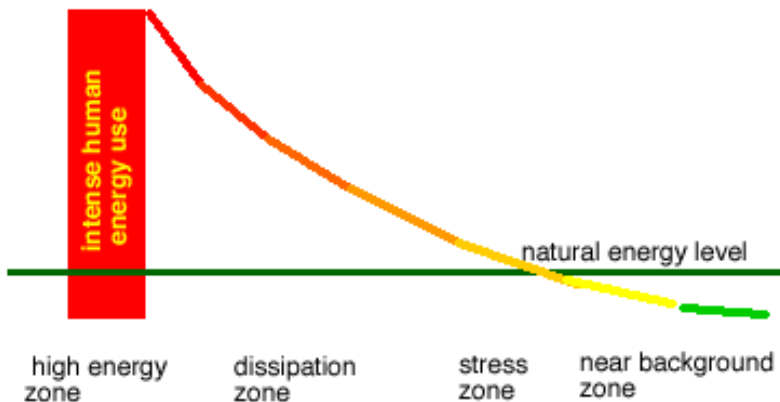


Figure 5. - Dissipation zones based on relationship to natural levels of power density.

One of the consequences of modern industry is that processes have been concentrated to allow for higher mechanical and thermal efficiency. This concentration leads to high energy densities at particular locations. Table 4 shows some areal power densities for common industrial activities. These power zones range from cars (15 kWatts/m^2), to American homes that might have an average power consumption of 5 kWatts and are 200 m^2 , which leads to a 1 kW m^{-2} power density. Nuclear plants for which the reactor generates 20 mega Watts and yet it is only 10 m^2 in size. The core of a nuclear power plants has about the same power density as the inside of a volcano (Ripl and Wolter 2002).

Table 4. Area power densities of different objects and activities in our society. (Conversion factors used are: 1 hp = 0.75 kW, 1000 kcal/day = 0.048 kW)

object	area power density (kWatts/m²)
200 hp car - total size (10 m ²)	15
200 hp car interface with road (4 wheels x 100 cm ² for each tire)	3750
200 m ² home or apartment that uses 120 kwhr/day	0.025
nuclear power plant core (20 megaWatt/10 m ²) <i>**recalculate size**</i>	2000
human (2000 kcal/day / (1 m ²))	0.1
human plus subsistence agriculture (10,000 kcal/day applied over 1 hectare)	0.00005
solar energy input at noon in summer	1.4

5.3 Starting Steps

Determine the boundary of the ecosystem area you are studying. For example, is it a watershed or multiple watersheds? It will be important to set this boundary large enough such that most of the processes are happening within the ecosystem, and the major processes are not crossing the boundary. For example, if you are studying a lake with only slow turnover and low river input, you could put the bounds around the lake. But if you were studying a lake that has high flushing rates from large river input and output, you'd need to include these rivers into your system for evaluation of the scales of the processes.

Identify the major physical features especially those that would determine process rates. These could be the volume of a lake or length of a river. At the smaller scales, the size of objects in the landscape is the "texture". For example, the size of trees in a forest or the size of boulders and riffles in a stream determines the texture.

Within this area and in consideration of the physical features, estimate the rate of important processes; don't forget to add in the long-term, slow processes. These often turn out to be some of the most important considerations. Intentionally look for processes that represent a wide range of rates, from seconds or minutes up to decades. Scanning for a range of processes in this way helps to avoid missing some factor that might be very important.

5.4 Measuring processes

A variety of techniques need to be used to measure processes that are at different scales. Below are some examples of techniques that can be use to address different questions in environmental science.

A. Species biodiversity (down to smallest scale)

- a. Quadrats (10 cm or 1 m, maybe larger): Count all the species in an area
- b. Multiple quadrats within a larger grid: Use a 10x10 meter grid and count random quadrats within that
- c. Transect: Count all the species that touch the transect line

B. Habitat types and connectivity (intermediate scale)

- a. Transect across study area: count all the habitat types encountered

- b. Areal mapping: Identify different habitat types by characteristic vegetation from areal maps or satellite images. Verify a number of spots with on-the-ground measurements.
 - c. Conductivity or corridor: Verify that there are no significant barriers.
- C. Current and historical land use
- a. Written documents for history of the impacts
 - b. Photographic documentation, with geo-referenced photographs or digital images

5.5 Level 3 - cross scale issues

Cross scale analysis is more than just measuring and comparing at different scales.

Different information at different scales

See Costanza -

5.6 Mistakes we make when we fail to account for scale

Outline notes to be filled in for the next version.

Are there appropriate limits to growth rate or power input

- so that it doesn't overwhelm the natural powers (Adams 1988)
- or eliminate landscape for cooperativity in the future

Discount rate for calculating costs of environmental projects

- assuming one rate to hold across large difference in time scales is the mistake
- leads to:
 - unfavorable rates of return from ecosystem projects compared to financial markets
 - difficulty in assessing long term impact of environmental damage, such as global warming (see the Stern Report - www.sternreview.org.uk)

Rates are assumed to be constant if averaged over a long enough time.

- ignores the importance of dissipative structures and pulsing in self-organizing structures that control these processes
- the mean levels can't explain these processes

Different cultural views of time

- cyclic
- pulsing
- linear

Psycho-economic studies on perception of time and risk

- brains are "wired" to make decisions on short time differently than on long term
 - McClure et al Science October 15, 2004
- inability to understand how to slow down (Wolfgang Sachs 1999)

5.7 Scale effective solutions

Applied and mission-driven scientific research needs to provide workable solutions for environmental problems. In the past, I interpreted this effort as the attempt to understand some problem at a small scale, find a solution at that scale and then address the "scale up" issue. For algal culture work, this meant studying a process at the flask scale (< 1 liter), then going to bench-top (5 to 10 liters), then to proto-scale production (20 to 30 liter carboys) and finally to large scale (100+ liters). For lake ecophysiology, this meant studying the processes at flask scale, mesocosm size in lake bags (100 + liters), near shore transects at scales of 100s of meters. This "scale up" problem is a significant intellectual challenge. It is not as simple as just studying larger volumes. Often there are fundamentally different processes operating at different scales.

My new view of this is that we need to solve the problem at an appropriate scale (Schumacher 1973). This scale might be a small hydrologic unit of a marsh, a section of stream, or a part of a watershed. If I can find a possible solution can be proposed and implemented in this situation then it should be possible to replicate this solution many times rather than "scaling up". It is important that the solution meets the criteria of solving the problem AND being financially feasible. For example, it seems possible to provide drip irrigation for a small farm using solar power, a shallow water pump, some pipes, storage tank and drip tape. This solution can be applied to several acres and could pay off the investment over several years of selling market vegetables and fruit (such as watermelon). This combination of technologies fits this scale and is financially feasible. Installing drip irrigation not only breaks even financially but also provides social and ecological benefits that are much harder to account for with dollars. Other similar projects might be a small-scale pump that moves water through a wetland to remove phosphorus. The payment would come from incentives for P-removal. The benefits from increased marsh growth for migratory bird food or enhancement of fish habitat are side-products of the P-removal.

In both of the examples above, appropriate technology is applied to a problem at one scale and provides an "effective" solution. The goal is to solve the problem and provide economic, ecological and social benefits in the process. The solution is "scale effective" or in Wendell Berry's (1981) words, solves the problem "in the pattern" of the environment. This "pattern" may be the specifics of the topology of the watershed, the individual farmer's need for drip irrigation in one part of his land, or taking advantage of the diversity in fringe marshes to a lake. Instead of taking a solution and making it bigger, which is the common practice justified by trying to achieve "economies of scale" (an efficiency argument, this approach takes a solution that is feasible at one scale and simply replicate it over and over again.

There are other instances of small-scale technologies. We currently use networks of computers, cell phones, and other almost disposable individual products that are combined into a resilient and durable network. Constructing a network of small, appropriate technologies can allow for turnover of the individual units that leads to incremental improvement of the unit design and the possibility for re-arrangement of the units in a process of self-organizing such as preferential attachment.

Scale-effective solutions start with scientific adaptive management driven inquiry (Norton 2005) targeted at the central scale of the problem. Part of that solution needs to be that the technology and process that is implemented at that scale is independently financially feasible. The other benefits (to individuals, the community, or natural capital) do not need to be documented or explicitly compared to the financial benefits, thus allowing a truly effective solution that focuses on the quality of the outcome (Drucker 2006). Then, instead of increasing efficiency by scaling up to larger scales with higher energy density and potentially increasing indeterminacy (Adams 1988, Pahl-Wostl 1998), the working unit is replicated many times. Focusing on local solutions for small patches of the environment transforms the problem from attempting to finding an efficient solution of scale efficiency

(following the traditional approach in which an intractable scaling-up process is required and may be one of the most difficult aspects of the overall project) to one that is looking for an effective scale solution that employs appropriate technology and looking for the highest quality outcome.

Simon Levin (1992) states that "the problem of pattern and scale is the central problem in ecology, unifying population biology and ecosystems science, and marrying basic and applied ecology" and claims that working across scales is one of the outstanding intellectual challenges for science and management. In my experience studying the history of the Klamath Basin and working with many people and agencies on these lakes, it seems that current lake restoration approaches reflect the general paradigm of science and industry, which is based on the assumption that there are "causes" to each outcome and that if we can identify the "cause" then we have to work to remove or minimize that factor. In addition, if there is a general factor of causation, then we can treat the problem more efficiently through large-scale application of whatever method we use to remove the factor. For example, the current thinking is that phosphorus is the factor that leads to lake eutrophication and we want to remove phosphorus input then it is most efficient (economically and policy) to do this for the entire lake basin. This traditional science/management paradigm also puts the scientist in the role of identifying the specific cause and passing information about that factor to managers in a policy neutral and "unbiased" manner. In particular, evidence for causative factors should be sought that are based on controlled experiments and a high degree of scientific certainty with little need for interpretation or judgment. As the management paradigm is shifting to a more complex view it is expected that the scientist-observer will be more involved in all aspects of monitoring, observing, judging, speculating and innovating.

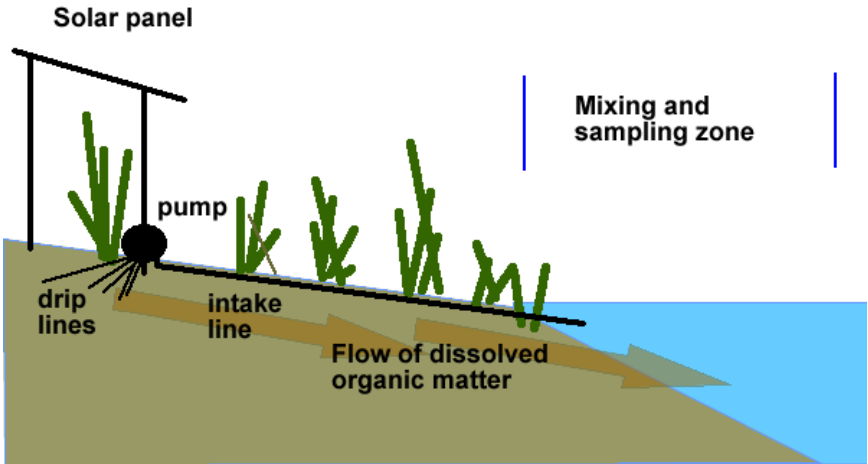


Figure 5. A schematic of using solar energy to pump water through a constructed fringe marsh.

The project described here shows the development of my research involvement in the Klamath Basin to be more active in proposing feasible solutions. This particular piece of work would simultaneously demonstrate that appropriate, renewable-energy technology could be installed at a small scale and demonstrate the environmental benefits of that project (reduced phosphorus in the lake, decreased algae in the lake, and wetland building). The project is also designed from the beginning to be replicable at this scale. If successful, there would be no need to redesign the technology to attain "efficiencies of scale". The project is effective at this scale and that can be simply expanded out. Although we may be proud of our large-scale civil projects in the past (dams, dredging, and levees), many of our previous successes turn out to be our present day environmental challenges. Small-scale projects that are networked together represent a new domain of human innovation (social and technological networking). For example, neighborhoods in San Francisco are joining together to buy solar equipment and get them off the grid (For Profit Activism –

Economist Jan 29, 2009). The value of these networks is in their inherent flexibility, adaptability and resiliency.

5.8 Case Study: The importance of considering scale in lake treatment

Upper Klamath Lake and Agency Lake are two closely associated lakes in Southern Oregon. In fact, as a result of The Nature Conservancy breaching the levees last October 30 (2007), there is more connection between these two water bodies. Both of these lakes are shallow (average depth 4.2 meters) and hyper-eutrophic. According to the Atlas of Oregon Lakes (Johnson et al 1985) Upper Klamath Lake is the largest (by area) lake in Oregon with an area of almost 25000 hectares (62000 acres). The drainage basin is 9415 km² (3810 square miles) and includes Crater Lake to the north and the Klamath and Sycan marshes to the northeast.

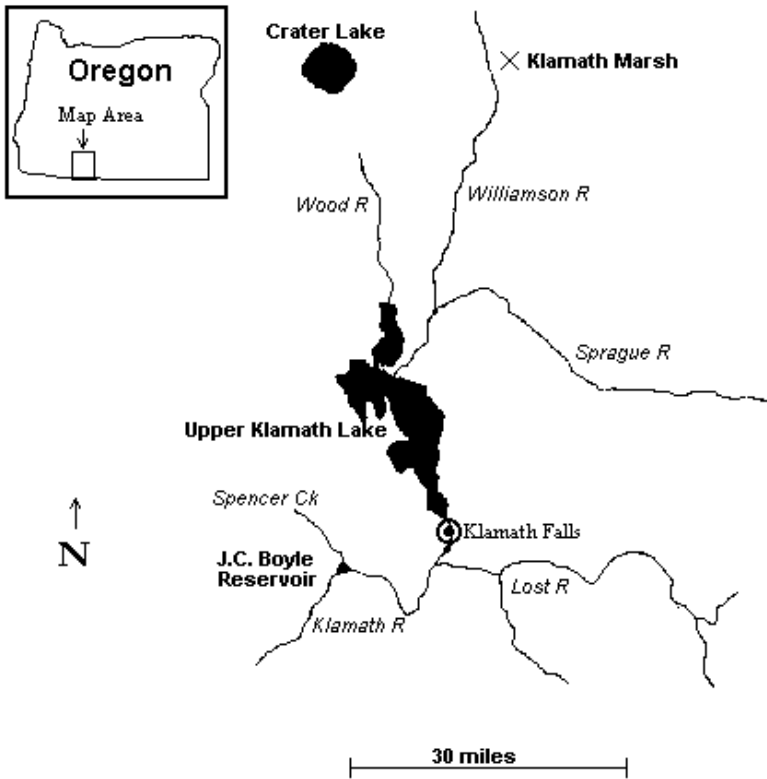


Figure 6. Location of Upper Klamath and Agency Lakes.

The water in these lakes is a valuable natural resource that is being shared by many people for many purposes. The general goal of the natural resource managers, citizens and scientists working in this area should be to understand this resource well enough to turn it into a sustainable resource that will maintain the freedom of choice for how the water and land are used by future generations. To do this, our society needs to meet two objectives; first we need to improve the current health of the lake (assuming that we don't want to pass a impoverished resource with few choices on to future users) and second we need to devise a plan to use the resource in a way that avoids "traps". A trap is a situation that is easier to get into than to get back out, i.e. changes in state that is not easily or readily reversible. These two objectives are necessary conditions

for creating a sustainable resource but still may not be sufficient to guarantee in any sense that the lake health and natural capital services will be sustainable.

In the grand context of these social, economic and scientific objectives for lakes, our group's research goals were much narrower. We wanted to help understand the immediate causes and mechanisms that lead to blooms of the cyanobacterial species *Aphanizomenon Flos-Aquae* (AFA), examine several existing hypotheses for the control of these blooms by either P interception or humic-rich marsh waters. An important part of the project for us was to provide this information in a context that will help manage these lakes for water quality and fish survival. Our research project is problem based, rather than curiosity based (Norton 2005). The situation in the lakes is that there is too much algae at some time that leads to decreased water quality and when the algal bloom crashes, the oxygen depletion is so severe that it leads to fish kills of the endangered suckers. This situation is a "problem" because we prefer cleaner water and we prefer to maintain the biodiversity of fish in the basin. Thus our problem-based approach reflects the values that society has for the uses of the lake.

Water quality and quantity is a "wicked" problem

Although a list of problems with Upper Klamath and Agency Lakes is standard (high nutrients, high chlorophyll, extreme alga growth, bloom crashes that lead to anoxia, disruption or death to endangered sucker populations), not everyone values the water in the same way. Of the major types of problems we usually deal with (simple, common pool resources, information and wicked), the water resources in this basin are definitely a "wicked problem" which have the following characteristics:

- people put different values on the outcome of having cleaner lake water

- as we develop more understanding of the lake system, some people's values change
- the problem is exacerbated by its history in which more water was promised than is available during many years
- there is a broad range of important space and time scales from the entire basin to individual bays in the lake and from days to decades



Figure 7. Harvester machine for skimming AFA off the surface of UKL. An obvious example that not everyone wants to have lower algal concentrations in the lake.

The best way to address a wicked problem is to employ the three principles of adaptive manage that have been described by Norton (2005) (table 5). This approach is suited for complex ecosystem management situations because it demands local evidence and experience to be primary sources of information and puts this into context using multiple scales. Addressing multiple scales forces managers to use a variety of techniques to address those different scales.

Table 5: Three major tenets of adaptive management (Norton 2005)

Experimentalism	emphasize experimental approaches that guide taking actions (including research and management) that will reduce the uncertainty in the future
Multiscalar analysis	use models and approaches that span time and space scales
Place sensitivity	adopt the local place, including natural resource and the people using it, as the perspective from which multiscalar management orients

Hypotheses for control of water quality

There are three active hypotheses that address the control of algal blooms in these two lakes; phosphorus limitation and two versions of the "limno-humic" hypothesis. All of these hypotheses follow from the problem narratives for these lakes (Table 6) which all start with land use changes that include farming and creating levees in the lake. These three narratives were considered in examining the algal response and attempting to devise measurements and/or manipulations that would help us discriminate between these possible mechanisms. An important point is that the underlying hypothesized causes would be operating at different scales and remediation or lake restoration by re-establishing this control would be both at different time and different space scales.

Table 6. Narratives for the problem of too much algae in Upper Klamath Lake and Agency Lake. The three narratives describe how phosphorus, humics blocking light, or humics as inhibitory agents may have controlled the algal population before changes in the basin and lake.

P control	Humics – light	Humics- inhibition
land use changes		
More non-point sources for P	Less marsh connected to the lake	
Increase in external loading	Less humic material into lake	
Initial algal growth	Higher transparency (without humics) allows faster algal growth	Lower inhibition by humics allows faster algal growth
Positive feedback cycles with internal loading of P from sediments	Colony growth in spring outstrips grazing control by Daphnia	
uncontrolled AFA growth which leads to blooms and crashes		

Scale of processes and measurements

The processes that we are most interested in for these lakes were the ones that could lead to rapid accumulation of the algae, AFA, or dissipation of a bloom and factors that might vary from year to year. The biological factors are the intrinsic growth rate of AFA, the rate at which these cells can adapt to a set of conditions, photoadaptation over the day that may limit or promote growth, and lake circulation patterns that could form or break-down a bloom through hydrodynamic (rather than biological) mechanisms. The relevant time and space scales for these processes are shown in Figure 8. Figure 8b shows how our

experimental approach was to deliberately "bracket" these time and space scales by using a combination of monitoring approaches including: point samples, dataloggers set at one point, weekly measurements from defined sampling stations spread across the lake, transects (see below) and satellite images or aerial photographs. All of these data except for the transects were available through public data sources, however we collaborated with USGS and the Bureau of Reclamation to share data.

We implemented high-resolution transects to collect data that would connect between established monitoring stations, go across gradients that might be shifting and to provide a more synoptic view that could be linked to the satellite information. We used a combination of Hydro-Lab and Turner instruments and a GPS that were all connected to a datalogger (Table 7). The response time is an important characteristic of the probes that we selected because we had to move the boat through the water at a set speed in order to get an image of the transect (or to connect multiple transects for a 2-D view).

Table 7. Instrumentation, frequency of sampling and spatial resolution for the high-resolution transects. The boat speed was 1.4 meter per second.

Parameter	Method	Distance (frequency)
Location	Differentially corrected GPS	1.4 m (1 sec)
<i>in vivo</i> chlorophyll a fluorescence	Turner Designs SCUFA	
Turbidity	Turner Designs SCUFA	
<i>in vivo</i> phycocyanin fluorescence	Turner Designs CYCLOPS - PC	
<i>in vivo</i> CDOM fluorescence	Turner Designs CYCLOPS - CDOM	
Conductivity	Hydrolab Sonde 5	8.4 m (6 sec)
Luminescent DO		
pH		
Temperature		

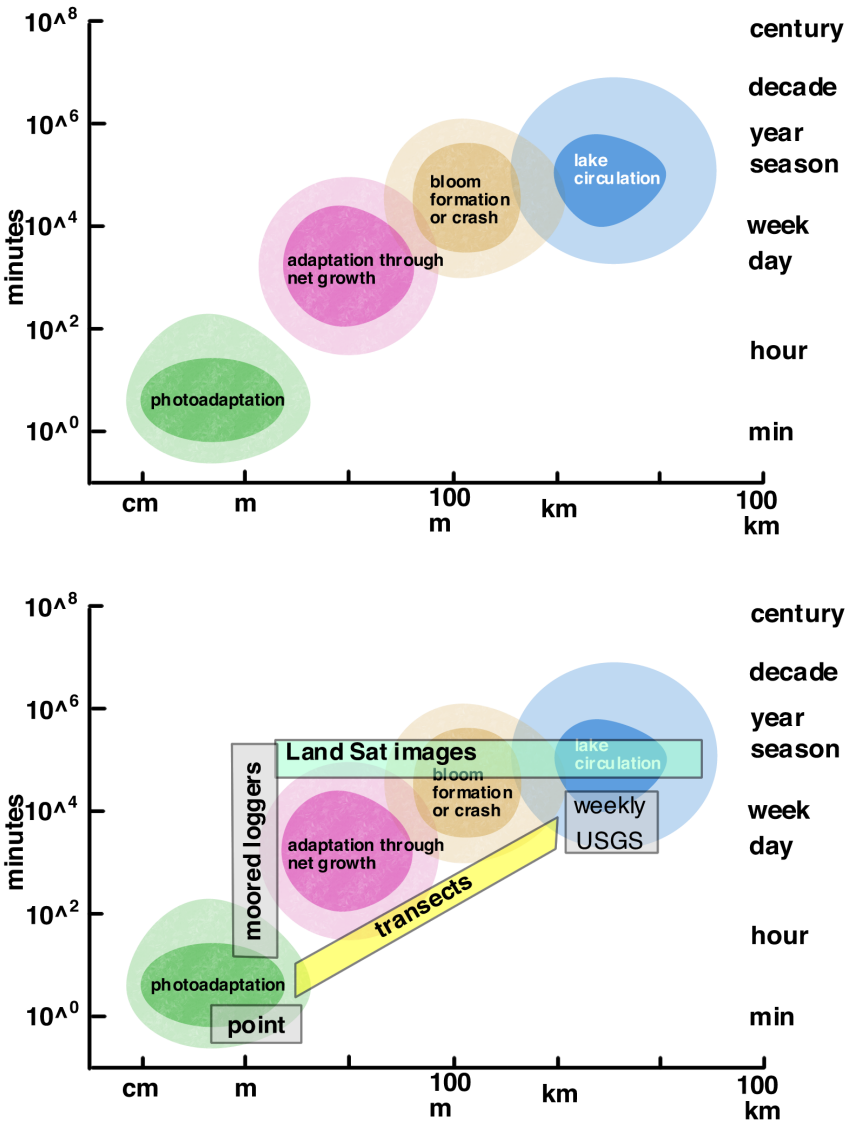


Figure 8. a) Relevant time scales of natural processes in Upper Klamath and Agency Lake. b) Bracketing of these scales with a combination of measurement and monitoring approaches.

Limiting the phosphorus loading to the lake has been estimated to take several decades (as discussed later) and the TMDL process that is used to drive and manage P-reductions applies is being applied to the entire upstream basin. In contrast, although wetlands have been removed from the entire lake, restoration of in-lake or adjacent marshes is taking place on the scales of kilometers of shoreline and areas of 10 to 1000 hectares. These marshes can be re-established on time scales of 5 to 10 years and the impact on water quality could be extremely local (only several hundred meters away from the marsh edge) and during limited times of the year (such as when water is being pushed through the marsh). Thus the current restoration tools work on very different scales.

Example of working across scales

The impact of humic material being introduced to the lake is a good example of the utility of examining the problem over multiple time and space scales. Humic rich water is being pumped into Agency Lake during the summer. This water has been stored in the Agency Lake Ranch behind a levee, and the Bureau of Reclamation pumps it out during a certain window of time. One part of the "limno-humic" hypothesis states that the input of humics should inhibit the growth of AFA and decreases the AFA bloom. In order to assess if this water is having any effect on the lake we have to consider the multiple scales of lake mixing and algal growth.

As an example of the coordinated measurements that can help describe the processes, we conducted transects on the same day as LandSat image and in a zone that overlapped continuous data loggers installed by the Bureau of Reclamation and USGS. The LandSat flies over every 16 days so we had to match our sampling schedule to that. The satellite information, even its raw form shows the variations in the distribution of algae across the surface and, in particular, the clearer zones around the pump input. The transects help combine the spatial and temporal information.

5.9 Summary