EVALUATION OF WATERSHED CONTROL OF TWO CENTRAL FLORIDA LAKES: NEWNANS LAKE AND LAKE WEIR

By

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Chairman: T. L. Crisman
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This dissertation relates lakes and watersheds by analyzing spatial patterns with GIS and simulation models of lake inputs associated with non-point sources. The flow of water and its constituents use energy transformations to organize landscape function and structure. This organization was evaluated with measures of materials, energy and emergy (a measure of real wealth based on prior work of nature and economy). Two Florida lakes and their watersheds, Newnans Lake and Lake Weir, were studied.

The convergence of materials and energy makes these lakes centers of high emergy in the watershed hierarchy. In these watersheds, there was also an area of concentration in human settlements. The spatial chronosequence of watershed influence increased with

economic development. The extent of influence was determined by both soil type and land use and was not concentric to the lake.

A spatial model estimated the average yearly total phosphorus input to Newnans Lake from non-point sources at $4.3x10^4$ kg/yr. Using Vollenweider loading relationships, phosphorus accounts for almost half the average algal chlorophyll concentration in Newnans Lake. Estimated average yearly total phosphorus input to Lake Weir is $3.4x10^4$ kg/yr, and accounts for all of the average chlorophyll concentration.

A simulation model of in-lake functions using oligotrophic calibrations responded to increased phosphorus input with a 20% increase in total biomass. The simulation with eutrophic calibration responded with a 10% increase. A hypereutrophic simulation oscillated with frequency controlled by the fish - zooplankton populations.

Simulated trophic state indices, using equations from Huber et al. (1982), was 78 for Newnans Lake and 38 for Lake Weir. This compares to a long-term observed index of 75 and 42, respectively.

Newnans Lake has higher emergy use in the watershed and lake, $2.5x10^{21}$ sej/yr and $1.1x10^{19}$ sej/yr respectively. Lake Weir uses $9.2x10^{19}$ sej/yr in the watershed and $1.0x10^{18}$ sej/yr in the lake. Newnans Lake watershed contributes 73 million Em$/yr to the lake — about 8% of the total watershed real wealth and about 800 Em$ per visitor. Lake Weir's watershed contributes 1.3 million Em$/yr to the lake — about 27% of the watershed and about 5 Em$ per visitor.

CHAPTER 1
INTRODUCTION

Where the telescope ends, the microscope begins. Which of the two has the grander view?

—Victor Hugo, 1862

Observation and intuition suggest an intimate connection between a lake and its watershed. Lake ecosystems respond to economic activity and material flows from their watersheds (Fluck et al., 1992a; Dierberg et al., 1988; Wetzel, 1983; Vollenweider, 1970). Still, there are unresolved questions in limnology and landscape ecology concerning this relationship (Lowe et al., 1997; Canfield, 1988). This dissertation evaluated watershed-lake relationships using systems concepts, computer simulations, geographic information methods, and the principles of energy hierarchy affecting spatial organization. Emergy concepts (Odum, 1996) were used to classify watersheds and lakes and to evaluate benefits of management alternatives.

As a single drop or torrential flood crest, water is a conduit for energy transfer throughout the biosphere. Pervasive and awesome at any scale, water cradles life, sculpts landforms and destroys economies. Water, carrying energy with it, is a tangible reality that defines the productivity, structure and diversity of every ecosystem in its path, and sets earth apart as a unique planet in the next larger scale, this solar system.

Water flows organize the land and lakes, using patterns of energy transformation to create function and structure. Whereas water flowing downhill from the landscape to the lake is the more familiar pattern, the lake also exerts an influence on its watershed, as expected with symbiotic self-organization (Odum, 1994; Allen, 1986; Salthe, 1985). Examples of this influence are the effect of the lake on the surrounding microclimate and the economic development that accompanies recreational use.

Increasing human presence in watersheds alters land cover, use and ultimately drainage patterns, thus affecting the quality, quantity, and timing of stormwater runoff. Aquatic environments on the receiving end of this discharge may experience changes in trophic state and shifts in species dominance (Cooke et al., 1983; Wetzel, 1983). Predicting surface water changes that result from increased development in a watershed may provide important management insights for avoiding negative impacts downstream. Consequently, research is needed to improve prediction of the cumulative impact of increasing watershed development on freshwater systems. This is especially critical as developed and developing nations alike become increasingly dependent on surface water resources.

This dissertation quantifies several important features of the watershed-lake system using energy paths, and their systemic impacts. The elements of focus are the study of runoff and its constituents within a watershed, the response of lakes receiving the input, and, in the opposite direction, the effects of lakes on the watershed.

Numerous hydrological models estimate overall runoff quantity, nutrient loading and timing changes, but do not provide watershed management criteria for optimum retention strategies (Adamus and Bergman, 1995; Heidtke and Auer, 1993). Many surface water quality indices, such as trophic state and total phosphorus, are static and minimize the contributions and interactions of macrophytes, consumers and watershed inputs (Canfield and Hoyer, 1992, Huber et al., 1982). Integrated long-term studies of terrestrial-aquatic dynamics in subtropical areas are few, and simulations of watersheds and lakes together using an overall system perspective and criteria of overall benefit are largely absent.

Models providing a better understanding of these spatial and cumulative temporal effects can be used by planners to reduce the negative impacts of watershed development. Simulated models and benefit indices can direct development to less sensitive areas, assist in prioritizing conservation of more sensitive areas, and identify critical locations for water retention and quality monitoring.

Two Florida lakes (Newnans and Weir) of different depths and trophic state were related to their watersheds. Patterns of development were analyzed, and nutrient, energy and emergy budgets related. Suggestions were made for managing the watershed using different scenarios of economic development that were consistent with system organizational principles.

Concepts and Perspectives

The central question in this dissertation concerned the coupling of a shallow lake and its watershed. A natural energy hierarchy is formed when both material and energy flows from a landscape scale converge on the lake, but the watershed also has a hierarchy of human settlements with an economy and concentration of information (Huang, 1998; Odum, 1994).

One method for assessing this hierarchy is to quantify the impact of cumulative watershed landscape changes on Florida's lakes. Changes in water influx from increasing development create energy and material pulses from a large landscape and carry constituents perhaps best left in upstream systems. These pulses and convergence of materials inarguably affect the downstream surface waters where nutrients are concentrated into a much smaller area. The following concepts were used in this study for analysis and synthesis of these relationships.

Scale of Components

All systems have components at many scales, defined by turnover times, territory, and energy consumption and output (Odum, 1994). A basic triadic structure representing three fundamental and contiguous systems levels is the minimum sufficient to study a process, its causes and its influence (Salthe, 1985). In Figure 1.1, the main components of the watershed are represented from lower left to upper right according to the scale of replacement time and territory of support and influence. Three levels presented for evaluating the lake in relationship to its watershed are the lake itself, in the middle, the surrounding natural systems, ranked below the lake, and the human economy, information and structure within the watershed, ranked higher than the lake. This ranking is proposed as a hypothesis.

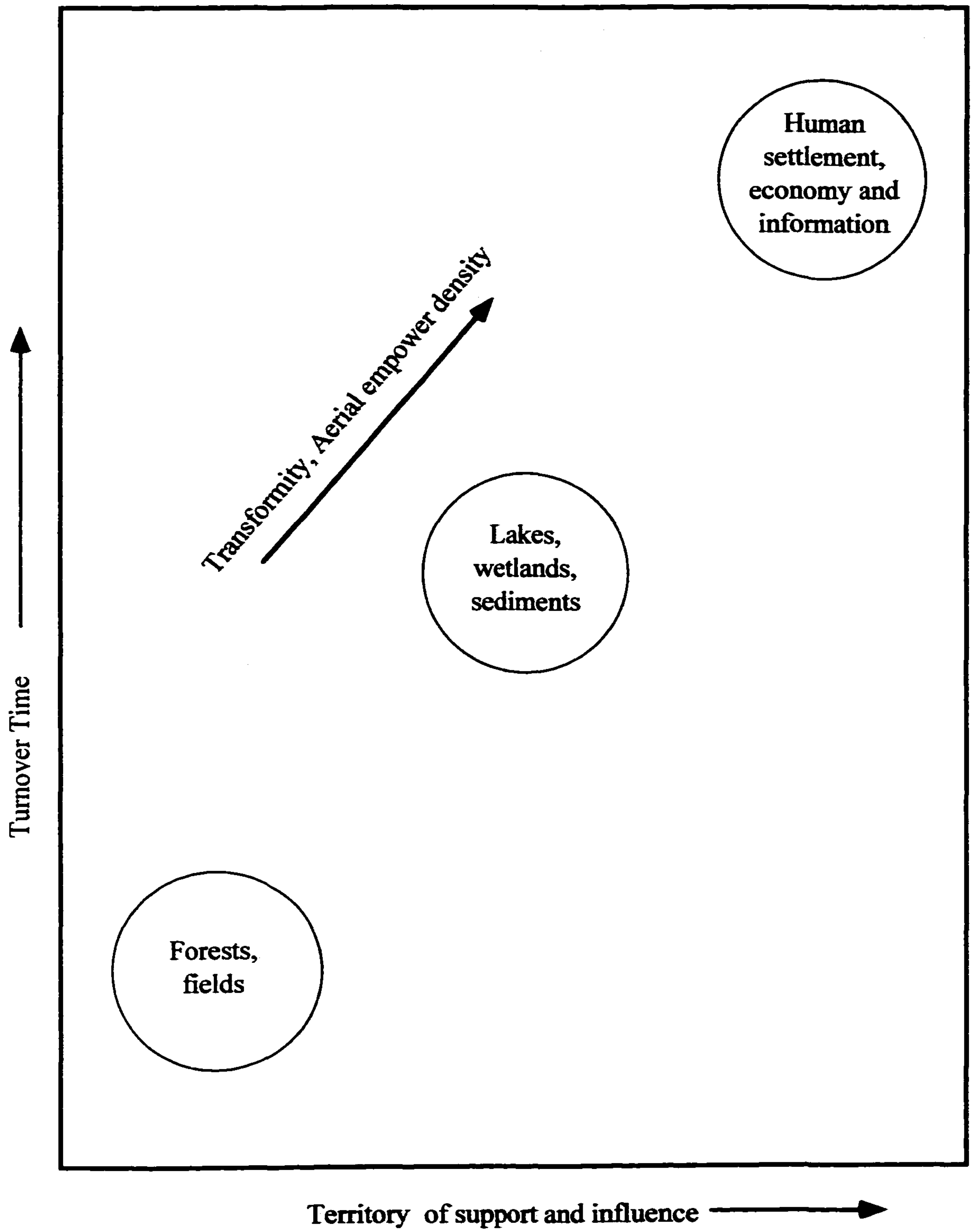


Figure 1.1. Components of a watershed-lake system on a graph of turnover time and territory.

Energy Systems Diagram

The components of any system are organized as an energy hierarchy because energy flows of many small processes converge and are transformed to make larger scale processes (Odum, 1994). The food chain from phytoplankton to fishes is an example. Components and processes of a system can be represented with an energy systems diagram in which the main energy flows converge from left to right (Odum, 1994).

The energy systems diagram in Figure 1.2 represents the main components of the watershed (Figure 1.1). Abundant lower quality energy (sun, wind, and rain) enters the system from the left. Important inflows from the economy of the surrounding region are delivered to the system in a more concentrated form and are shown entering from the right. Examples of these flows are electricity, fuels or information.

A pathway represents an influence a component has on others. Natural areas provide inputs to a city in the form of foods and aesthetic property values, among other things. The city exerts control over the natural systems through recreational use, development and management policy.

Emergy and Empower Valuation

Emergy can be used to evaluate the energy that has previously been required to make a component or flow, and is calculated from data on energy flows that converge into a product or process (Odum, 1996). Emergy is the available energy of one kind (solar energy) previously consumed in energy transformations. Empower is the rate of flow of emergy. Evaluating all pathways in solar emergy units (solar emjoules per time) is a way

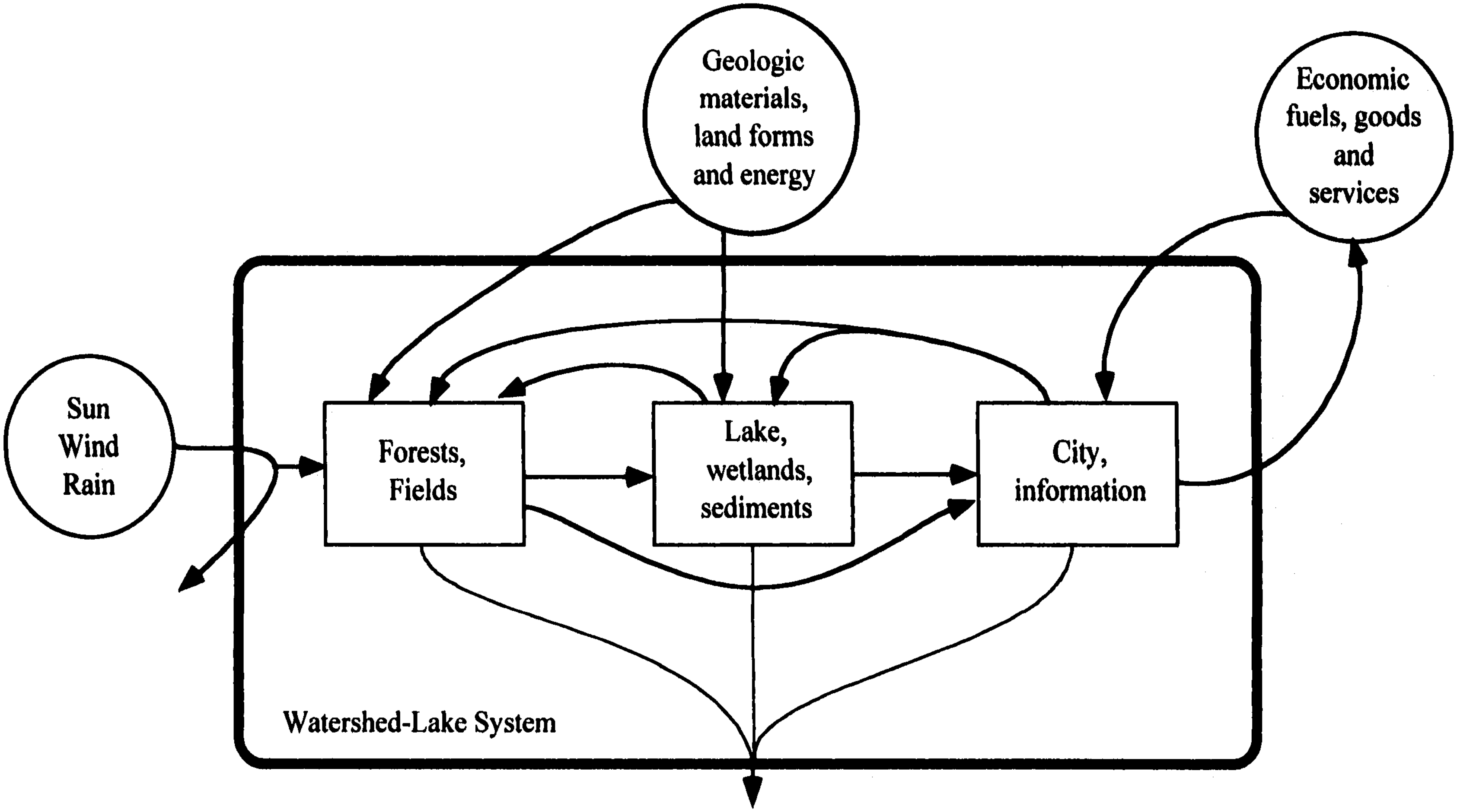


Figure 1.2. Energy systems diagram of a lake watershed including an area of urban settlement.

of putting all inputs on a common basis including human services and information. Because it accounts for previous contributions, emergy is useful for evaluating storages such as those in soils and sediments (Odum, 1996).

Transformity

Transformity is the ratio of emergy to the energy available within any individual, population, commodity, service or system (units: solar emjoule/Joule) (Odum, 1996; Odum, 1994). Transformity can be used as an indicator of energy quality because it measures what has gone into a unit of energy in the item, and because it increases with each energy transformation (Odum, 1996). In an energy systems diagram, transformity increases from left to right (Figures 1.1 and 1.2).

Transformities for many commodities and natural energy flows have already been calculated and can be used to determine the amount of emergy that a similar item contributes to a system. Transformities are dependent on the process used to create any entity and show variation between studies. High values result when an inefficient process is used as the basis for evaluation (Odum, 1996). Transformities should be selected from studies of systems similar to the one being evaluated, or computed with representative information.

Transformity and Control

The energy hierarchy determines the scales at which controls of the system are exercised (Odum, 1994; Salthe, 1985; Allen, 1982). Items with larger territories and storages, control smaller scale functions with faster turnover times. Presumably, larger entities occur as a result of more energy transformations and concentration, and can exert influence over smaller items having more diffuse energy storage. Consequently, assuming an efficient process, a joule of energy of high transformity also has more influence than a joule of lower transformity. The hierarchy represented in Figure 1.2 depicts many higher transformity items on the right returning controlling actions to exert large effects on items to the left. For example, agencies with high transformity are part of the information component, and exert considerable influence on a lake when water level stabilization plans are implemented.

Multistage Processes of Material Flows

Materials such as nutrients circulate within a watershed system while receiving some inflow from outside and releasing some outflow to the surroundings. Most of the pathways in Figure 1.2 are accompanied by material flows.

Watersheds are naturally engineered, multi-step, cascading treatment processes for materials draining toward a lake (Figure 1.2). Developed areas recycle materials to the watershed in the form of runoff and its constituents, and the intervening natural terrestrial systems sequester nutrients on the way to the watershed focal point, a lake in this case. If these treatment stages are decreased or eliminated, the larger scale watershed process is short-circuited, creating pulses and increased convergence of materials and their emergy within the lake.

Some materials are also returned from the lake to the watershed, thus dispersing nutrients and energy outwards. Migration of fish and birds and human use of the water or lake products are examples of this reversed distribution.

Emergy per Mass and Concentration

Since available energy is required to concentrate substances, the emergy per mass of any solution increases with the concentration of the element in the water, and is greater than the chemical energy of the element by itself (Odum, 1996). One relevant example is the phosphorus present in watershed runoff. Phosphorus is delivered in concentrated forms, such as fertilizer or industrial reagents, to components high in the watershed hierarchy - agriculture and urban economies. The phosphorus not immediately used is diluted by rain, irrigation or flushing water, and low concentration solutions are dispersed to components lower in the hierarchy - forests, wetlands and lakes.

The emergy of a material can be calculated by multiplying the known mass delivered to a system by the ratio of emergy to mass. These ratios have, in many cases, been evaluated in previous studies. This is particularly useful when the item is present in the system, not from a process of energy concentration, but rather as a material in a recycle pathway. Recycling materials disperse (right to left in Figure 1.2) in the energy hierarchy. Because the original energy was used in the process of concentration, the remaining energy requires a concentrated pulse to be useful as it disperses its influence over a larger area (Odum, 1996; Odum, 1994).

As runoff moves downwards through the watershed, the actual concentration of runoff constituents may not change significantly. However, the spatial concentration of water and phosphorus increases and carries with it the emergy of all the runoff and constituents used in moving to the point of concentration. This includes the geopotential emergy inherent in the watershed slope.

Empower Density

The amount of emergy flowing through a system over some unit time is it's empower (Odum, 1996). Spatial areas with convergence of emergy, such as cities, will have a higher concentration of empower than areas using less emergy, such as forests (Odum, 1996). By measuring the total emergy flux per unit area, a relative density value is obtained, similar to measures of development density used by city planners. This empower density (areal empower density) is useful in identifying the centers of energy hierarchy.

Spatial Organization

Just as hierarchies of convergence are evident in flows of materials and energy through food webs to fish populations, pathways of the energy hierarchy also form converging patterns in space on a landscape scale (Lambert, 1999; Huang, 1998; Odum 1994) . For example, waters from runoff converge into larger streams of increasing order, and convergence of services, information and materials within the landscape concentrate into cities. Large central cities are surrounded by many smaller towns and even smaller villages and clusters of residence, interspersed with the agricultural and natural systems providing environmental services. The smaller towns ship goods to the city, and the city in turn exerts control over the smaller by returning information, services and dictates for production.

Larger energy flow builds greater spatial structure (Odum 1994) evident in urban centers, mountains and perhaps lakes. They are dependent upon inflows from the surrounding landscape — the more structure built, the larger the support area required.

Record of Lake Functions

Short-term lake functions are influenced by both the inflow of constituents from the watershed and recycling of nutrients stored in the sediments. Frequently, pulsing storm events deliver large quantities of emergy as water, kinetic energy, nutrients and other terrestrial contributions. Wind energy is transformed into kinetic energy in the water, scouring the bottom and resuspending sediment. The materials and energy stored in these sediment components, therefore, constitute a history of contributions to the lake.

Emdollars

Production and use of real wealth by the economic system depends on availability of environmental resources and services. These assets are measured by emergy and its economic equivalent, emdollars (abbreviated Em$).

Emdollars are the part of the gross economic product associated with an emergy flow or storage (Odum, 1996). The emdollar value of an item is determined from its proportion of the emergy of the entire economy. Emdollars are, consequently, a measure of the real wealth in the system, including not just monetary payment for human services, but also the services provided by the environment.

The total emergy consumed within a system divided by its economic production provides an emergy/money ratio for an economy in a particular year. This ratio, when divided into an emergy value for natural resources under study, is useful in determining an economic equivalent (Odum, 1996).

Estimating Benefits of Lake Management

The benefits of different management scenarios can be evaluated with emergy and emdollars. More emergy production and use means more real wealth contribution to the economy. Policies for lake and watershed management can be dedicated to maximizing emergy and emdollars, but emergy can also be used to examine the efficacy of other objectives, for example longer term carrying capacities for lakes and watersheds.

As well documented in ecology, when two factors interact in production, output is greatest when neither is limiting (Odum, 1994; Odum, 1983). One of these factors will contribute more energy, while the other will have a higher transformity. The relationship between light and phosphorous availability is an example. When the component higher in the energy hierarchy (e.g. phosphorus) feeds a matching quantity of emergy back to the unit inputting emergy at the lower level (e.g. light), system production is maximized with more efficiency in emergy use, and limiting factors are balanced (Odum 1996).

Previous Studies

The following review of published studies cites many ways used previously to relate lakes and watersheds in Florida and elsewhere.

Shallow Lake Limnology

Questions concerning the role of the watershed in eutrophication of shallow lakes center around whether the response to increased availability of in-lake nutrients is greater than the effect of watershed inputs. Studies to determine the importance of internal loading contributions to eutrophication have been inconclusive (Hansen et al., 1997; Schelske, 1989). Some studies of shallow lakes show a direct reduction in trophic state variables with reduction in external loading (Scheffer, 1998; Lowe et al., 1997).

Shallow lakes (<3 m) have two unique properties that create phosphorus and productivity dynamics differing from deeper temperate lakes. Thermal stratification is short-term or absent, decreasing the amount of time that phosphorus is segregated from the epilimnion (Scheffer, 1998). Further, less wind energy is necessary for resuspension of bottom sediments, increasing the fraction of nutrients recycled into the upper water column (Scheffer, 1998; Carper and Bachman, 1984).

However, resuspension of noncalcareous sediments can also provide adsorptive sites for phosphorus, thereby reducing its availability, at rates varying with pH levels. This interaction is particularly favored under oxygenated conditions often present during mixing. (Hansen et al., 1997; Olila and Reddy, 1995)

Shallow lakes in Florida often do not develop a stable thermocline at any time in the year (Whitmore et al., 1996) and are subject to frequent sediment resuspension (Brenner et al., 1990). However, the majority of Florida lakes are softwater with noncalcareous soils (Canfield et al., 1982). Consequently, productivity may not increase due to in-lake resuspension, and watershed inputs may then still impact lakes with significant sediment nutrient deposits.

Nutrient Dynamics and Loading

A connection between point-source nutrient loading and increasing eutrophication in lakes has been documented in many cases (Scheffer, 1998; Cooke et al., 1993; Wetzel, 1983). Elimination of these inputs has provided varying degrees of reclamation success, and initially, depth of the lake was thought to be the determining factor (Cooke et al., 1993). However, recent studies in the Netherlands have shown reduction in eutrophication of shallow lakes following decreases in point-source nutrients (Scheffer, 1998).

Vollenweider (from Scheffer, 1998 and Wetzel, 1983) constructed an empirical mathematical model linking average phosphorus loading to a lake from the watershed to the concentration of both phosphorus concentration (P_{wc}) in the water column and algal chlorophyll (Chl). Both are ratios of phosphorus loading (P_i) to retention time (T_r).

$$P_{wc} = c * P_i / (1 + T_r^{\,0.5}) \qquad (1)$$

$$Chl = 0.55 * P_i / (1 + T_r^{\,0.5})^{0.76} \qquad (2)$$

Many studies have estimated watershed phosphorus loading to lakes based on empirical coefficients of export from specific land uses (Reckhow et al., 1980; Huber et al., 1982; Gottgens and Montague, 1987; Heidtke and Auer, 1993; Adamus and Bergman, 1995; Harper, 1996). Although the majority of the loading reduction emphasis has been point-source loads, reduction of non-point source loads has become of greater interest recently. Agricultural runoff appears to be a primary focus (Young, et al., 1989; Srinivasan and Arnold, 1994).

Some studies have shown that increases in watershed development are approximately proportional to phosphorus loading to lakes (Weibel, 1969), but another large scale Florida study showed no correlation between the amount of land in development and the overall trophic state of the lake (Huber et al., 1982). This is likely due to other geological and soil conditions both at the point of runoff and in the intervening distance to the lake, as shown in the pilot study for this project (Brandt-Williams, 1995). This study shows that while the percentage of developed land use did not correlate with trophic state or chlorophyll concentrations in seven Florida lakes, phosphorus loads from non-point sources calculated from deposition, soil, and drainage properties correlated strongly with both trophic state and chlorophyll.

Spatially Distributed Surface Flow Models

There are two primary approaches to incorporating spatial variation into runoff and seepage models: stochastic and raster-based geographical information systems (GIS). Stochastic approaches use probability density functions to translate the uncertainty of randomized input data into probability distributions for the output response from the model, and have been in use for some time (Chow et al., 1988). Recent research in stochastic methods for spatially distributed hydrology models has focused on reducing the number of simulations required to generate output curves (Braud et al., 1995; Kool et al., 1994), and more recent use of neural networks may increase this method's applicability to spatial variations.

Despite increasing ability of stochastic models to generate field data measures, lack of specific mapping references hinders their use for appropriate remediation siting. GIS models, while allowing greater flexibility in handling spatial variability, also involve high levels of computational time. Therefore, a certain amount of parameter lumping is still used. DeVantier and Feldman (1993) completed a review of lumped and distributed models through 1993.

Three recent studies of interest attempt to limit parameter lumping, using either a physics based approach or higher resolution spatial data. Julien et al. (1995) apply Green-Ampt equations to each map cell to determine infiltration for an individual storm event, and use two-dimensional Saint-Venant equations of continuity and momentum to model flow between cells. Excess overland flow is automatically routed to connected channels and modeled with kinematic wave functions. The model requires soil texture and deficit data, Manning's roughness coefficients, basin connectivity and geometry, and rain. Nutrient transport functions are not included.

Heidtke and Auer (1993) used a GIS-based non-point source loading model to assess water quality in a New York lake. Empirical land use and soil parameters affecting phosphorus runoff were incorporated into a modified Universal Soil Loss Equation to calculate an estimated load from each basin cell (1 hectare). Comparison to known tributary loading showed similarities between the model and empirical evidence. A suggestion for a method to compare to water quality was provided, but actual comparisons were not tabulated.

Adamus and Bergman (1995), using empirical nutrient and runoff coefficients determined in Florida from mean runoff and pollutant loads, presented distribution maps for the entire St. John's River watershed. The results were based on average land use densities and the four basic hydrological soil groupings. No correlation with water quality was presented.

Lake Valuation

Classification of lakes usually involves division into three categories of productivity: eutrophic (highly productive), mesotrophic (moderately productive) and oligotrophic (unproductive). Numerous models, both quantitative and qualitative, have been put forward as methods for classifying lakes and reservoirs and to assist in determination of problem systems, as well as prioritization of reclamation efforts. (Wetzel, 1983; Huber et al., 1982).

Early indices used presence or absence of indicator species to rank eutrophication, and Nygaard's algal ratio was often used (Wetzel, 1983; Taylor, 1978). Nygaard's ratio of typically eutrophic species to common oligotrophic species is not applicable, however, in areas where the species used do not commonly exist (Taylor, 1978), and it is not a measure of water quality perceived by the public (Kratzer, 1979).

One of the most commonly used multi-parameter indices is Carlson's Trophic State Index (TSI), although his original intention was that each index (Secchi disc, chlorophyll and total phosphorus in the water column) be used in relation to each other to infer limiting factors and the presence of other light inhibitors. Carlson devised a log transformation of empirical data available for temperate lakes so that a ten point difference was directly proportional to a doubling (or halving) of algal biomass for each parameter. (Carlson, 1970)

This TSI is insufficient for nitrogen limited lakes, uses relationships between parameters established in temperate lakes, not Florida, disregards macrophyte populations, and does not provide a single management index. Huber et al. (1982) proposed a modification of Carlson's TSI using a Florida lake data base that is now often used in Florida studies. Several permutations were offered to account for phosphorus or nitrogen limited systems, as well as nutrient balanced lakes. An index greater than 60 is considered eutrophic; the split between oligotrophic and mesotrophic is still nebulous. Macrophytes were not included.

A traditional valuation of lakes has always been the number of users or monetary advantage to the local economy, both in recreational value and waterfront property taxes. However, uses of oligotrophic and eutrophic lakes are very different, and monetary values are generally inversely proportional to trophic state index values.

Paleolimnology

Sediment cores from lakes have been suggested as a way to reconstruct a history of lake productivity using both remains of organisms and phosphorus (Brenner et al., 1993; Smol, 1992; Binford et al. 1986; Frey 1969). Using inferences from current water chemistry and species communities and the connection to surficial sediments, longer term function and structure are implied and can be used to determine the original trophic state of the lake (Smol, 1992). Because much of sediment deposition in a lake originates in the watershed, lake sediments contain a history of basin disturbance (Binford et al., 1986).

However, caution in interpreting the results in shallow, wind-stressed lakes is advised (Whitmore et al. 1995) because of frequent sediment redistribution. Further, shallow lakes are subject to photochemical oxidation of bottom sediments, limiting the use of sedimentary pigments as a comparative tool (Flannery et al., 1991).

Both C/N ratios and total phosphorus (TP) in sediment cores have been used to evaluate Newnans Lake. A study by Flannery et al. (1991) resulted in low and stable C/N ratios, suggesting that Newnans has been eutrophic for some time. Whitmore et al. (1998) found steadily increasing phosphorus deposition. Gottgens and Crisman (1993) found differing levels of TP deposition dependent on position in the lake, with increasing deposition near the inflow (north) and decreasing deposition near the middle and outflow (south).

Lake Weir's core (Crisman et al., 1992) shows a sharp increase in TP accumulation between 1970 and 1980. An equally steep decline in TP is exhibited between 1980 and 1990.

Watersheds Evaluated

Two lakes in Central Florida (Figure 1.3) were included in this study, Newnans Lake, near Gainesville, and Lake Weir, near Ocala. Newnans Lake has a 20:1 watershed to lake ratio, with a relatively flat, forested watershed and extensive cypress, bayhead and mixed hardwood swamps surrounding the entire lake perimeter. Lake Weir has a 5:1 watershed to lake ratio, with a steeper watershed than Newnans. Weir's watershed was predominantly citrus groves and pasture until the mid-1980s, and is now predominantly residential and pasture.

Newnans Lake

Newnans Lake is located due east of Gainesville, Florida, in Alachua County (29°40' N, 82° 12' W). Newnans is part of the Oklawaha River basin and is located in the Central Valley physiographic region (Canfield, 1981). The lake has a water surface area of 2,965 ha, and the elevational watershed has approximately 58,000 ha land area. The mean depth is 1.6 m (Lassi and Schuman, 1996), and the estimated flushing rate is 0.6 years (Gottgens and Crisman, 1993). The average fetch is approximately 2.41 km.

Two small creeks, Little Hatchett Creek and Hatchett Creek, are the main tributaries flowing into the lake, and Prairie Creek is the single surface water outlet. Little Hatchett Creek has an average annual flow rate of about 4 cfs, and Hatchett Creek's annual flow is 18 cfs. Prairie Creek has a weir, and the range of flow is dependent on the lake surface elevation. At the average elevation of 65 ft NGVD, outflow discharge is about 20 cfs (Robison et al., 1997).

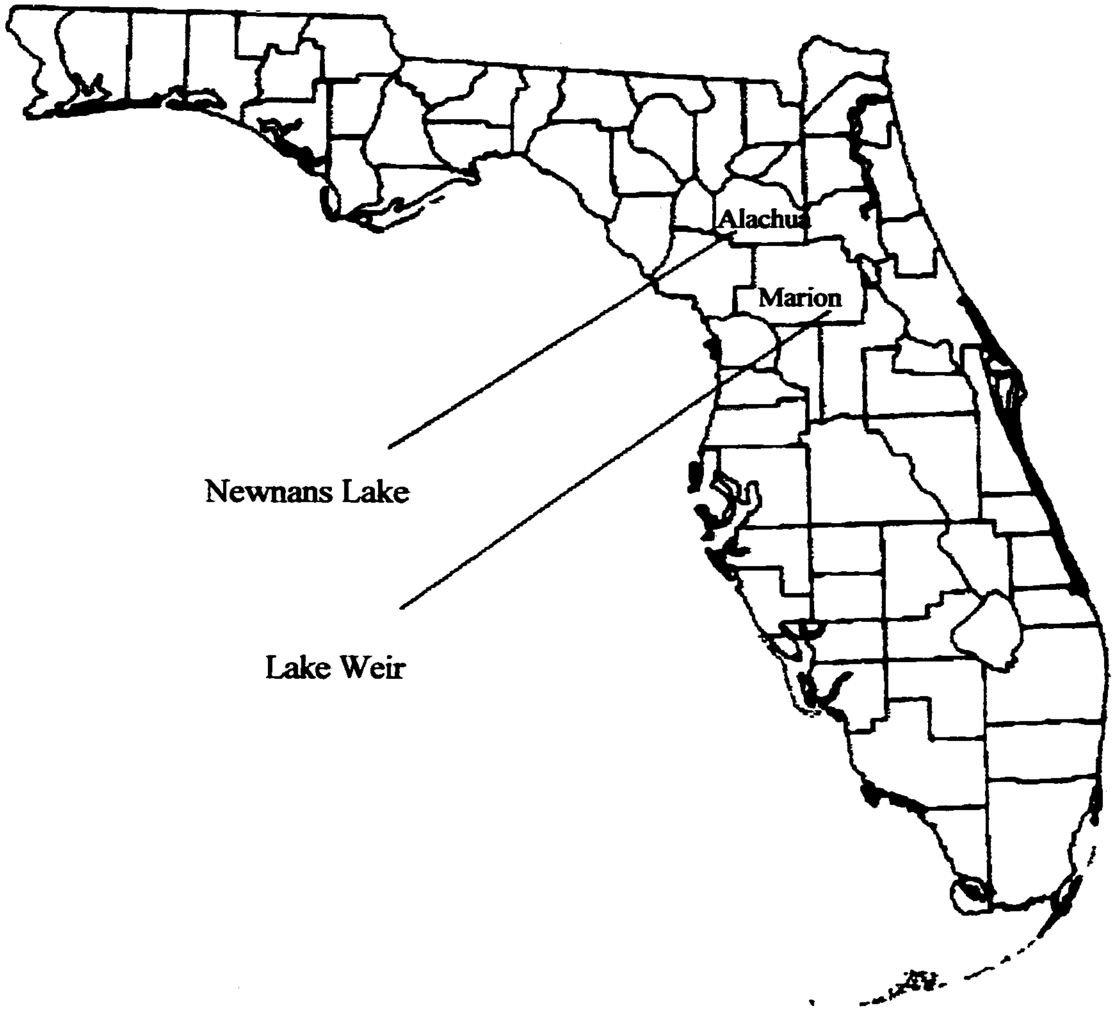


Figure 1.3. Watershed locations in the state of Florida.

Newnans is typically classified as a naturally eutrophic, softwater lake with a pH near 7 (Canfield, 1981). Despite its eutrophic condition, Newnans' N: P ratio has risen from 17 to 31, indicating balanced nutrients in the 1970s but some phosphorus limitation in the 90s (Huber et al., 1982; Lakewatch, 1999). Newnans is highly colored and exhibits high variability in this parameter (Canfield, 1981; Gottgens and Montague, 1987). Newnans does not appear to develop a thermal stratification in the summer (Canfield, 1981).

Lake Weir

Lake Weir is located about 15 miles southeast of Ocala, Florida (29° 01' N, 81° 56' W), in Marion County, Florida. It is located in the Oklawaha River basin in the Sumter Upland physiographic region (Canfield, 1981). The lake surface area is about 2300 ha and its elevational watershed covers about 12,100 ha. However, about 2400 ha is depressional and does not contribute runoff to the lake. The mean depth is 7.1 m (calculated from Ott and Chazal, 1966), and the longest fetch is about 2.26 km.

To the west, a canal and wetland area connect Lake Weir to Little Lake Weir. A canal also connects the lake to a large hardwood swamp to the north (Marshall Swamp). Lake Weir's average elevation is 57' NGVD, and Marshall Swamp is at about 50' NGVD.

Lake Weir is a mesotrophic lake with trophic state indices reported in the range of 41 to 54 (Canfield, 1981; Huber et al., 1982; Lakewatch, 1998). It is a softwater lake with a pH around 7 and very little organic color (Canfield, 1981). Weir does develop a 1°C temperature differential at certain times in the year (Canfield, 1981).

Plan of Study

This dissertation explores the relationships of lake and watershed using literature, empirical data, spatial and temporal modeling, and emergy evaluation indices. The overall organization and hierarchy of lake watersheds was studied using the following procedures:

1. Using methods of geographic information systems (GIS), a sequence of historical maps (1950, 1970 and 1990) was constructed that included land uses, geology and landforms, hydrological properties, nutrient storages and flows, and energy characteristics.
2. The storages, budget and cycle of phosphorus were developed for the watersheds and lakes. Simulation models related phosphorus to the influences of the watershed and human settlement.
3. Emergy characteristics were evaluated for the main components of the watershed and lakes including phosphorus, areal concentration of emergy flows, transformities, and other indices of energy transformation and hierarchy.
4. Limnological characteristics of the lake ecosystems were related to the watershed inputs including productivity, food chains, and the effect of watersheds on lake classification. Responses were studied with a lake simulation model.

Synthesis of these results was used to consider the position of lakes in the emergy hierarchy of the earth, to understand the level of reciprocal control between a watershed and a shallow lake, to examine spatial patterns that develop in changing watershed systems, and to propose management alternatives.

CHAPTER 2
METHODS

Map Preparation and Data Sources

A series of maps of land use, soil and rain for each watershed, for select time periods, was used to explore changing energy, emergy, water and phosphorus inflow to each lake. Three time periods – 1950, 1970, 1990 – were mapped and compared using a geographical information system (GIS). MapFactory is a raster-based (cell or grid) analysis GIS useful for simulating spatial movement defined by equations.

Elevation and Watershed Delineation

Elevations were digitized from USGS 7.5-minute topographical quadrants and assumed constant throughout the 40 years of the time series analysis. All but one of the quadrants was constructed on 5-foot intervals. The remaining 10-foot interval map was kriged (mechanically interpolated using GIS) over the contours and the benchmark points to produce 5-foot contour areas.

The watershed was delineated using a GIS command that spreads upwards from a given point and stops when a downhill elevation is encountered. The elevation of each study lake was used as the initial point of spread, and all uphill cells were considered part of the larger basin within which the study lake was the focal point. All smaller lakes within this basin were then used as points for upward spread to determine their individual drainage areas within the larger lake basin. These smaller sub-basins were subtracted from the larger basin, splitting the shared ridge between the study lake basin and the outlying lake sub-basin. This final basin was considered to be the rain catchment area draining into the study lake.

Land Use and Cover

The area of individual land use for each basin was configured from USGS topographical quadrant maps (1966–1970 series). Land use for 1990 was determined using 1988–1993 quadrant updates by USGS and aerial photos. Land use for 1950 was interpreted from 1949 aerial photos using comparisons to similar areas of known land use in 1968 photos. Groundtruthing to verify land use and to determine industry and agricultural type was conducted extensively throughout both watersheds by visits to existing sites, and via county records for historical sites.

Land use was divided into 15 categories:

1. open, vacant, or range lands (considered unmanaged turf)
2. golf courses (managed turf)
3. urban with residential, commercial, and institutional structures assumed to be using a centralized waste water treatment system
4. outlying residential, commercial, and institutional on septic systems
5. industrial
6. mining
7. landfill
8. roads, parking lots and airport tarmacs
9. agriculture - orchards (perennial)
10. agriculture - row crops (annual)
11. forest

12. forested wetlands
13. herbaceous wetlands
14. lakes and ponds
15. streams.

Soil Maps

Soil coverages for each watershed were obtained by digitizing maps in the National Cooperative Soil Survey for each county. The soil classes were then standardized and aggregated for key parameters of interest (hydrologic capacity and clay content).

Soils were first grouped according to the four hydrological categories designated in the United States Soil Conservation Service (USSCS) soil surveys. USSCS determines groupings by the amount of water absorbed when thoroughly wet (USSCS, 1985) and considers infiltration, vertical drainage and clay content. Group A refers to soil that has low runoff potential, D has high runoff potential, and B and C fall between these two extremes. If a soil had two categories assigned because of potential drainage capability, the pumping benefit was neglected, and the category with the highest runoff potential was assigned.

Soil hydrology was also characterized and mapped by permeability (in/hr), capacity (in/in) and depth to the first relatively impermeable horizon (<0.6 in/hr). The use of these physical parameters is explained in the chapter on model development.

Rain Data

Rain data were obtained from the National Oceanic and Atmospheric Administration (NOAA) for recording sites within each watershed. Because no individual site had data for all the years under study, all available data were averaged for

1950, 1970 and 1990 for all sites recording rainfall within the watershed. Consequently, rainfall was considered to be equal throughout the watershed.

Dynamic Simulation Models

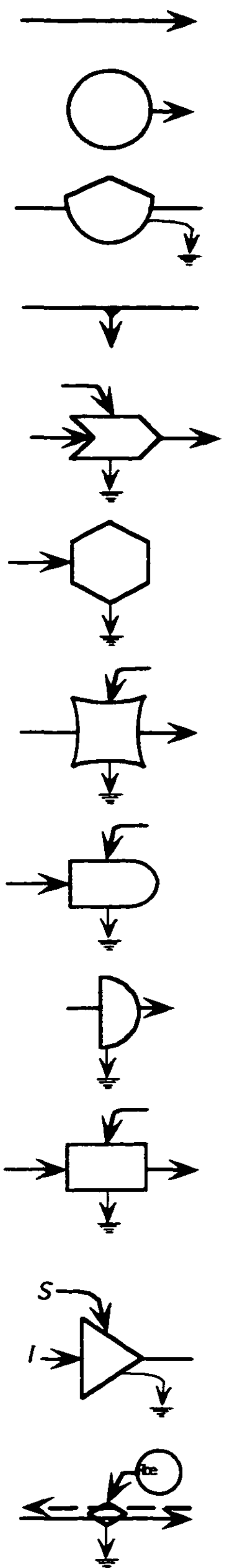
Energy language symbols and their intrinsic mathematics (see Energy Systems Symbols and Definitions, Fig 2.1), were used to develop temporal models of both a lake system and its watershed. An energy system diagram was first constructed representing the variables considered important in defining key interactions within the lake and between the lake and its watershed. The resulting diagrams were translated into mathematical equations representing changes in each variable over time, and these equations were solved using a BASIC computer program.

System Diagram

The concept of constructing a system diagram and the hierarchy of arrangement are discussed extensively in (Odum, 1994), but are briefly described below.

System frame. A rectangular box represents the boundaries selected.

Forcing functions. Any input that crosses the boundary is an energy source, including pure energy flows, materials, information, the genes of living organisms, services, as well as inputs that are destructive. All of these inputs are given a circular symbol and are arranged around the outside border from left to right in order of concentration with sunlight on the left and information and human services on the right.



Energy circuit: A pathway whose flow is proportional to the quantity in the storage or source upstream.

Source: Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank: A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

Heat sink: Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.

Interaction: Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both;control action of one flow on another; limiting factor action;work gate.

Consumer: Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

Switching action: A symbol that indicates an outside agent causing one or more changes in a pathway or interaction

Producer: Unit that collects and transforms low-quality energy under control interactions of high-quality flows.

Self-limiting energy receiver: A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.

Box: Miscellaneous symbol to use for whatever unit or function is labeled.

Constant-gain amplifier: A unit that delivers an output in proportion to the input *I* but is changed by a constant factor as long as the energy source *S* is sufficient.

Transaction: A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 2.1. Energy systems symbols and definitions (Odum, 1994).

Pathway line. Flows are represented by a line and include pure energy, materials, and information. Money is shown with dashed lines. Lines without arrowheads flow in proportion to the difference between two forces and represent a reversible flow due to concentration gradients.

Outflows. Any outflow that still has available potential, materials more concentrated than the environment, or usable information is shown as a pathway from any of the three upper system borders, but is not shown exiting from the lower border. Degraded or dispersed energy, with insufficient quantity or quality to do work in the modeled system, is shown as very thin lines leaving at the bottom of the diagram with a single arrow representing a heat sink.

Adding pathways. Pathways add their flows when they either join or enter the same tank. Every flow in or out of a tank must be of the same type and measured in the same units.

Intersection. Two or more flows that are different, but required for a process, are drawn to an intersection symbol. The flows to an intersection are connected from left to right in order of their transformity, the lowest quality one connecting to the notched left margin. An example of this multiplicative interaction is the connection between light and phosphorus required for photosynthesis.

Counterclockwise feedbacks. High-quality outputs from consumers, such as information, controls, and scarce materials, are fed back from right to left in the diagram. Feedbacks from right to left represent a loss of concentration because of divergence, with the service usually being spread out to a larger area.

State variables. Storages of materials are shown as tanks within each system compartment. Changes in the system can be recorded as fluctuating accumulations within each tank . In simplified system diagrams, not to be confused with aggregated diagrams, the actual simulation details, such as tanks and complex interactions flowing into each tank, are often not presented. However, a state variable is always implied for every process within the diagram.

Material balances. Since all inflowing materials either accumulate in system storages or flow out, each inflowing material such as water or money needs to have outflows drawn.

Aggregated diagrams. Aggregated diagrams are simplified from the detailed diagrams, not by omission of components, but by combining them in categories aggregated with the purpose of answering a specific question.

Simulation Example

A simple one-tank simulation is used to explain the simulation methodology used in this dissertation. A diagram of water inflow, outflow and accumulation (Figure 2.2) illustrates arrangement of sources and material inflows and outflows.

The associated differential equation used to define the material balance and a graphical representation of water accumulation over a two-year period are included (Figure 2.2). The programming application QBASIC was used in this example and all the simulations included in this dissertation, both to iterate the equation over a given time interval and to plot the changes in accumulations with time.

Emergy Evaluation

Emergy values were used to compare land uses and soils within each watershed, in-lake functions, changing watershed systems over the forty year study period and phosphorous in different solution concentrations from different sources. Empower densities, transformities and storage emergy were the primary indices used for comparison.

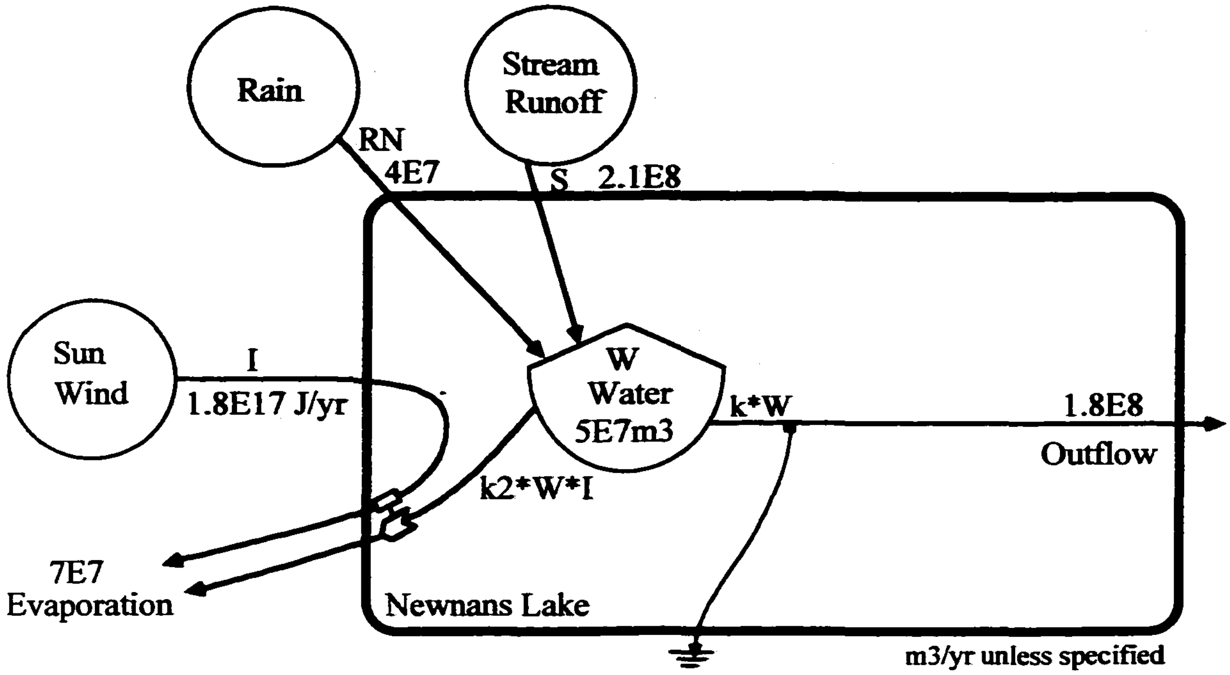
Emergy Tables

A sample emergy analysis table is presented in Table 2.1. The associated system diagram is illustrated in Figure 2.3. This table represents flows per unit area and time (J/ha/yr). An explanation of the information presented in each column of the table is given in Table 2.2. Emergy analysis was used to evaluate the lake-watershed interface, soils and land use in the watershed, and sediments in each lake.

Emergy Indices

Several emergy indices were used to draw inferences from emergy analyses of the lake-watershed interface, economic use of the lake, and land use within the watershed. Comprehensive descriptions of these indices and their uses are presented in Odum (1996), but brief descriptions of these indices are given below.

The *solar transformity* of an item or flow is the solar emergy that would be required to generate (create) a unit of that object or resource efficiently and rapidly. Figure 2.4 shows the solar transformity defined as the solar emergy required to produce one joule of another form of energy. Solar transformities of one or more products are



Equation

$$\frac{dW}{dt} = RN + S - k*W - k2*W*I$$

Calibration of coefficients at steady state

$k*W = 1.8E8$ $\quad k = 1.8E8/5E7 = 3.6\ yr^{-1}$

$k2*W*I = 7E7$ $\quad k2 = 7E7/(5E7*1.8E17) = 7.8E{-}18\ J^{-1}$

Initial conditions

I = 1.8E17
RN = 4E7
S = 1E8
W = 4E7

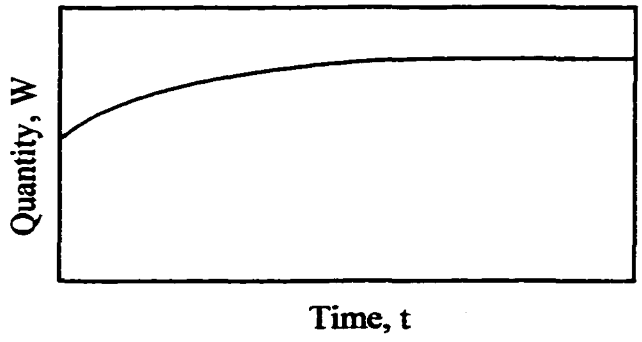


Figure 2.2. Simulation example: aggregated water budget for a lake, values used for calibrating coefficients and the differential equation.

Table 2.1. Example of emergy evaluation: annual production of one hectare of Bahia grass* (see Figure 2.3).

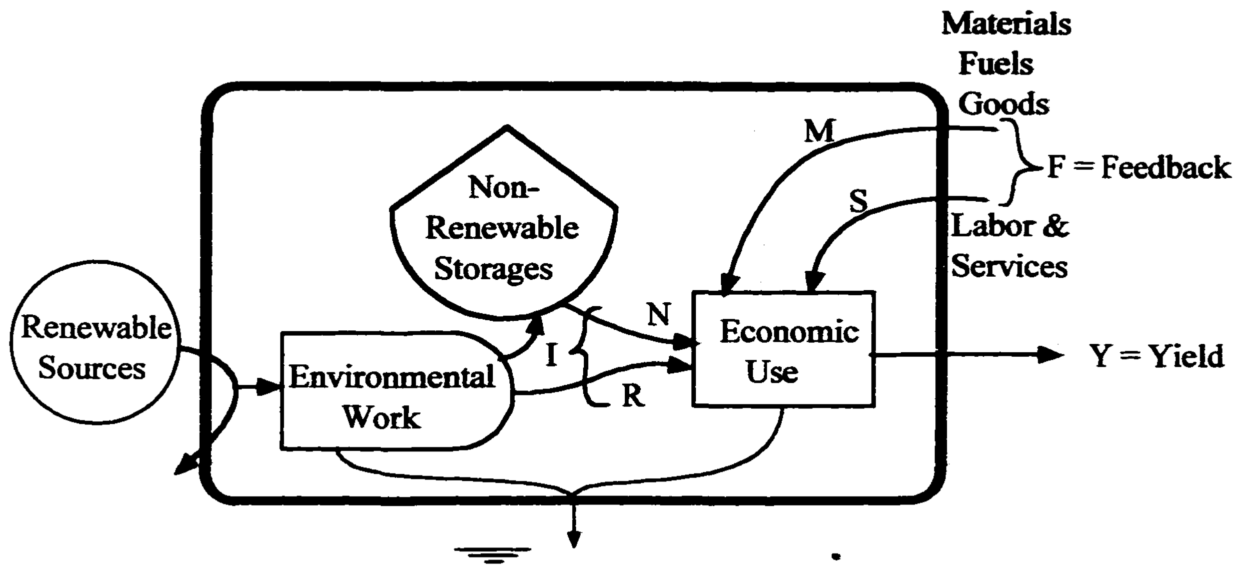
Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E11 sej/yr)
RENEWABLE RESOURCES (R)					
1	Et	J	5.43E+10	1.54E+04	8368
NONRENEWABLE ENVIRONMENTAL RESOURCES (N)					
2	Net Topsoil Loss	J	6.33E+07	7.38E+04	47
	Sum of free inputs (sun, rain omitted)				8415
PURCHASED INPUTS (M, S)					
3	Fuel	J	2.82E+06	6.60E+04	2
4	Phosphate	g P	7.38E+03	2.20E+10	1623
5	Nitrogen	g N	1.55E+04	2.41E+10	3728
6	Lime	g	3.73E+05	1.00E+09	3730
7	Labor	J	-	-	0
8	Services	$	-	-	0
9	Sum of purchased inputs				9083
10	**YIELD (Y)**	g, dry	3.63E+06		
		J	6.88E+10		
11	**TRANSFORMITY of yield**			4.80E+08	
12	**EMERGY PER MASS of yield**			2.50E+04	

* Simplified from Appendix Table D.1

1. Includes contributions of sun, wind and rain

11. Total inputs divided by energy of yield

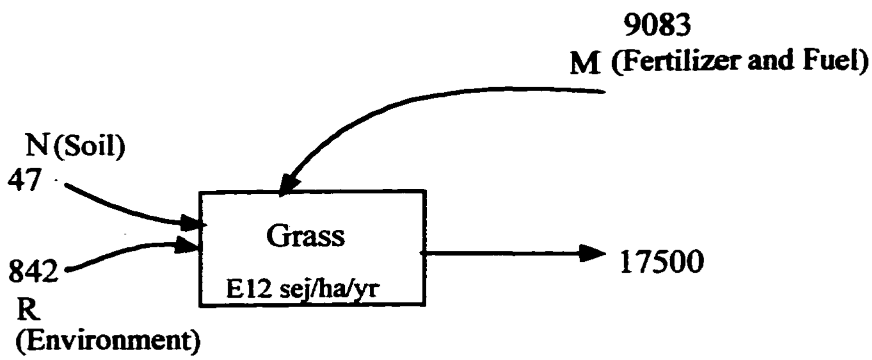
12. Total inputs divided by mass of yield



$$\text{Emergy Yield Ratio} = \frac{Y}{F}$$

$$\text{Emergy Investment Ratio} = \frac{F}{I}$$

(a)



Emergy Yield Ratio = 17500/9083 = 1.93

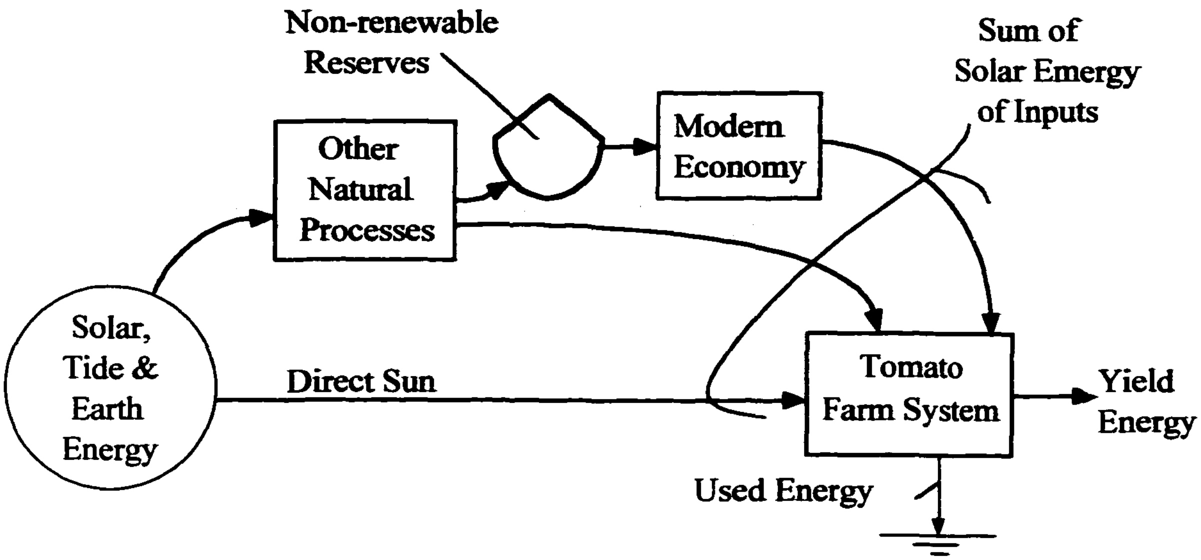
Emergy Investment Ratio = 9083/842 = 10.79

(b)

Figure 2.3. Example of emergy analysis : a) definition of two indices - emergy yield ratio and investment ratio; b) simplified emergy diagram for grass example in Table 2.2 .

Table 2.2. Description of information presented in an emergy table.

Column	Description of Information
One	line item number: corresponds to the number of the footnote in the table where raw data source is cited and calculations shown
Two	name of the flow or item stored: shown on the aggregated diagram
Three	raw data in joules, grams, or dollars: taken or calculated from various sources
Four	transformity in solar emjoules per unit (sej/joule; sej/gram; or sej/dollar); see definition Table 2.4
Five	solar emergy contributed by the flow or item stored: the product of columns three and four
Six	real wealth value in emdollars for a selected year: obtained by dividing the emergy in column number five by the emergy/money ratio for the selected year



$$\text{Solar Transformity of Tomatoes} = \frac{\text{Solar Emergy of Inputs}}{\text{Yield Energy}}$$

$$= \frac{1617\ \text{E}13\ \ \text{sej/ha/yr}}{4.43\ \text{E}10\ \ \text{J/ha/yr}} = 365{,}000 \text{ solar emjoules/Joule}$$

Figure 2.4. Diagram explaining solar transformity.

obtained from each analysis. Solar transformities for main inputs from global climate are obtained from world energy budgets, and transformities for sources to each system come from previous analyses cited in each table's footnotes. Examples of energy sources with abundant but low quality energy are the sun (transformity of 1 sej/J) and wind (transformity of 300 to 1500 sej/J). Electricity from a coal plant requiring larger emergy inputs to produce more concentrated energy has a transformity of 160,000 sej/J.

Empower density (aerial empower density) is a measure of the emergy utilized in a unit area per unit time. It is a measure of the intensity of development and natural resource use for the system under study.

The *emergy yield ratio* is the emergy of an output divided by the emergy of those inputs to the process that are fed back from the economy (see Figure 2.3). This ratio indicates whether the process contributes more to the economy than is purchased from it for the processing. Ratios for typical agricultural products range from less than one to six (Odum, 1996). Values less than one may be obtained when the yield is calculated separately with a transformity from another source of data. In recent years, emergy yield ratios of fossil fuels have ranged from three to twelve (Odum, 1996.

Emergy investment ratios relate the emergy fed back from the economy to the emergy inputs from the free environment (Figure 2.3). These ratios indicate if a process is economical in using the economy's investments in comparison to alternatives. To be economical, the process should have a similar or lower ratio to its processes competing for investment. If the ratio is less, the environment provides more to the process, costs are lower, and its prices tend to be less so that the product competes in the market. If an emergy investment ratio is higher than alternatives, the intensity of inputs invested from the economy is greater, and impact on the environment is greater.

The *emergy exchange ratio* is the ratio of emergy received for emergy delivered in a trade or sales transaction. For example, a trade of wood for oil can be expressed in emergy units. The area receiving the larger emergy receives the larger real wealth and has its economy stimulated more.

The *emergy/money ratio* is obtained by dividing the total emergy used by the combined economy of man and nature in the country for that year by the gross national product. This number becomes smaller as the country's economy becomes more developed and more dependent on purchased goods and services from outside. A developed country with low emergy/money ratio gains a net benefit from purchasing products from less developed countries with a high emergy /money ratio.

CHAPTER 3
RESULTS

Results of this study are divided into three sections concerned with the two models developed to quantify the connection between watershed and lake and the use of simulations to develop management indices. In the first two sections, the development of the model and data sources are presented first, followed by the simulation results. In the third section, the derivation of indices and resulting values are presented together.

PART 1: SPATIAL WATERSHED MODEL

Development of Material Flows

A spatial model accounting for water and phosphorus export from different land uses on specific soil types was developed. One of the objectives was to determine a coarse level of aggregation at which long term watershed control of a shallow lake could be evaluated. This serves two purposes. It makes a model of this magnitude manageable, improving the potential for future use by water management agencies, and selects a scale appropriate to the study of cumulative effects. Assessing the overall effect of ongoing changes within the watershed was the priority, not prediction of drainage for every short-term storm event. This shorter time scale precludes the study of a larger system hierarchy.

Theoretically, unique linkages of land use and geohydrology control water and nutrient export that a given land use contributes to the lake. Further, the soils and natural systems on the drainage path between one area and the lake can modify the contributions of that area to the lake. Geographical information systems were used to track the flows through the watershed in order to calculate the spatial patterns of energy and material that develop and change as land uses in the basin change.

Geographical information systems (GIS) link a data set defining a specific variable (attribute) to a set of geographically referenced points on a map. Examples of attributes are rainfall and elevation, and a separate map (layer) is prepared for each property. Grid-based GIS divide a map into unit areas (cells) that become referenced points, each with a single attribute value. The seven attribute maps used in this model were annual rainfall, land use categories, annual phosphorus deposition, land cover (vegetated or impervious surface), soil hydrology, soil clay, and elevation.

Combining base map layers (Figure 3.1) creates new data sets describing the linkage between base attributes. These base attribute maps were also reclassified or related to each other by computation and used to represent the physical interactions that occur as water and phosphorous move across the landscape. For example, land cover was ranked by the percentage of impervious surface due to paved surfaces and roofs in each cell, then used to simulate runoff from those surfaces. A flow chart of the map layer computations described in the following sections is shown in Appendix A.

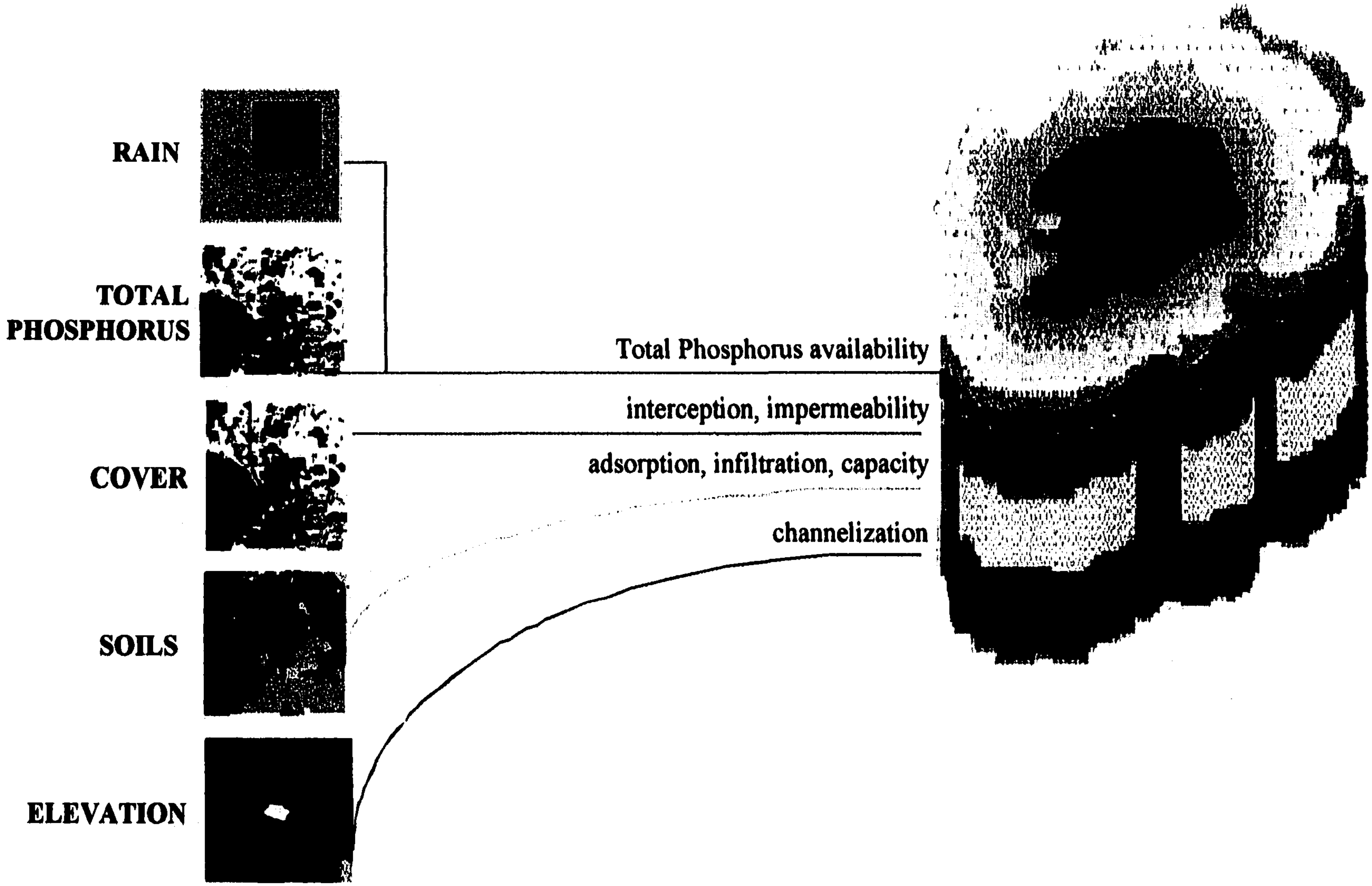


Figure 3.1. Map layers used as data in spatial model and the hydrology functions derived from each data set. Linking these maps with mathematical functions allows them to be used as boundary conditions for solving continuity equations governing the flow of materials through the watershed.

Simulation of Water Budgets in GIS

The transport of water, or any material, through a watershed is governed by the conservation of mass. Consequently, the fate of water in any area can be summarized by a fundamental continuity equation describing the water budget at any point in time.

$$\text{Rain} + \text{Runin} - \text{Infiltration} - \text{Runoff} - \text{Evapotranspiration} - dS/dt = 0 \qquad (1)$$

where dS/dt is the rate of change of water quantity in each area.

Run-in from adjacent areas is dependent on the mass balance within that area. The total runin volume is contingent upon the number of adjacent areas contributing, and is determined by elevation differences between areas. Infiltration volumes are a function of soil porosity and can be determined by the infiltration rate and maximum available capacity. Runoff (export) occurs both when impervious surfaces preclude infiltration and when soil capacity is exceeded.

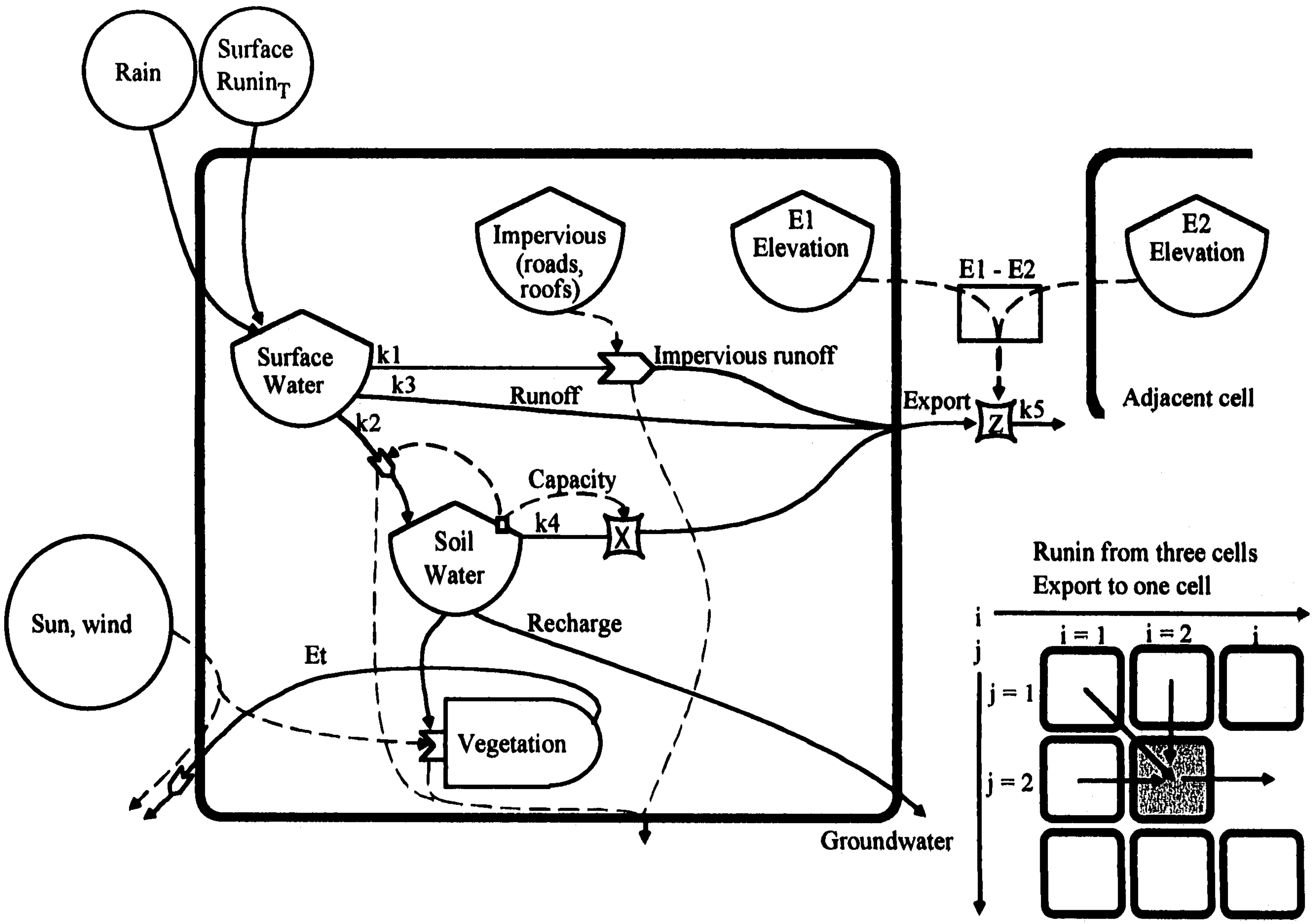
This model calculated a water budget for each cell based on average annual rainfall and average soil conditions. Overall storage was considered constant, and therefore, dS/dt is negligible. The time increment for remaining terms in the mass balance is one year. An energy system diagram illustrating the variables and interactions affecting water for each cell is shown in Figure 3.2.

Algebraic manipulation of map layers was used to solve these mass balances within each cell using the attributes governing infiltration and runoff. Water flow between cells was modeled using functions provided by MapFactory. Drainage in MapFactory simulates overland sheet flow and is dependent on the slope differential between each cell. Total water volume reaching the lake was calculated by summing the individual cell values at the perimeter of the lake.

Figure 3.2. Energy system diagram illustrating water budget in a single cell and movement into next cell. Solid lines carry water. Dashed pathways are energy flows affecting water. Et = evapotranspiration.

Difference Equations

Surface water runs off or infiltrates	$dSurfwater = Rain + Runin_T - k1 * Impervious * Surfwater - k2 * Soilwater * Surfwater - k3 * Surfwater$
Sum of run-in from adjacent contributing cells	$Runin_T = Runoffcell_{11} + Runoffcell_{21} + \ldots + Runoffcell_{ij}$
Soil water in excess of average saturation conditions either exceeds capacity and runs off or is dispersed through evapotranspiration or recharge of groundwater aquifer	$dSoilwater = k2 * Soilwater * Surfwater - X * k4 * Soilwater - (Et + Recharge)$ where X = 1 when soil capacity exceeded where Et and recharge is assumed equal to water in excess of average saturation conditions
Direction of export of all water leaving the cell is dependent upon elevational differences between cells	$Exportwater_{ij} = Z * k5 * (k1 * Impervious * Surfwater + k3 * Surfwater + X * k4 * Soilwater)$ where Z = 1 if elevation1 > elevation 2


Rain
Surface Runin$_T$
Impervious (roads, roofs)
E1 Elevation
E1 - E2
E2 Elevation
Surface Water
k1
k3
k2
Impervious runoff
Runoff
Export
Z
k5
Adjacent cell
Capacity
k4
X
Soil Water
Recharge
Sun, wind
Et
Vegetation
Groundwater
Runin from three cells
Export to one cell
i
j
i = 1
i = 2
i
j = 1
j = 2

Infiltration and Runoff Calculations

Water entering each cell was subject to one of two immediate consequences. It fell either on a totally impervious surface such as a roof or road, or it fell on a vegetated surface with variable infiltration capabilities.

Maps representing the percentage of impervious surface associated with each use were derived from land use maps. Values from the literature for the fraction of rainfall leaving each particular land use, based on average vegetation and impervious surface (Table 3.1), were used to create this map. This percentage was used to calculate a split between water leaving a cell without further interaction, as surface runoff, and a flow available for further interaction with the soil.

Water falling on unpaved surfaces was subject to infiltration into available soil spaces. If the soil capacity was exceeded, excess rainfall became runoff. The rainfall rate subject to infiltration was determined using the average rain intensity (in/hr) in the watershed for 2 year 60 minute events (Frederik, et al. 1977). Because this model tested the efficacy of long-term averages, total annual rainfall (in) was assumed to be evenly divided into these 60-minute events. The water flow exceeding soil capacity was considered surface runoff and added to the runoff from impervious surfaces.

The amount capable of infiltrating was calculated from the soil permeability (in/hr), unit capacity (in/in) and available volume (inches to impermeable soil horizon) for each soil category (SCS, 1985). This was converted to the percentage of an average rain event infiltrated. Calculation for each soil type is summarized in Appendix B.

Water that remained in each cell from infiltration was assumed to be drained from the cell prior to the next rain event, either by evapotranspiration or recharge. This assumption allowed the soil hydrology values to remain constant at their average saturation levels throughout the year being modeled.

Phosphorus Uptake, Adsorption and Deposition

Annual phosphorus deposition was divided by total annual rainfall to determine the concentration of phosphorus in solution for each cell. This concentration of phosphorus was assumed to travel with water, either downward into the soil, where it remained sequestered for plant uptake and diagenesis, or over the soil surface into the next cell. However, before moving into the next cell, this surficial phosphorus was subject to adsorption. The amount of clay in the soil was used to estimate the amount of surficial phosphorus likely to adsorb in each cell. The percentage of phosphorus adsorbed was assumed to be linearly related to the percentage of clay in the top 6-12" of soil. The model of phosphorus flows and storages and their link to the water budget are shown in Figure 3.3. Clay properties are presented in Appendix B.

Most phosphate runoff data available in the literature are in the form of empirical averages for total phosphate concentrations in storm water runoff (Harper, 1996; Adamus and Bergman, 1995; Heidtke and Auer, 1993; Gottgens and Montague, 1987; Huber et al. 1982). The values from various land uses with differing use densities are presented. However, these studies are averaged over several study sites where the underlying soil and geology are often different. As a result, concentration values account for and lump many soil infiltration and impervious surface characteristics. Using these values for phosphorous export would defeat the purpose of using a spatially specific model. Consequently, rates of atmospheric deposition and fertilizer application rates from the

Table 3.1. Impervious surface for different land uses.

Land use	% Impervious surface	Reference
Agriculture	6	a
Range/Open	6	a
Commercial	77	a
Industrial	71	a
Residential	39	a
Water	0	a
Wetland	0	a

a. Brown and Tilley 1995

Table 3.2. Average phosphorous deposition rates.

Source	Amount	Reference
Dry atmospheric		
agricultural	0.066 g/m2-yr	a
non-agricultural	0.027 g/m2-yr	a
Rain	0.167 g/m3 rain	a
Orange groves	1.12E4 g/ha-yr	b
Soybean cultivation	1.05E4 g/ha-yr	b
Sod	7.63E3 g/ha-yr	b
Residential landscape	3.36E3 g/ha-yr	c
Urban landscape	3.0E3 g/ha/yr	c

a. Huber, et al. 1982

b. Fluck 1992

c. Non-impervious surface assumed landscaped with sod (level of fertilizer application, 50% of sod for residential use, 75% for urban/commercial use)

Figure 3.3. System diagram of the phosphorus model for each cell and its relation to water model in Figure 3.2. Energy pathways without water or phosphorus are dashed. Water paths are blue, phosphorus is green.

Phosphorus deposition on land surface in solution with stormwater

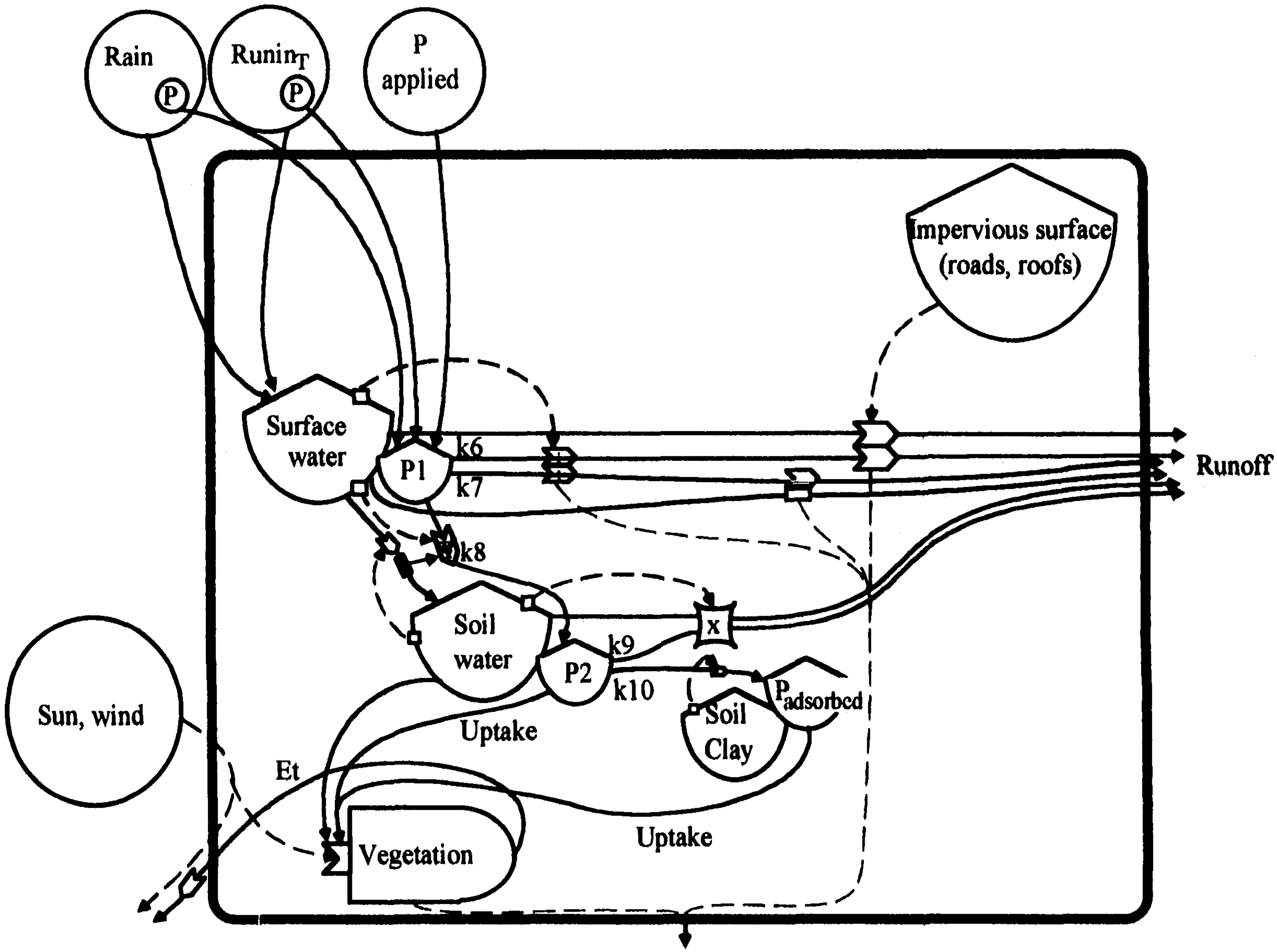
$$dP1 = P_{rain} + P_{runin} + P_{applied} - k6*[P1/Surfwater_{t=0}] * k1*Impervious * Surfwater - k7*[P1/Surfwater_{t=0}] * k3 * Surfwater - k8*[P1/Surfwater_{t=0}] * k2 * Surfwater * Soilwater$$

Phosphorus leaving soil pore water either from exceeding water capacity or adsorbed to clay

$$dP2 = k8*[P1/Surfwater_{t=0}] * k2 * Surfwater * Soilwater - X*k9* Soilwater * P2 - k10* Soilclay * P2 - Uptake$$

Adsorbed sites made available from phosphorus uptake by vegetation or diagenesis

$$dPadsorbed = k10* Soilclay * P2 - (Uptake + Diagenesis)$$


Rain
P
Runin$_T$
P
P applied
Impervious surface (roads, roofs)
Surface water
P1
k6
k7
k8
Runoff
Soil water
P2
k9
k10
x
Soil Clay
$P_{adsorbed}$
Sun, wind
Et
Uptake
Vegetation
Uptake

literature were used to determine phosphorous available for runoff (Table 3.2) assuming a steady state.

Movement Between Cells

Downhill drainage of water and phosphorous was simulated using the DRAIN function supplied by MapFactory. This function assumes that all material falling on a cell surface is available for sheet flow with flow direction dependent upon slope differentials between cells. The values from each cell are added to the adjacent cells into which they flow, and convergent pathways with high cumulative loads become evident.

This function by itself is incapable of calculating the amount of material left behind in an individual cell. It does, however, recognize material of varying amounts within each cell. By using a map with an estimate of the actual contribution from that cell to the lake, DRAIN becomes a tool capable of distinguishing differentials other than slope between the cell and the lake. Hence, an important component of the spatial model was the development of maps with the material export values resulting from the budget for each cell (Figures 3.2 and 3.3). These maps are the basis for maps that represent impediments to water and phosphorus leaving the surface of each cell. In GIS nomenclature, these are referred to as cost or friction maps. To avoid confusion with economic or hydrology terminology, they will be referred to as impediment maps in this study.

Impediment maps use a percentage figure to increase the difficulty for an entity, water or energy for example, to cross a cell. Theoretically, a cell with 100% export at a completely vertical slope would have the minimum effective travel distance for the quantity measured. Conversely, if nothing was exported and the cell was completely flat, the effective travel distance would be at a local maxima. The impediment to each material (water, phosphorus) leaving each cell was calculated from the mass balance calculations presented in Figures 3.2 and 3.3.

Using a GIS command (SPREAD) that calculates travel from the destination through each intervening specified impediment function, a measure of a distance from a specific exporting cell to the lake perimeter was calculated. This distance is related to, but not synonymous with, linear distance and becomes the effective proximity of that cell to the lake. A different impediment map was prepared for each material simulated and each year studied.

Total rainfall and phosphorus deposition was divided by the log of this effective proximity value, and this value was used to represent the amount of material exported from any specific cell actually reaching the lake. This new map was then used as the basis for cumulative drainage into the lake.

Verification

Model results for total annual runoff were compared to runoff values calculated using the Soil Conservation Abstraction Method. Runoff values from the spatial model for Newnans Lake were within 8% of the SCS method. Weir estimates, on the other hand, were twice the SCS value. Calculations are presented in Appendix C.

The efficacy of the model in linking distributed watershed loads to the lake was evaluated in two ways. A simpler, one year regression analysis of seven Florida lakes was completed (Brandt-Williams, 1995; Brandt-Williams & Brown, 1997). This study compared phosphorus loading to total lake productivity, algal diversity and trophic state indices for seven Florida lakes included in a 1973 study of lakes receiving sewage effluent (Taylor, 1978). Estimated phosphorus loading was regressed versus several water quality parameters. One month load using rainfall from the month immediately prior to collection of data showed a significant and positive correlation with chlorophyll concentrations (r2= 0.946). Annual loads regressed versus Huber et al. (1982) trophic state indices resulted in a significant and positive correlation (r2=0.725) as well. An abstract and key results of this study are presented in Appendix C.

The second verification method calculated the estimated phosphorus to sediment ratio for each year in the chronosequence study and compared the value to paleolimnological records presented in other studies (Kuntz, 1995; Gottgens and Crisman, 1993). Sediment erosion quantities were calculated using a modified Universal Soil Loss Equation in each cell. The resulting value was "drained" through the watershed using a GIS function. Because sediment phosphorus is often reported as a ratio of grams total phosphorous to kilograms sediment, the total simulated phosphorus load was divided by the total simulated sediment load for the three time periods included in this study. Table 3.3 presents this comparison.

Development of Emergy Patterns

Emergy values for inputs specific to each land use were used to create maps illustrating concentration of energy within each watershed. One set of maps was created to depict the base emergy flowing into and stored within each map cell on an annual basis. Another showed the flow of emergy through the watershed with a storm event. Figure 3.4 presents a system diagram for inputs and storage included in these evaluations.

Table 3.3. Phosphorus quantities in sediment cores, Newnans Lake and Lake Weir (Gottgens & Crisman, 1993; Crisman et al., 1992), values approximated from graphs.

Core Date	Newnans* mg/g dry wt	Weir ug/cm^2/yr
c1900	8	na
1950	14	na
1960	27	15
1970	28	21
1980	30	8
1990	30	26

* top core only

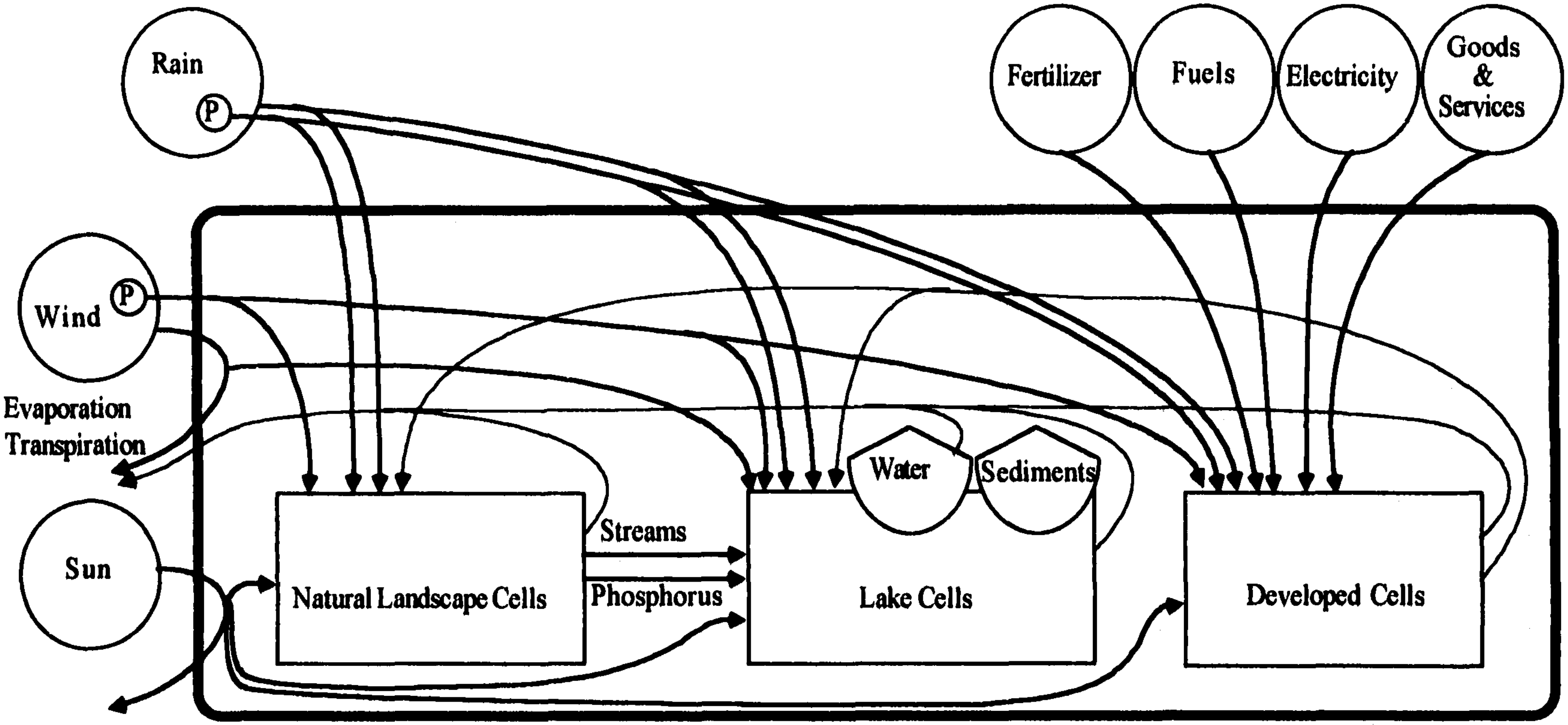


Figure 3.4. Diagram with empower pathways and emergy storage components included in calculations for each cell.

Empower Density Mapping

Empower density for natural and developed areas were applied to the land use maps for each time period included in this study. Values for the components included were obtained from previous studies and evaluations completed for this study. Tables 3.4 and 3.5 list values of emergy flow per hectare per year for each land use.

Emergy values for 1990 were used as the baseline evaluation for residential, urban and industrial land uses. Values for agriculture were taken from energy analysis completed between 1980 and 1989 (Fluck 1992). Some assumptions were made to prorate all land use emergy values for 1970 and 1950. Emergy for all natural areas remained constant because no monetary values are included in the analysis. Agriculture emergy was the same for 1990 and 1970, but 10% less in 1950 to account for inflation differences in service dollars. The emergy evaluation tables for residential, urban, and agricultural commodities are presented in Appendix D.

Tables 3.6 (Newnans Lake) and 3.7 (Lake Weir) and Figure 3.5 provide the details included in the evaluation of emergy flow into the lake. Table 3.8 presents summary emergy data for both lakes for all years evaluated. Additional calculations are presented in Appendix E.

Emergy Accumulation Maps

The DRAIN command in MapFactory was used to show pathways of emergy movement in water and phosphorus through the watershed. As water or phosphorus first left a cell, its emergy was calculated by multiplying the mass by an emergy per mass ratio appropriate for the dispersion process initiated. As this runoff converged on an

Table 3.4. Empower densities for watershed land use, 1990

Land use	empower density E14 sej/ha/yr	Reference
Forested wetland	4.7	a
Forest	4.8	a
Grassland	8.4	b
Herbaceous wetland	11.0	c
Soybeans	19.5	b
Lake	19.6	b
Oranges	36.0	b
Rural residence, Alachua Co.	709.0	b
Mining	7030.0	c
Urban, Gainesville	20300.0	b
Industry estimate, Alachua Co.	3000000.0	b

a. Orrell 1997
b. Brandt-Williams 1999 this study)
c. Odum 1996

Table 3.5. Empower densities for land use in 1950 and 1970 (natural areas are assumed the same as 1990).

Land use	empower density E14 sej/ha/yr	Reference
1950		
Soybeans	17.6	b*
Oranges	32.4	b*
Rural residence, Alachua Co.	567.0	b+
Mining	5624.0	c
Urban, Gainesville	16240.0	b+
Industry estimate, Alachua Co.	2400000.0	b+
1970		
Rural residence, Alachua Co.	638.0	b*
Mining	6327.0	b*
Urban, Gainesville	18270.0	b*
Industry estimate, Alachua Co.	2700000.0	b*

b. Brandt-Williams 1999 (this study)
c. Odum 1996
* 10% lower than 1990
+ 20% lower than 1990

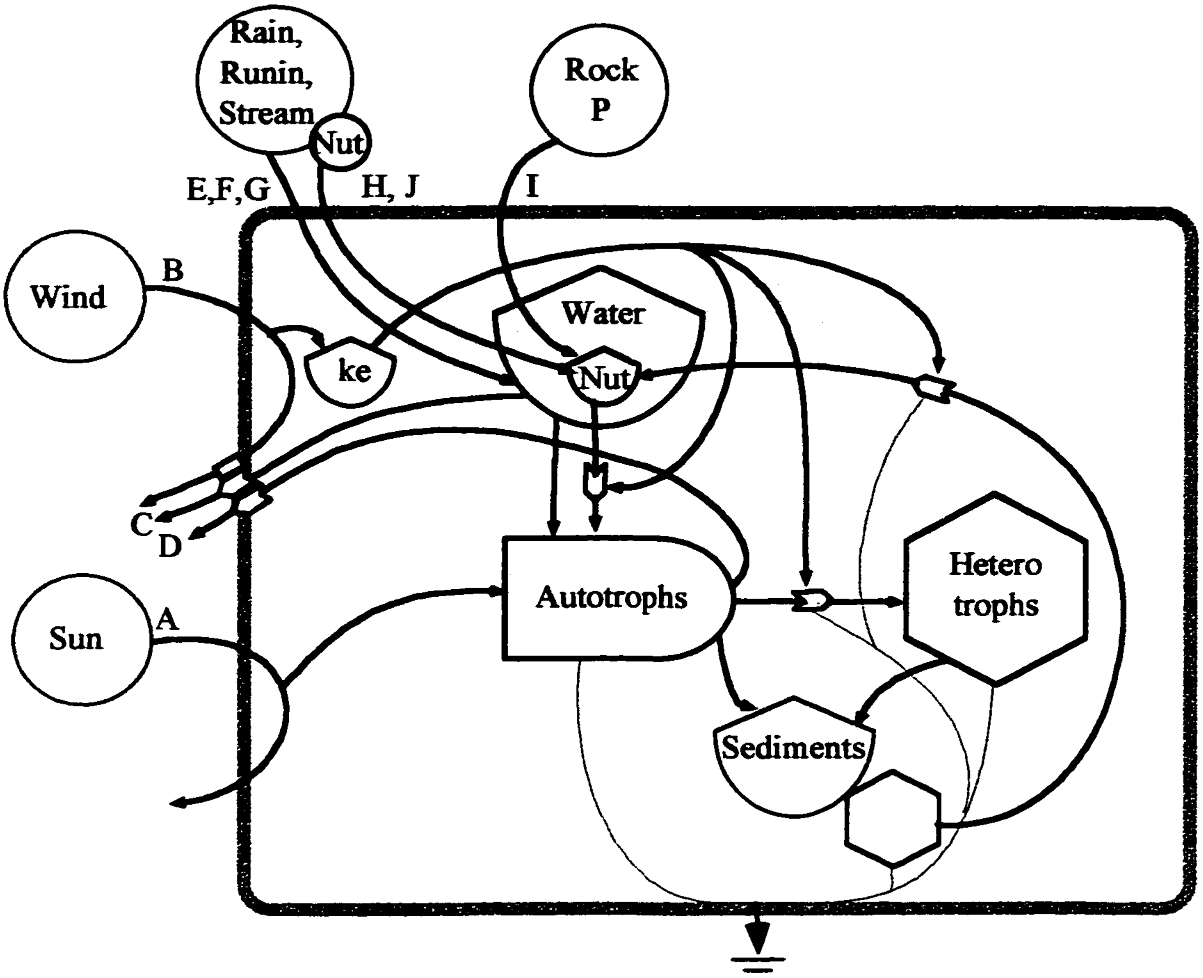


Figure 3.5. Diagram of inputs to lake, for use in emergy evaluation in Table 3.6.

Table 3.6. Emergy analysis of Newnan's Lake watershed/lake interface, 1970.

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E15sej/yr)	1970 EM$ (E4 US$)
Atmospheric inputs						
A	Insolation	J	1.78E+17	1	178	2
B	Wind shear	J	2.61E+14	1.50E+03	391	5
C	Rain, chemical potential	J	1.96E+14	1.82E+04	3574	45
D	Transpiration emergents	J	1.03E+12	1.54E+04	16	<1
E	TP in Rain	g	7.14E+06	2.00E+06	<1	<1
		Total atmospheric (sun omitted)			3981	50
Watershed inputs						
F	Stream, geopotential	J	1.38E+13	1.85E+03	26	<1
G	Stream, chemical potential	J	1.60E+03	1.82E+04	<1	<1
H	Sediment	J	3.16E+12	7.30E+04	231	3
I	Runoff, non-point	J	1.25E+15	6.31E+04	79077	99
J	TP in streams	g	3.70E+09	6.85E+09	25318	32
K	TP in runoff	g	4.28E+07	6.85E+09	293	4
				Total watershed	104945	131
		Total emergy/lake/yr			108927	136
		Total emergy/ha/yr			36	
Transformities						
1	Phytoplankton			6.59E+12 sej/g		
2	TP in water column			2.90E+13 sej/g		
3	Water			6.16E+05 sej/J		

Notes:

TP = total phosphorus

A Annual energy = (Avg. Total Annual Insolation J/yr)(Area)(1-albedo)

Insolation:	6.90E+09	J/m2/yr	(Vishner, 1954)
Area:	3.01E+07	m2	
Albedo:	0.14		(Odum, 1987)
Annual energy:	1.78E+17 J/yr		

B Wind mixing energy =

(density, kg/m3)(drag coefficient)(geostrophic wind velocity3,m3/s3)(area)

u = wind velocity (m/s) = 3.58 m/s

Table 3.6 continued

	geostrophic wind velocity =	5.97 m/s	
	Energy = 1.3 kg/m3 * 1E-3 *212.77 m3/s3 * 3.14 E7 s/y * 3.01E7 m2		
	Energy/yr =	2.61E+14 J/yr	
C	Rain, chemical potential = (rain,m)(lake area,m2)(1E6 g/m3)*G		
	Rain, m	1.32E+00 m	
	Lake area, m2	3.01E+07 m2	
	G, free energy, J/g	4.94E+00 J/g	
	Energy/yr =	1.96E+14 J/yr	
D	Transpiration from emergent and floating macrophytes		
		14.2 ha cover	(Huber et al., 1982)
		7.30E+10 J/ha, estimated transpiration	(Odum, 1996)
E	Phosphorous in rain =	area * rainfall * concentration	
	Area =	3.01E+07 m2	
	Rainfall =	1.4224 m/yr	(~52 in, NOAA, 1995)
	Concentration =	0.167 g/m3	(Brezonik, 1969)
	Annual amount =	7.14E+06 g/yr	
F	Stream, geopotential, J/yr = (flow volume)(density)(dh)(gravity)		
	Hatchett Creek		
	flow,cfs =	18 cfs	(SJRWMD, 1997)
	dh, m =	76 m	(Brandt-Williams, 1999)
	Energy/yr = 18cfs*0.028317m3/ft3*3.1536E7sec/yr*1E6g/m3*7 1.20E+13		
	Little Hatchett Creek		
	flow, cfs =	4 cfs	(SJRWMD, 1997)
	dh, m =	53 m	(Brandt-Williams, 1999)
	Energy/yr =	1.86E+12 J	
G	Stream, chemical potential = (volume flow)(density)(G)		
	G = (8.33J/mole/deg)(300°K)/18 g/mole)*ln[(1E6 - S) / 965000] J/g		
	S, ppm =	5.9	(calculated from turbidity, SJRWMD, 1997)
	Flow,cfs =	18 cfs	
	Energy/yr =	1.60E+03 J/yr	
H	Sediment = (Sediment kg/yr)*(1E3 g/kg)*(avg. % organic)*(5.4 Cal/g OM)*(4186 J/Cal)		
	Energy = (2.8E7 kg/yr)*(1E3 g/kg)*(0.5% Organic)*(5.4 Cal/g)*(4186 J/Cal)		
		= 3.16E+12 J/yr	
I	Runoff, nonpoint = (volume/yr)(G) = (Volume,m3)(4.82 J/g)(1 E6 g/m3)		
	Volume=	2.60E+08 m3/yr	
	Energy/yr =	1.25E+15 J/yr	
	Transformity =	6.31E+04 sej/J	
	Transformity calculated from spatial simulation of total emergy at lake perimeter divided by total volume of water converted to Joules		

Table 3.6 continued

J	**Total phosphorus in streams**		
	= (volume,cfs)(P,mg/l)(0.02831,m3/ft3)(3.1536E7,sec/yr)(1E-3 g/mg)(1E6 L/m3)		
	Volume ,cfs =	1.80E+01 cfs	(SJRWMD, 1997)
	Average concentration, mg/l	0.23 mg/l	(SJRWMD, 1997)
	Average TP mass =	3.70E+09 g/yr	
	Transformity =	1.82E+04 sej/g	(Appendix D)
K	Phosphorous in runoff from spatial model		
	Annual amount =	4.18E+07 g/yr	
	Transformity =	6.85E+09 sej/g	
	Transformity calculated from spatial simulation of total emergy at lake perimeter divided by total mass of phosphorus		

Transformities calculated from this analysis

1	Phytoplankton, g		
	= (avg. chlorophyll a concentration, g/m3)(lake volume, m3)(2g phytoplankton/g Chl a)		
	Avg Chl a =	0.231 g/m3	(Huber et al., 1982)
		1.65E+07 g	
2	TP in water column, g	= (avg. TP in water column, mg/L)(lake volume, m3)	
	Average concentration	0.105 mg/l	(Huber et al., 1982)
	Total g	3.76E+06	
3	Water, J = (lake volume, m3)(1E6 g/m3)(4.94 J/g)		
	Volume	3.58E+07 m3	(SJRWMD, 1997)
	Energy stored	1.77E+14 J	

Table 3.7. Emergy analysis of Lake Weir watershed/lake interface, 1970.

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E15sej/yr)	1970 EM$ (E4 US$)
Atmospheric inputs						
A	Insolation	J	1.58E+17	1	158	2
B	Wind shear	J	2.32E+14	1.50E+03	347	4
C	Rain, chemical potential	J	1.74E+14	1.82E+04	3171	40
D	Transpiration emergents	J	1.03E+12	1.54E+04	16	<1
E	P in Rain	g	6.34E+06	2.00E+06	<1	<1
		Total atmospheric (sun omitted)			3534	44
Watershed inputs						
F	Runoff, non-point	J	3.22E+14	1.86E+04	6000	75
G	Sediment	J	8.70E+11	7.30E+04	64	1
H	P in runoff	g	5.26E+07	1.27E+10	668	8
				Total watershed	6732	84
		Total emergy/lake/yr			10265	128
		Total emergy/ha/yr			4	
Transformities						
1	Phytoplankton, g			4.47E+12 sej/g		
2	TP in water column, g			4.88E+12 sej/g		
3	Water, J			1.09E+04 sej/J		

Notes:

A Annual energy = (Avg. Total Annual Insolation J/yr)(Area)(1-albedo)

Insolation:	6.90E+09	J/m2/yr	(Vishner, 1954)
Area:	2.67E+07	m2	
Albedo:	0.14		(Odum, 1987)
Annual energy:	1.58E+17 J/yr		

B Wind mixing energy =

(density, kg/m3)(drag coefficient)(geostrophic wind velocity3,m3/s3)(area)

wind velocity (m/s) = 3.58 m/s

geostrophic wind velocity = 5.97 m/s

Energy = 1.3 kg/m3 * 1E-3 *212.77 m3/s3 * 3.14 E7 s/y * 2.67E7 m2

Energy/yr = 2.32E+14 J/yr

C Rain, chemical potential = (rain,m)(lake area,m2)(1e6g/m3)*G

Rain, m 1.32E+00 m

Lake area, m2 2.67E+07 m2

Table 3.7 continued

	G, free energy, J/g	4.94E+00 J/g	
	Energy/yr =	1.74E+14 J/yr	
D	Transpiration from emergent and floating macrophytes		
		14.2 ha cover	(Huber et al., 1982)
		7.30E+10 J/ha, estimated transpiration	(Odum, 1996)
E	Phosphorous in rain =	area * rainfall * concentration	
	Area =	2.67E+07 m2	
	Rainfall =	1.4224 m	(~52 in, NOAA, 1995)
	Concentration =	0.167 g/m3	(Brezonik, 1969)
	Annual amount =	6.34E+06 g/yr	
F	Sediment =		
	Energy = (7.7E6 kg/yr)*(1e3 g/kg)*(0.5% Organic)*(5.4 Cal/g)*(4186 J/Cal)		
		= 8.70E+11	
G	Runoff, nonpoint = (volume/yr)(G) =	(Volume,m3)(4.82 J/g)(1 E6 g/m3)	
	Volume=	6.68E+07 m3/yr	
	Energy/yr =	3.22E+14 J/yr	
	Transformity =	1.86E+04 sej/J	
	Transformity calculated from spatial simulation of total emergy at lake perimeter divided by total volume of water converted to Joules		
H	Phosphorous in runoff from spatial model		
	Annual amount =	5.26E+07 g/yr	
	Transformity =	1.27E+10 sej/J	
	Transformity calculated from spatial simulation of total emergy at lake perimeter divided by total mass of phosphorus		

Transformities calculated from this analysis

1	Phytoplankton, g		
	= (avg. chlorophyll a concentration, g/m3)(lake volume, m3)(2g phytoplankton/g Chl a)		
	Avg Chl a =	0.006 g/m3	(Huber et al., 1982)
		2.30E+06 g	
2	TP in water column, g	= (avg. TP in water column, mg/L)(lake volume, m3)	
	Average concentration	0.011 mg/l	(Huber et al., 1982)
	Total g	2.11E+06	
3	Water, J = (lake volume, m3)(1E6 g/m3)(4.94 J/g)		
	Volume	1.91E+08 m3	(SJRWMD, 1997)
	Energy stored	9.46E+14 J	

Table 3.8: Summary emergy values for Newnans Lake and Lake Weir

Item	Units	Value: Newnans	Value: Weir
Total emergy flow	E15 sej/yr	108927	10265
Empower density	E15 sej/ha/yr	36	4
Phytoplankton emergy/mass	sej/g	6.59E+12	4.47E+12
Water transformity	sej/J	6.16E+05	1.09E+04
TP emergy/mass	sej/g	2.90E+13	4.88E+12

adjacent cell, the emergy was added to the emergy of the same entity in that cell. The cumulative emergy reaching the lake perimeter was summed for all perimeter cells to determine total emergy input to the lake.

Phosphorous Emergy Per Mass Ratios

Different phosphorus transformities were used for each cell depending on either the estimated concentration of phosphorus in solution with rainfall or the source of concentrated input, such as fertilizer. Curves for continuous transformities for phosphorus solutions of known concentration were interpolated using previous transformity evaluations for rock phosphate dissolved in rain water and reagent grade phosphorus mixed with groundwater (Appendix F). Transformities for concentrated phosphate products were calculated using standard emergy accounting methods (Appendix F).

Final TP emergy per gram ratios were calculated in two steps. The total TP emergy was drained through the watershed, providing cumulative emergy values at every point in the watershed. These emergy values were divided by the grams of TP exported from that cell, giving the emergy per gram for TP within that specific cell. The average emergy per gram used in evaluating emergy flows into the lake was determined by dividing the total TP emergy flow by the TP load in grams.

Results: Landscape Properties

The following sections introduce maps illustrating basic watershed characteristics (basin morphology, soils and geology, and land use). Results from the two watersheds are presented together for immediate comparison. Elevation contours in the watershed are presented separately from the bottom contours of each lake. The lake surface is shown at average NGVD height in the elevation maps.

Soils for both watersheds are mapped using two different classifications. The first is the standard Soil Conservation Service hydrological grouping, previously discussed in Chapter 2. The second represents the total capacity for water infiltration as discussed in the model development section of this chapter. Geological maps are for information only and were not used in the simulation of the model.

Watershed Morphology, Newnans Lake

Figure 3. 6 presents an elevation profile for Newnans Lake watershed. The range of elevation for Newnans' basin is 16 m at the deepest lake point to 69 m at the northwest edge of the basin. The steepest slope is 45%, and the average slope is 10%. Mean lake level is 20 m (65' NGVD). The elevation map illustrates the relative flatness of the watershed in the area immediately surrounding the lake (black to dark gray), with high relief concentrated along the western edge of the basin.

Figure 3.7 is a bathymetric map prepared by the St. Johns River Water Management District. This map illustrates the flat, shallow morphology of Newnans Lake. The depth throughout most of the lake is less than 1.2 m (4 feet) with contours spread far apart. There is a relatively small pool in the central eastern section reaching a maximum depth of 3 m (10').

Watershed Morphology, Lake Weir

Figure 3.8 illustrates the elevation contours for the Lake Weir watershed. The range of elevation for the basin is 9 m, near the center of the main lake, to 57 m along the eastern ridge. The mean lake level is 18 m. The steepest slope is 45%, and the average slope is 20%. Although lower in elevation overall than Newnans Lake, the lake is deeper and the watershed steeper. However, Lake Weir's basin has several areas of intermittent depressional relief evident by the spotty dark to light contours throughout the lower map in Figure 3.11.

Figure 3.9 is a bathymetric map prepared by Ott and Chazal in 1966. The majority of the lake bottom is approximately 7 m (25 feet) below the lake surface, with a steep dropoff around the perimeter of the lake.

Soils and Geology, Newnans Lake

Soil hydrology distributions, determined by the Soil Conservation Service (SCS), are shown in Figure 3.10, and Figure 3.11 depicts more detailed soil hydrology distributions. Hydrologic soil class D is predominant in Newnans watershed, but soil group A borders the western edge of the lake and the northern drainage into Hatchett Creek. Soils classified by impedance to water transport (permeability times capacity) show higher heterogeneity but generally follow the same distribution pattern as shown by the SCS categories.

Figure 3.12 is a map of the underlying geological formations in Newnans' watershed, which lies mainly within the Hawthorne formation and Plio-Pleistocene Terrace deposits. The Ocala group surfaces in a small area of the southwest basin. The Hawthorne formation is a highly variable mix of quartz sand, clay, carbonate and phosphate overlying the Ocala group and ranges in thickness from a 200 feet to the east of the lake to 160 feet near Gainesville. Plio-Pleistocene deposits are fine to medium mixes of sand, silt and clay. The Ocala formation is 98% calcium carbonate. (SCS, 1982)

Soils and Geology, Lake Weir

Soil Conservation Service (SCS) soil hydrology distributions are shown in Figure 3.13, and Figure 3.14 depicts more detailed soil hydrology distributions. Hydrologic soil class A is predominant in the Lake Weir watershed. Soil groups C and D border the northeastern edge of the lake and the stream and wetland area north of Little Lake Weir. Soils classified by impedance to water transport (permeability times capacity) generally follow the same pattern of distribution as shown by the SCS categories.

Figure 3.15 is a map of the underlying geological formations in Lake Weir's watershed. This basin lies mainly within the Ocala group and the Hawthorne Formation.

Land Use Changes, Newnans Lake

Land use within the Newnans watershed for 1950, 1970 and 1990 are presented in Figures 3.16 through 3.18, respectively. Table 3.9 and Figure 3.19 provide area values for specific land uses and illustrate the magnitude of changes.

Four significant changes in land use occurred between 1950 and 1970. Residential and natural areas bordering Gainesville were incorporated into the city. Large tracts of deforested areas, about 700 ha, around Hatchett Creek and in the northwest watershed were reforested. Residential areas increased directly to the west of Newnans Lake and along Waldo Road. The number and width of roads increased.

There are fewer differences evident between 1970 and 1990. The Gainesville municipality increased in area near the far western edge of the watershed. Impervious surface at the airport increased, as did industrial development of the same area. In addition, existing residential clusters throughout the basin expanded in area and number of residents.

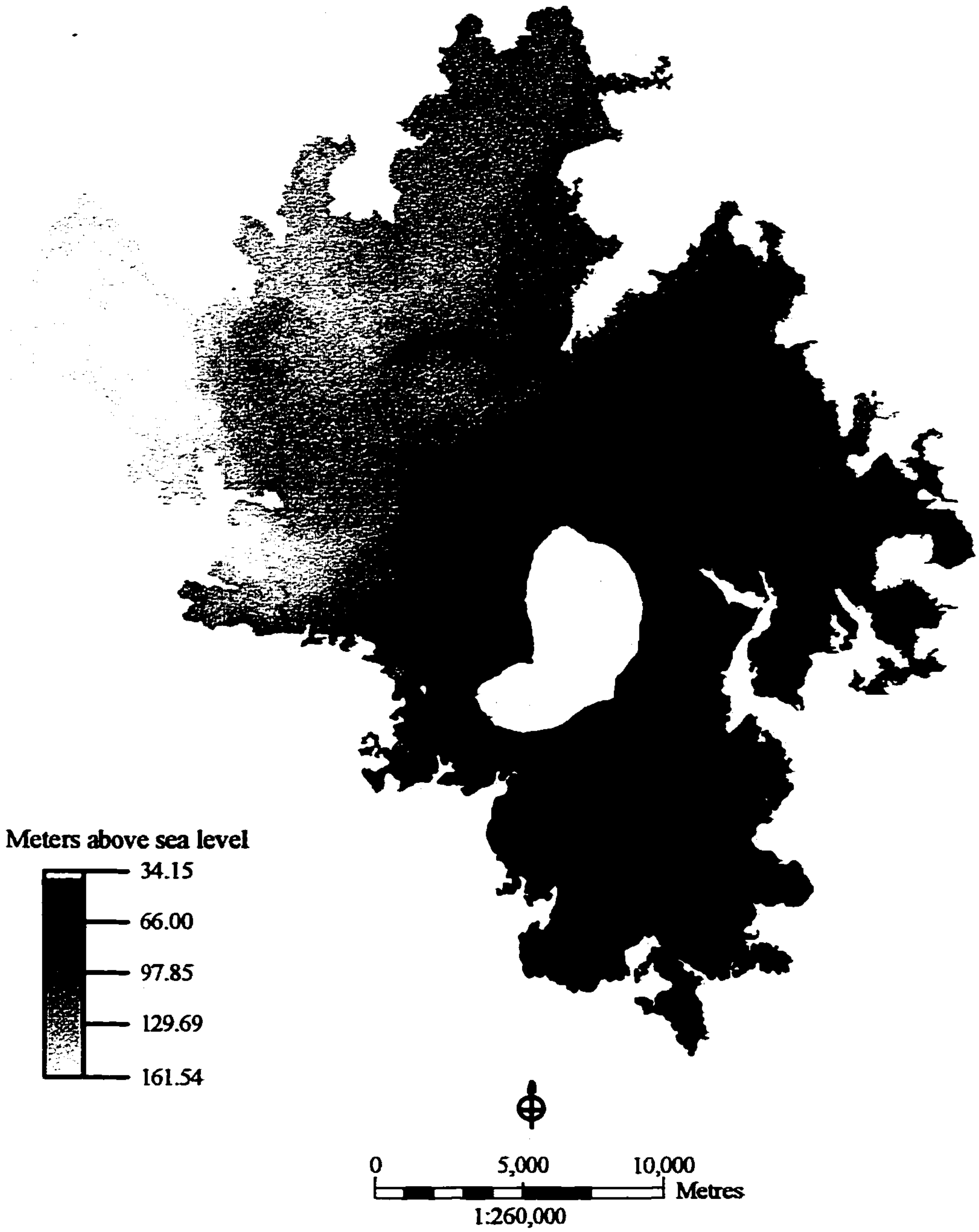


Figure 3.6. Elevation contours in Newnans Lake watershed.

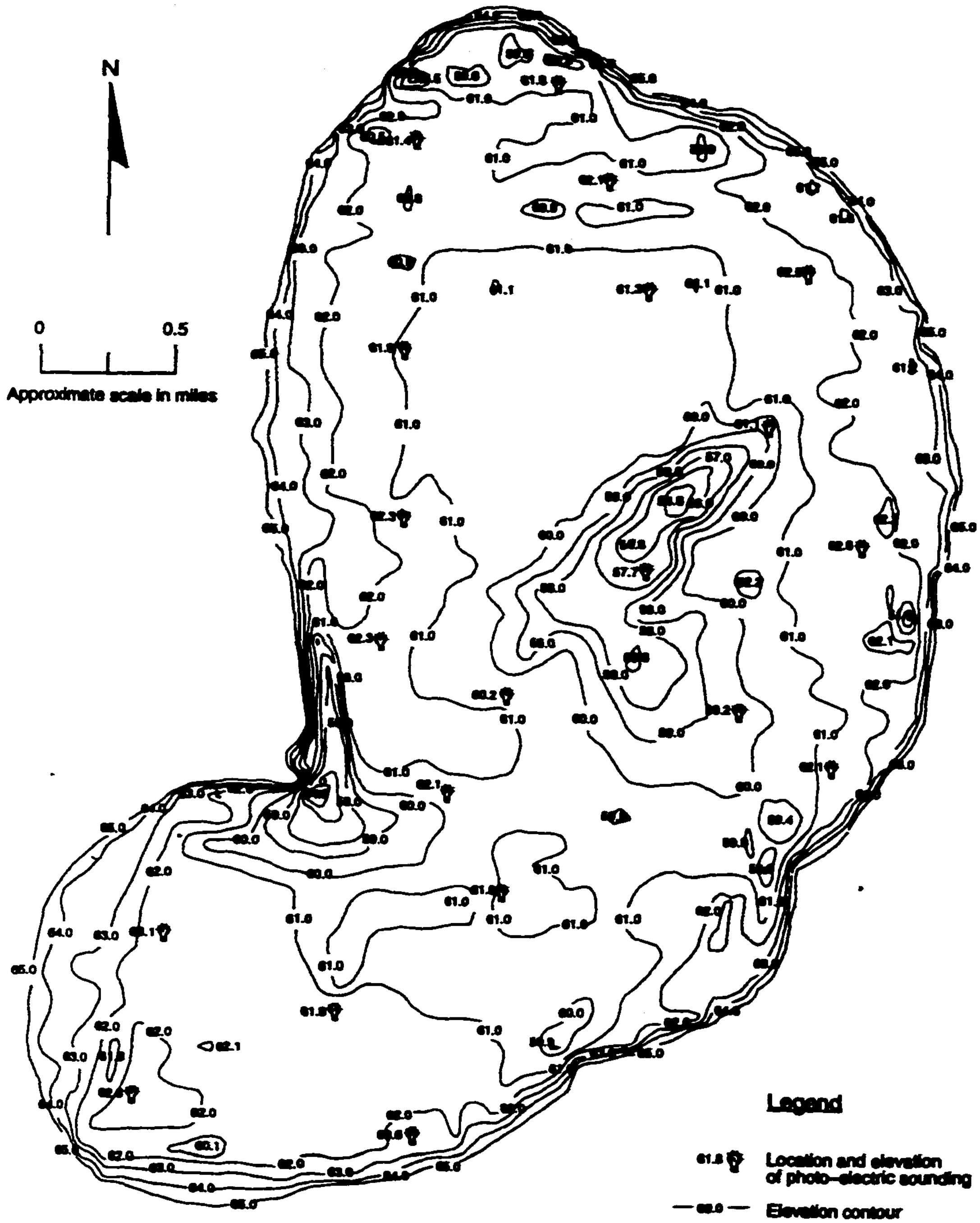


Figure 3.7. Elevation contours on the floor of Newnans Lake (SJRWMD, 1996).

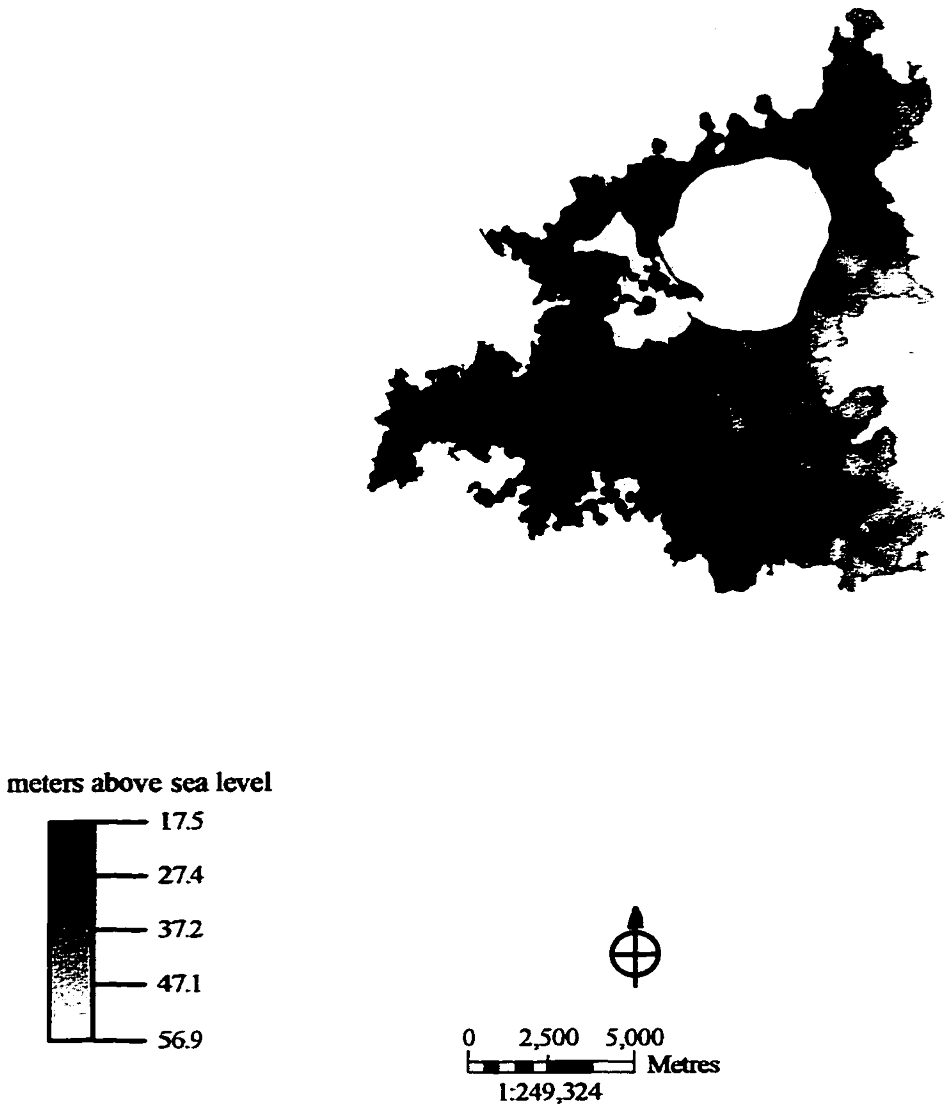


Figure 3.8. Elevation contours in Lake Weir.

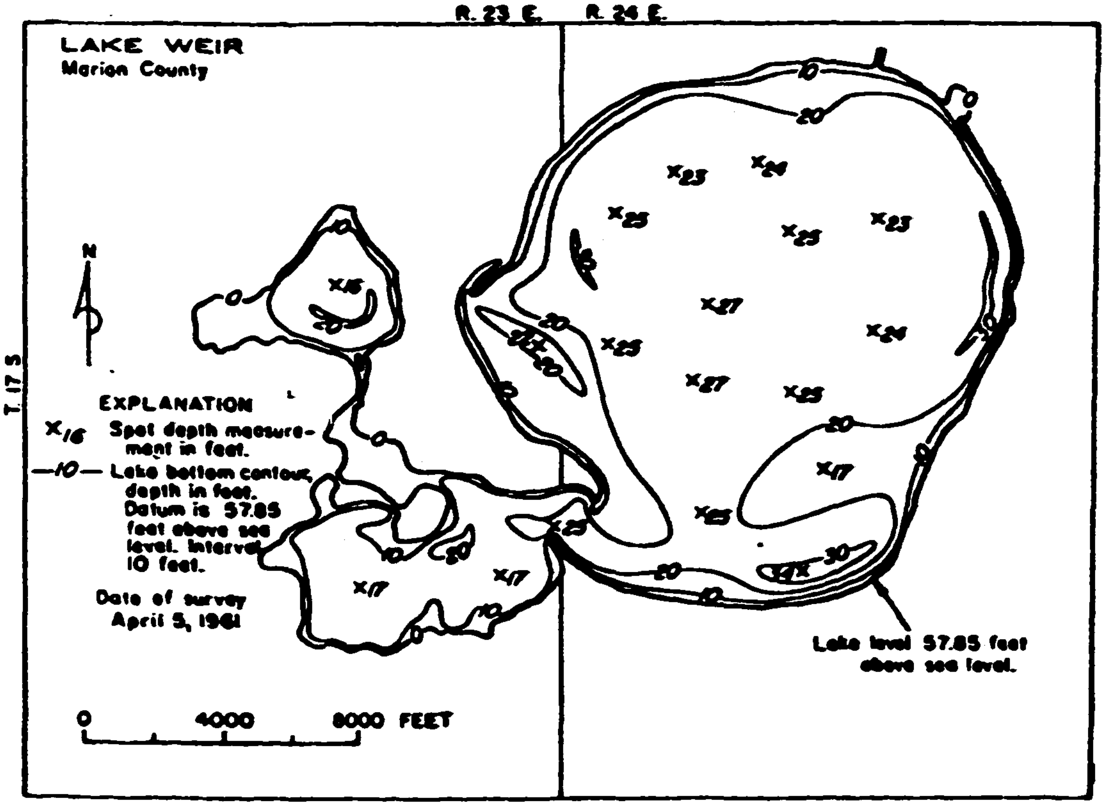


Figure 3.9. Lake Weir bathymetry (after Ott and Chazal, 1966).

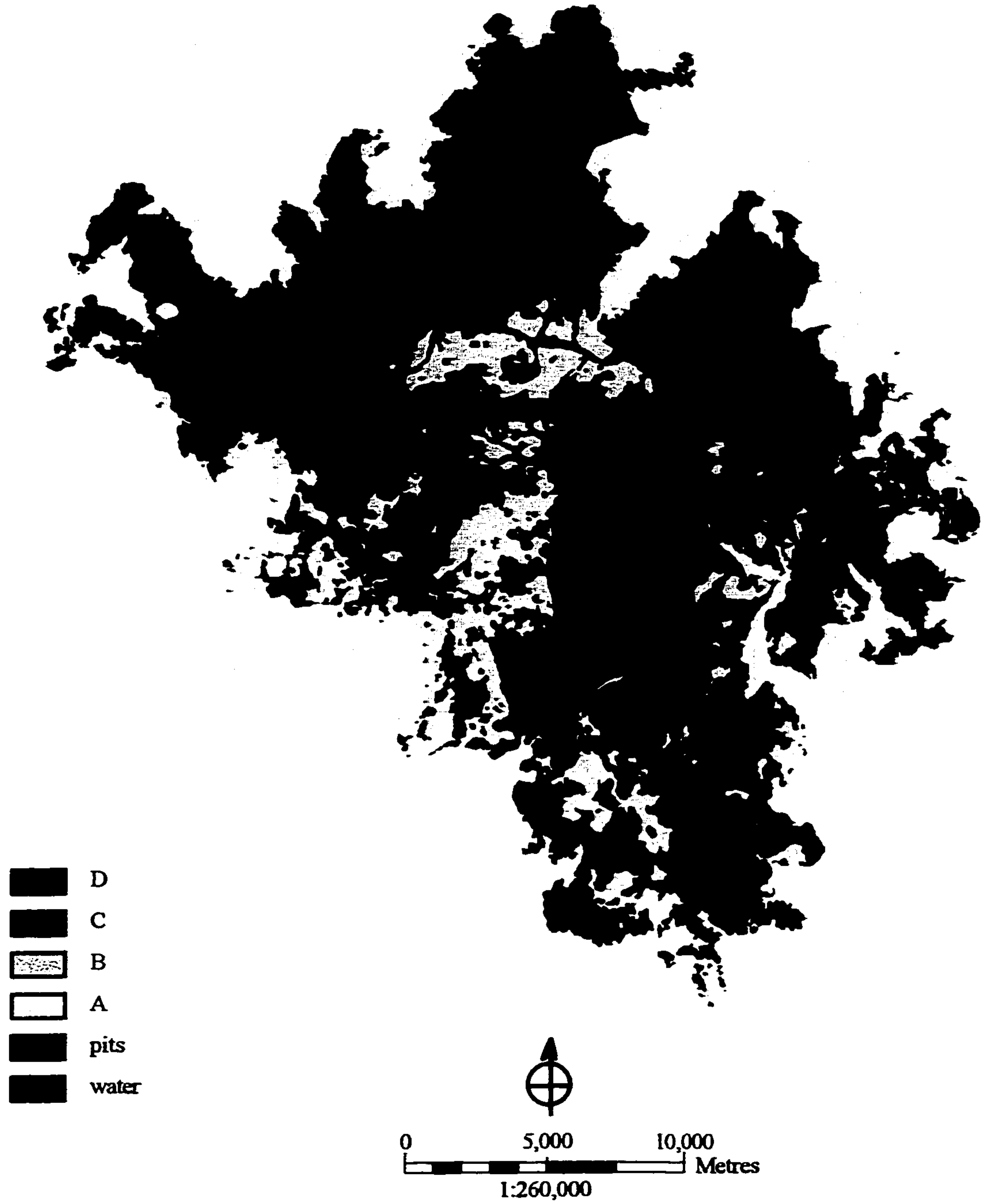


Figure 3.10. Hydrological soil classification groups in Newnans Lake watershed, as defined by Soil Conservation Service. Group D has high runoff potential, C has moderate potential, B has low runoff potential and A has little to no runoff potential (classification described in Chapter 2).

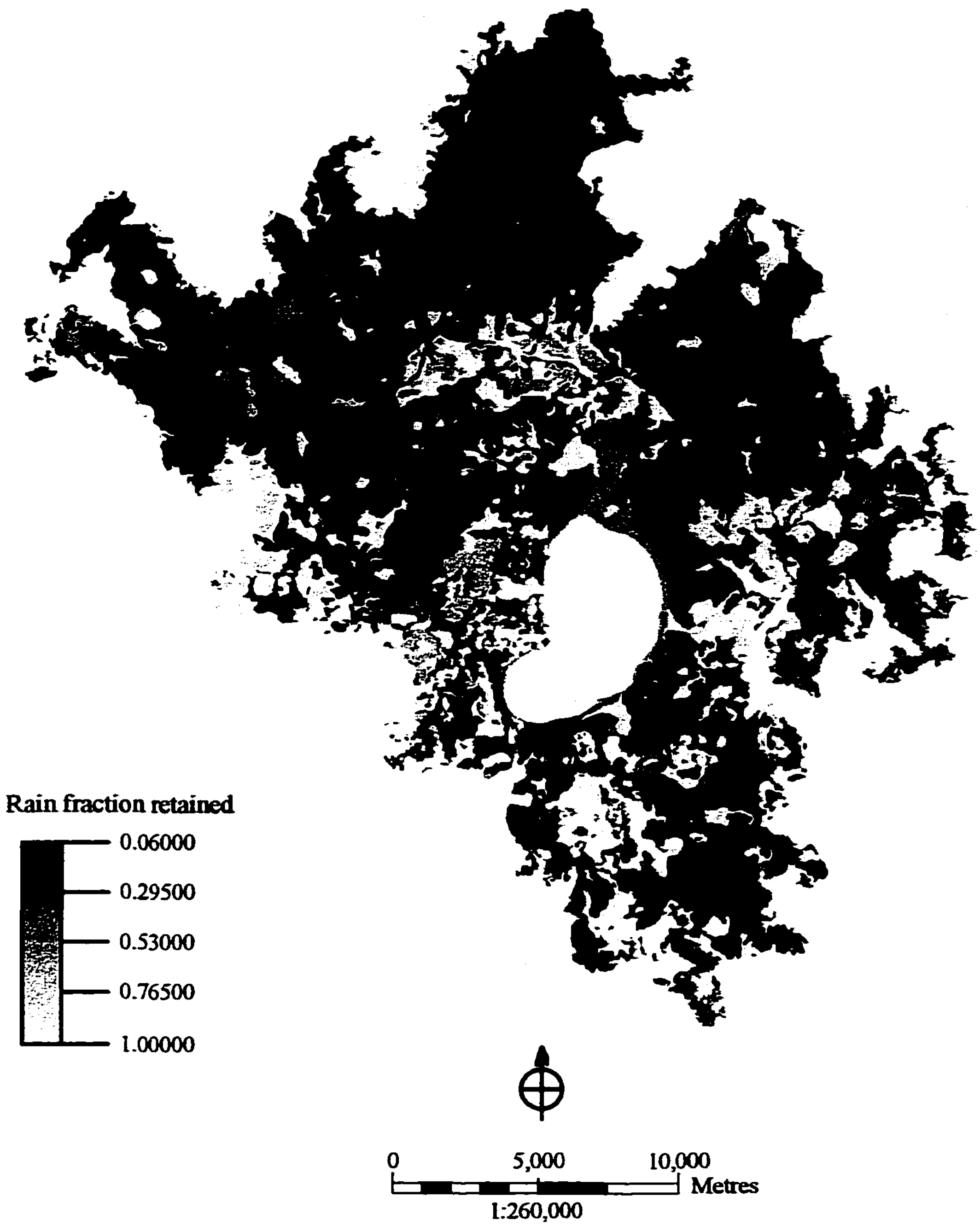


Figure 3.11. Soil impedance distributions, categorized by permeability and capacity, with values representing the fraction of an average rain event being retained within the soil column, Newnans Lake.

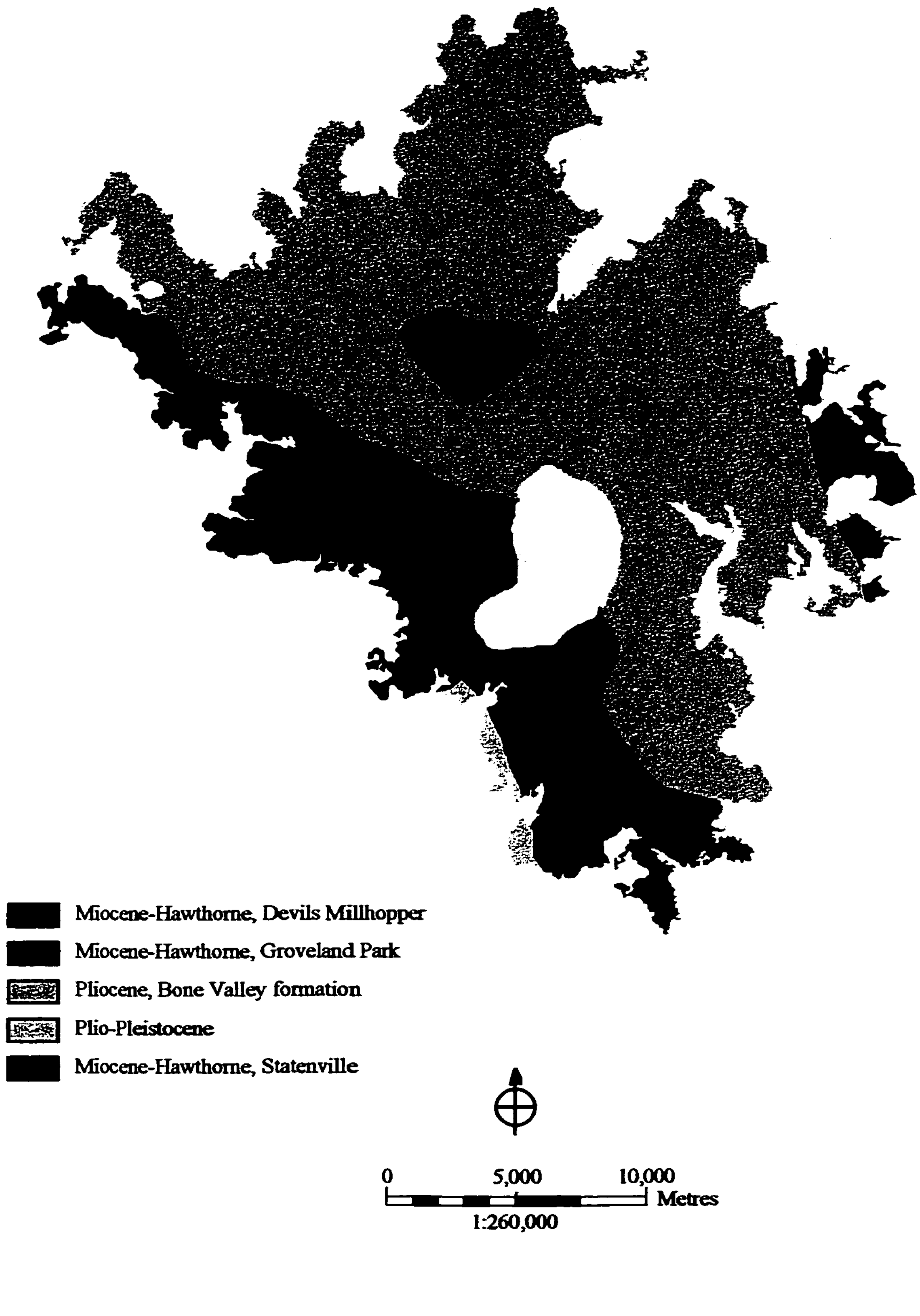


Figure 3.12. Map of subsurface geology formation, Newnans Lake (adapted from SCS, 1982).

Figure 3.13. Hydrological soil classification groups in Lake Weir watershed, as defined by Soil Conservation Service. Group D has high runoff potential, C has moderate potential, B has low runoff potential and A has little to no runoff potential (classification described in Chapter 2).

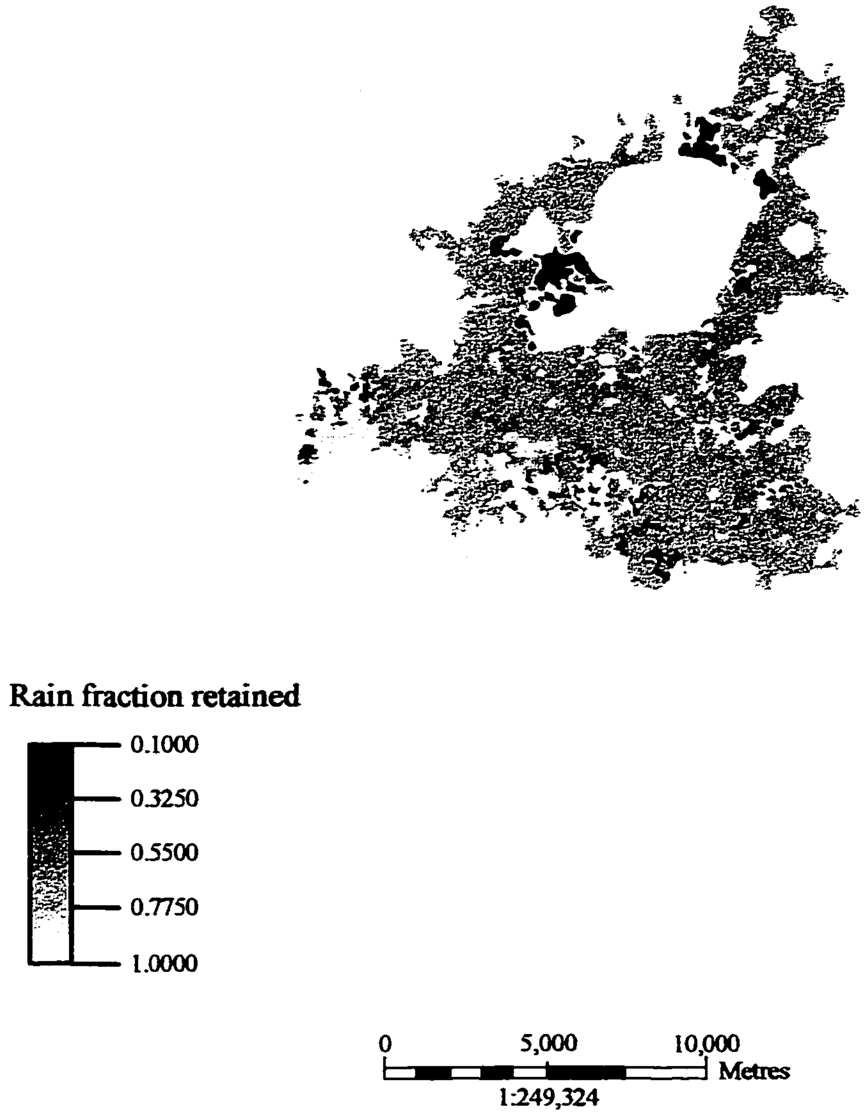


Figure 3.14. Soil impedance distributions, categorized by permeability and capacity, with values representing the fraction of an average rain event retained within the soil column, Lake Weir.

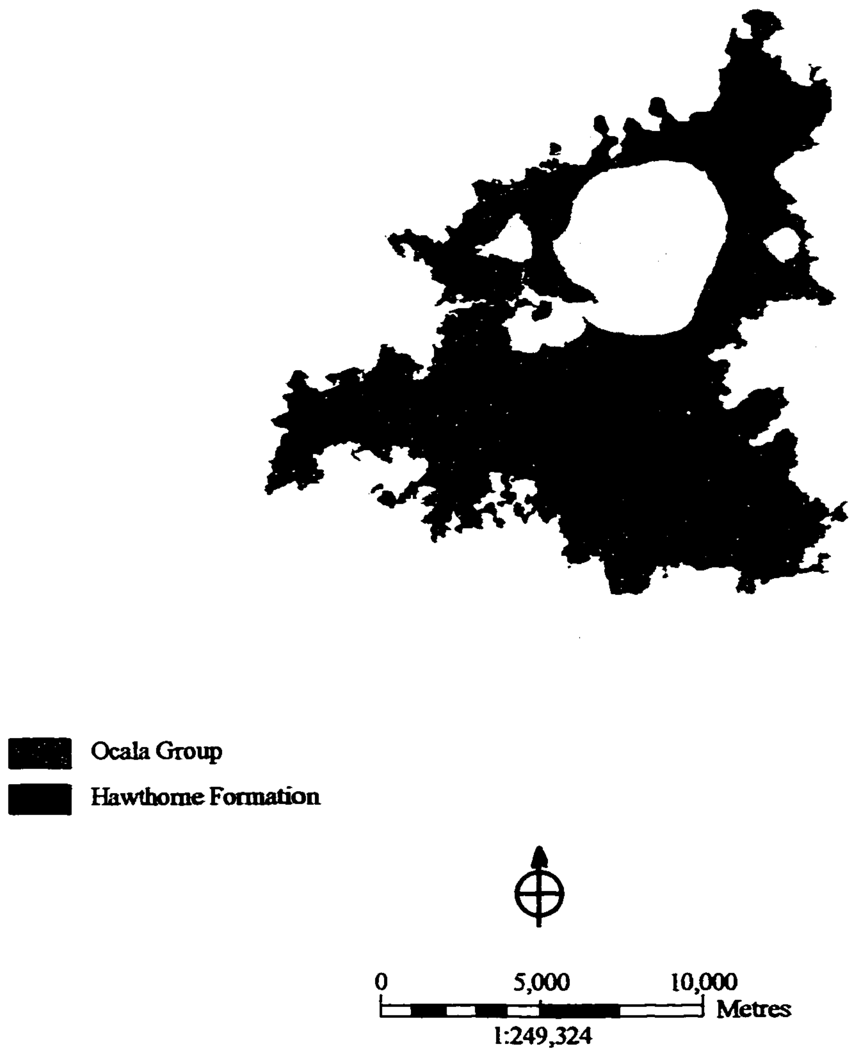


Figure 3.15. Map of subsurface geology formation, Lake Weir

Land Use Changes, Lake Weir

Figures 3.20 through 3.22 depict land use in the Lake Weir basin for 1950, 1970, and 1990, respectively. Table 3.10 and Figure 3.23 provide area values for specific land uses and illustrate the magnitude of changes.

The largest change in this watershed occured between 1970 and 1990 and was the conversion of orange groves throughout the watershed to range and residential land use, a total loss of 2355 hectares in production. Between 1950 and 1970, residential land use and agriculture increased throughout the watershed by approximately 400 ha, especially near the lake perimeter. A major highway was also built to the west of Lake Weir (U.S. Hwy. 441) between 1950 and 1970. A small section of urban area (Belleview) had encroached at the far west of the basin by 1990.

Results: Non-point Source Runoff Profiles

This section presents the results from the simulation of water, phosphorus and sediment movement through the watershed. Table 3.11 and 3.12 list overall material flows calculated in the spatial simulation for Newnans and Weir, respectively.

Water Profiles

Water movement through the watersheds is presented four different ways. The volume of water exported to the lake from each cell versus the number of cells exporting that volume is illustrated by a rank-order graph. The area of watershed contributing the largest amount of stormwater to the lake is mapped for 1950, 1970 and 1990. These areas of significant export were considered to be the "effective" watershed, as opposed to the actual watershed determined solely by elevational differences. Changes in watershed

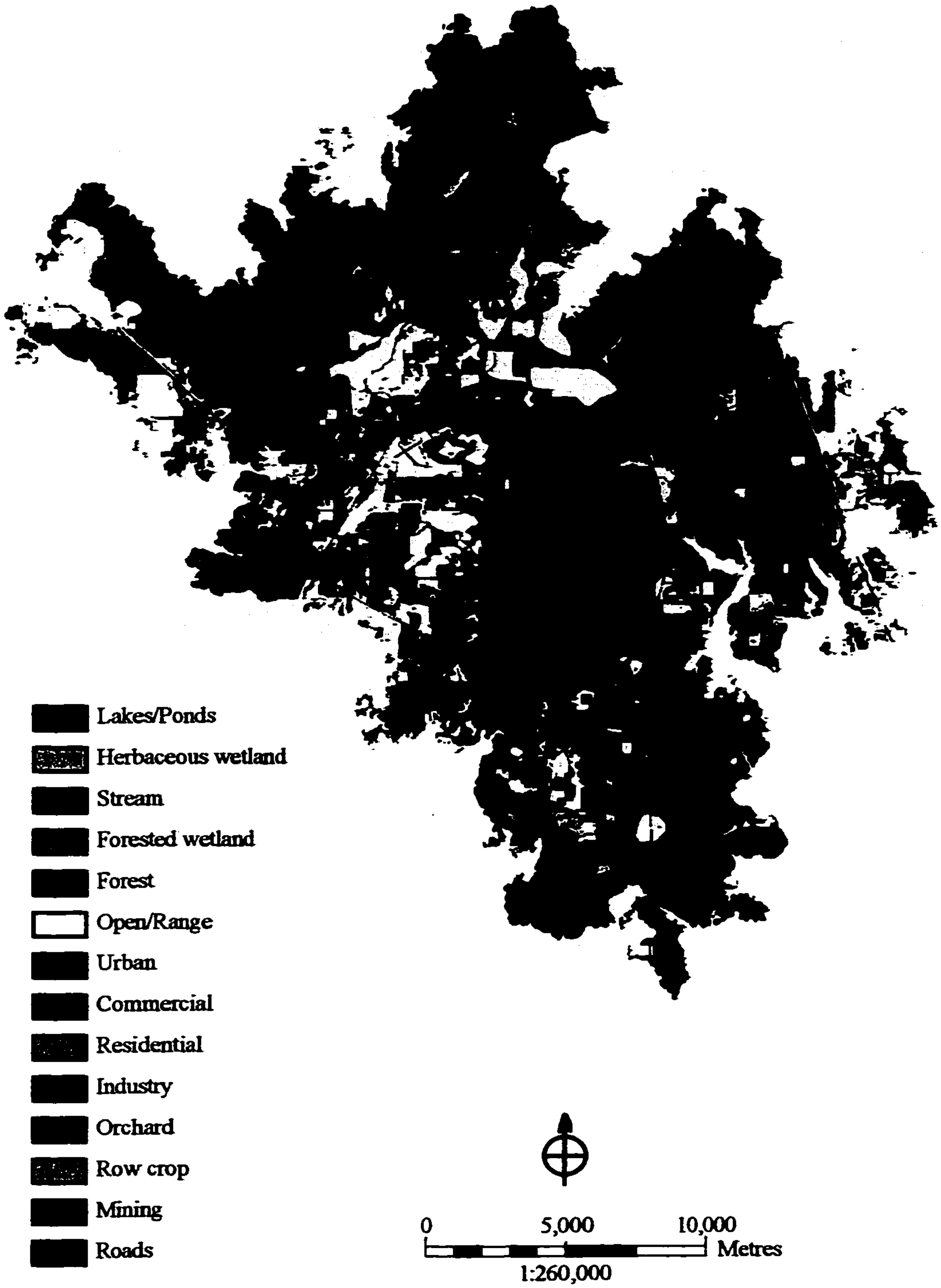


Figure 3.16. Newnans Lake watershed land use, 1950.

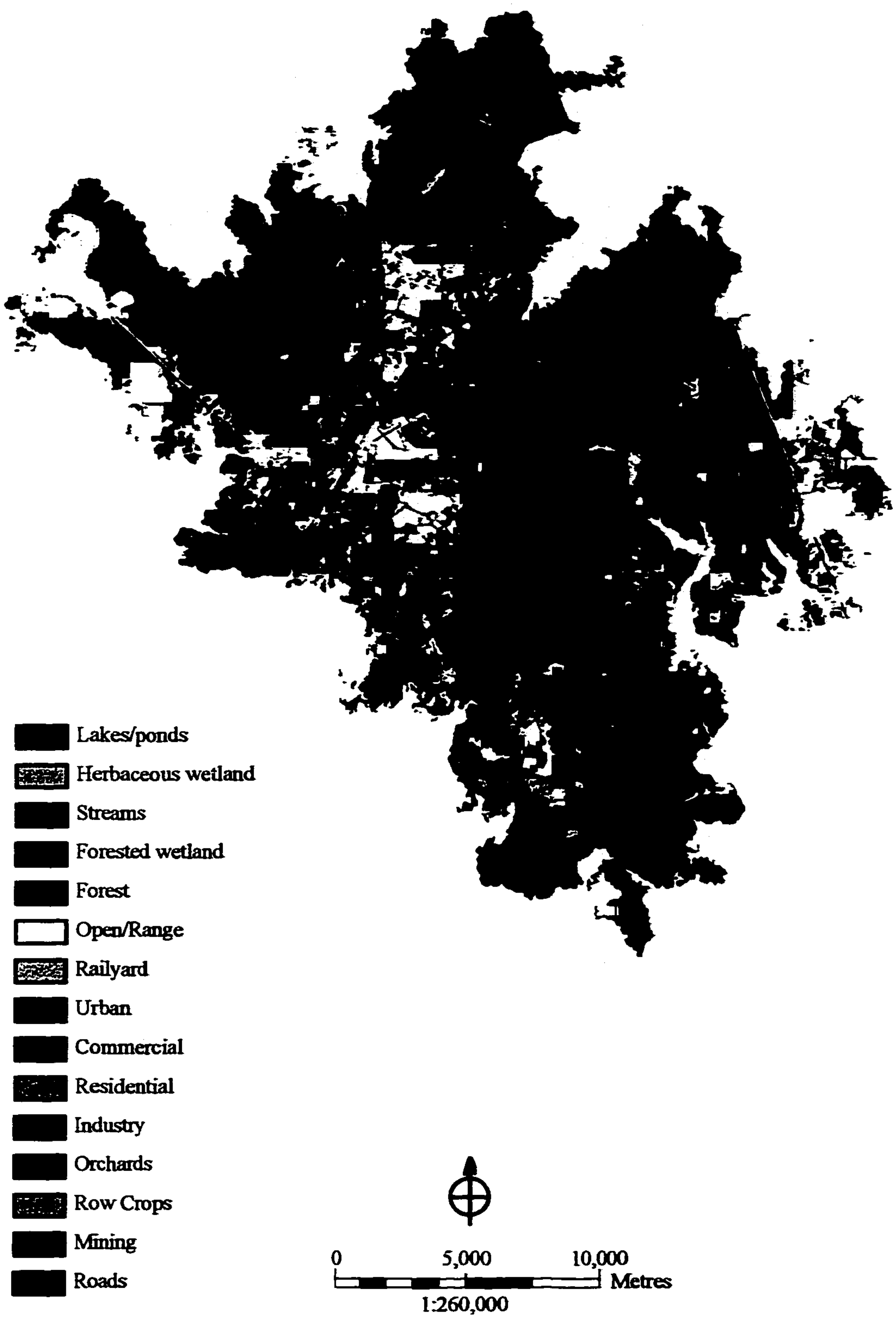


Figure 3.17. Newnans Lake watershed land use, 1970.

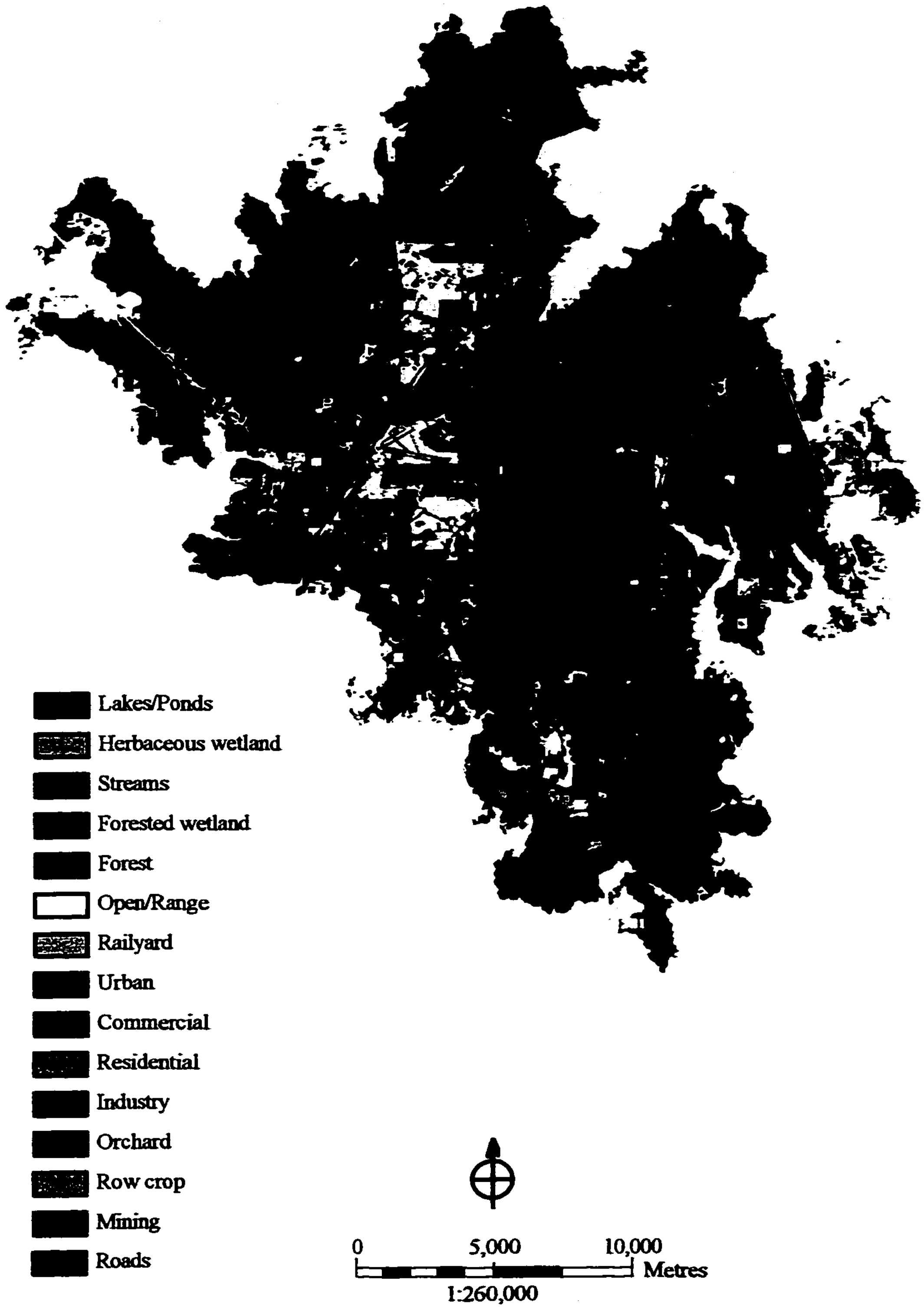


Figure 3.18. Newnans Lake watershed land use, 1990.

Table 3.9. Land use areas for Newnans Lake.

	1950	1970	1990	Change, % Basin
By Land Use, ha				
Water*	320	318	331	0.02%
Herbaceous Wetland	421	429	431	0.02%
Streams	628	629	588	-0.07%
Forested Wetland	7945	7990	7901	-0.08%
Forest	35086	35714	35330	0.44%
Open/Range	8226	6598	5813	-4.37%
Agriculture	200	143	129	-0.13%
Residential	911	1120	1341	0.78%
Urban	1060	1786	2550	2.70%
Industry	12	12	72	0.11%
Roads	410	481	732	0.58%
By Level of Development				
Natural	44400	45080	44581	0.33%
Cleared	8226	6598	5813	-4.37%
Developed	2593	3542	4825	4.04%

* Newnans Lake not included

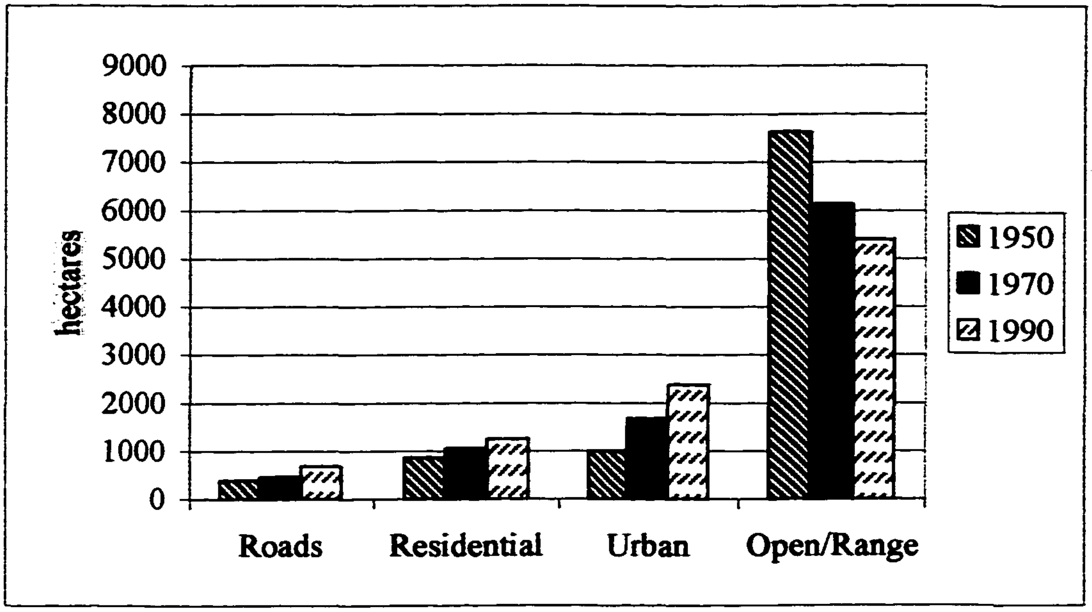


Figure 3.19. Highest land use changes in Newnans Lake watershed

Figure 3.20. Lake Weir watershed land use, 1950.

Figure 3.21. Lake Weir watershed land use, 1970.

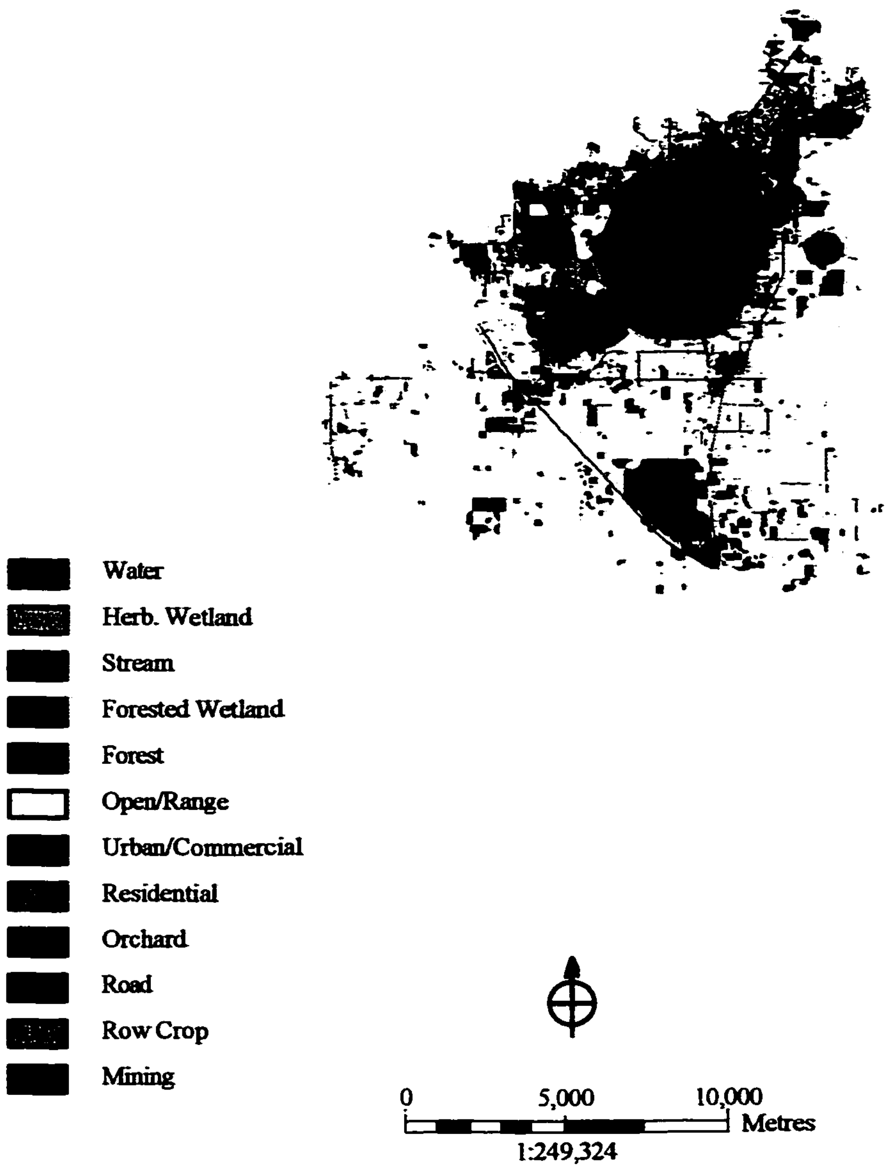


Figure 3.22. Lake Weir watershed land use, 1990.

Table 3.10. Land use areas for Lake Weir.

	1950	1970	1990	Change, % Basin
By Land Use, ha				
Water*	242	242	233	-0.09%
Herbaceous Wetland	218	156	168	-0.52%
Streams	3	3	3	0.00%
Forested Wetland	119	98	98	-0.21%
Forest	1407	1346	1315	-0.95%
Open/Range	5747	5569	6641	9.15%
Agriculture	1777	1910	253	-15.60%
Residential	178	320	790	6.26%
Urban	1	1	44	0.44%
Industry	0	0	1	0.01%
Roads	78	123	225	1.51%
By Level of Development				
Natural	1989	1845	1816	-1.77%
Cleared	5747	5569	6641	9.15%
Developed	2033	2354	1312	-7.38%

* Lake Weir not included

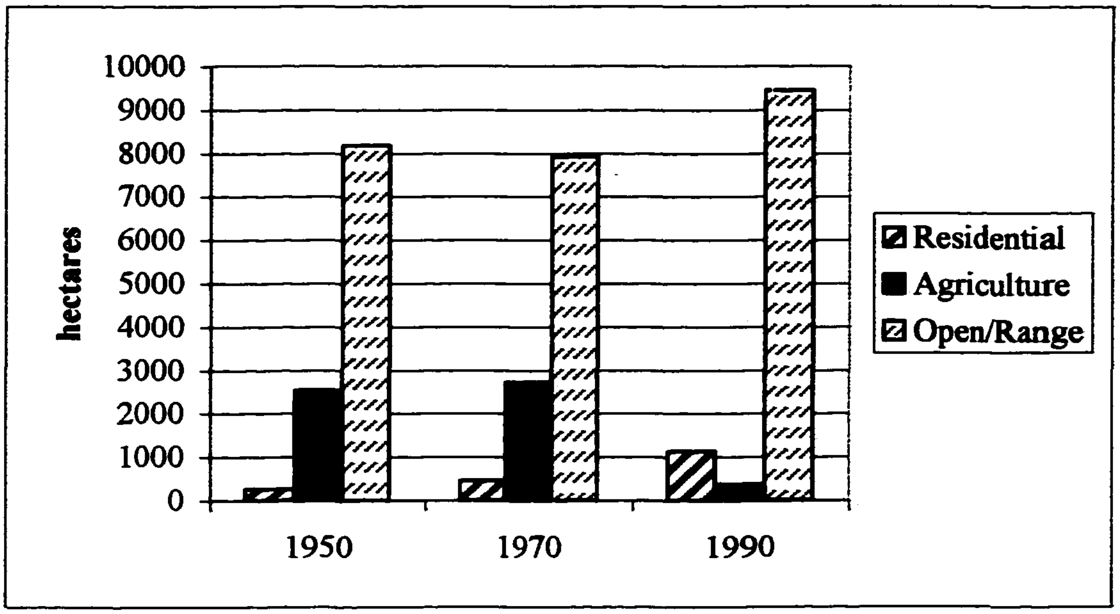


Figure 3.23. Highest land use changes in Lake Weir watershed

Table 3.11. Summary data for watershed loads to Newnans Lake from spatial simulations.

	Pre-development	1950	1970	1990
Phosphorous,g	3.87E+07	4.18E+07	4.25E+07	4.28E+07
Water, m3	2.66E+08	2.68E+08	2.68E+08	2.70E+08
Sediments, kg	2.77E+07	2.79E+07	2.79E+07	2.81E+07
Runoff, % of total rain	34.50%	34.80%	34.80%	35.10%

Table 3.12. Summary data for watershed loads to Lake Weir from spatial simulations.

	Pre-development	1950	1970	1990
Phosphorous,g	2.42E+07	4.97E+07	5.26E+07	3.40E+07
Water, m3	6.61E+07	6.66E+07	6.68E+07	6.71E+07
Sediments, kg	7.59E+06	7.64E+06	7.66E+06	7.70E+06
Runoff, % of total rain	30.21%	30.43%	30.51%	30.66%

export to the lake are illustrated by mapping the quantitative difference in stormwater runoff for each cell between 1950 and 1970 and between 1970 and 1990. Total estimated volumes of non-point source runoff for each year are also presented in Table 3.11.

Water profiles for Newnans Lake

The rank-order graph (Fig 3.24) shows an exponentially decreasing curve for Newnans Lake. In other words, there were a high number of map cells exporting less than 1,000 liters per year, and successively fewer cells exporting progressively higher amounts. This curve was generated by dividing cell data into 5,000 liter/cell increments and plotting the average of each increment.

All three maps of the effective watershed (Figure 3.25 - 27) show the majority of the watershed exporting less than 1 $l/m^2/yr$ (1,000 liters per cell). The watershed zone closest to the lake exports from 11 $l/m^2/yr$ (1E4 liters per cell) to 1,800 $l/m^2/yr$ (1E6 liters per cell). The middle zone exports, on average, 7 $l/m^2/yr$ (6,000 liters per cell).

Changes in export zones are most evident between 1950 and 1970 and mainly on the western shore of the lake. The high export zone immediately adjacent to the lake was approximately 5.24E7 m^2 in 1950, 5.68E7 m^2 in 1970, and 5.71E7 m^2 in 1990. This translates to an 8% increase between 1950 and 1970 and a 3% increase from 1970 to 1990. The middle zone grew less than 1% between 1950 and 1970, but increased by 5% from 1970 to 1990.

Areas of greatest export differences on a per cell basis occurred between 1950 and 1970 (Figure 3.28), with the highest runoff addition immediately west of Newnans Lake. However, the entire northwestern section of the watershed increased in export. This is the area of development evident in the land use maps, and is also the steepest portion of the watershed. The watershed to the north and northeast contributed slightly less between 1950 and 1970, most likely due to the 700 ha reforestation visible in this region. The remainder of the watershed is unchanged. Changes between 1970 and 1990 (Figure 3.29) exhibit a patchy distribution, with most potentially adverse conditions to the far west of the watershed in the Gainesville area and around the airport.

Water profiles for Lake Weir

The rank-order graph (Fig 3.30) shows an exponentially decreasing curve for LakeWeir similar to Newnans curve. In other words, there were a high number of map cells exporting less than 1,000 liters per year, and successively fewer cells exporting progressively higher amounts. This curve was generated by dividing cell data into 5,000 liter/cell increments and plotting the average of each increment, in the same way as Newnans curve.

All three maps of the effective watershed (Figure 3.31 - 33) show approximately half of the watershed exporting less than 1 $l/m^2/yr$ (1,000 liters per cell). The watershed zone closest to the lake exports from 11 $l/m^2/yr$ (1E4 liters per cell) to 1,800 $l/m^2/yr$ (1E6 liters per cell). The middle zone exports, on average, 7 $l/m^2/yr$ (6,000 liters per cell).

Changes in export zones are most evident between 1970 and 1990 and mainly in the southern portion of the watershed, but are not as apparent as changes in Newnans watershed with overall higher volume of runoff. The high export zone immediately adjacent to the lake was approximately 5.24E7 m^2 in 1950, 5.68E7 m^2 in 1970, and 5.71E7 m^2 in 1990. This translates to an 8% increase between 1950 and 1970 and a 3%

increase from 1970 to 1990. The middle zone grew less than 1% between 1950 and 1970, but increased by 5% from 1970 to 1990.

Areas of greatest export differences on a per cell basis occurred between 1970 and 1990 (Figure 3.34), with the highest runoff additions immediately north of Lake Weir and in the southern portion of the watershed. This is due to a switch in land use from citrus production to residential.

Phosphorus Profiles for Newnans Lake

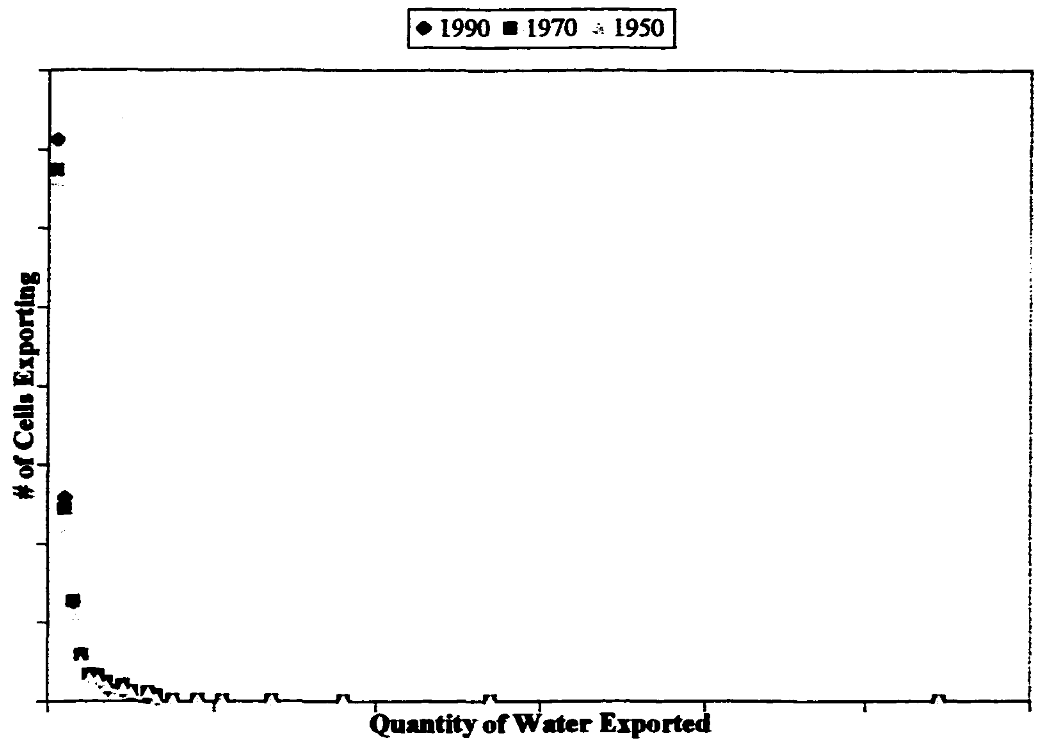
Estimated deposition of phosphorus is shown in Figures 3.36-3.38. High levels of deposition are evident in agricultural, residential and urban areas due to fertilizer use. All sets of maps are for 1950, 1970 and 1990, respectively.

Figures 3.39, 3.40 and 3.42 depict the quantity of phosphorus estimated to reach the lake from that particular cell. Because this is a function of both deposition and effective distance, the spatial configuration of export cells is different than for the deposition maps.

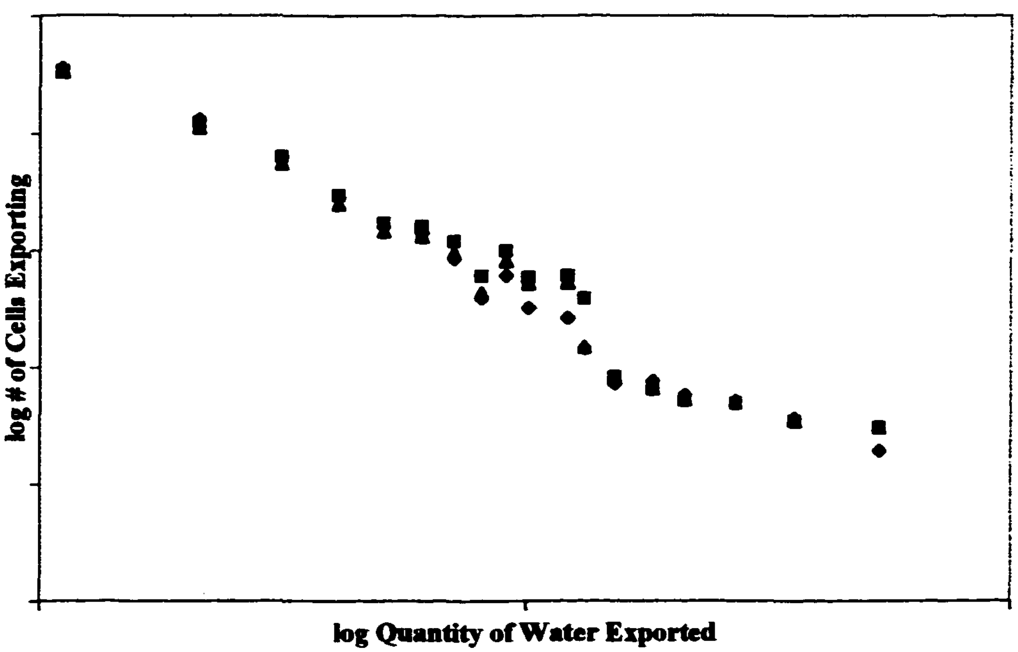
Phosphorus Profiles for Lake Weir

Figures 3.42 and 3.43 show high levels of phosphorus deposition throughout the watershed in 1950 and 1970 when citrus production was active. Citrus production ceased in the mid-80s, when it was replaced by some forested areas, but mostly open range and residential. Deposition profiles for 1990 reflect that change (Figure 3.44).

Figures 3.45 - 3.47 depict the quantity of phosphorus estimated to reach the lake from that particular cell. Because this is a function of both deposition and effective distance, the spatial configuration of export cells is different than for the deposition maps,



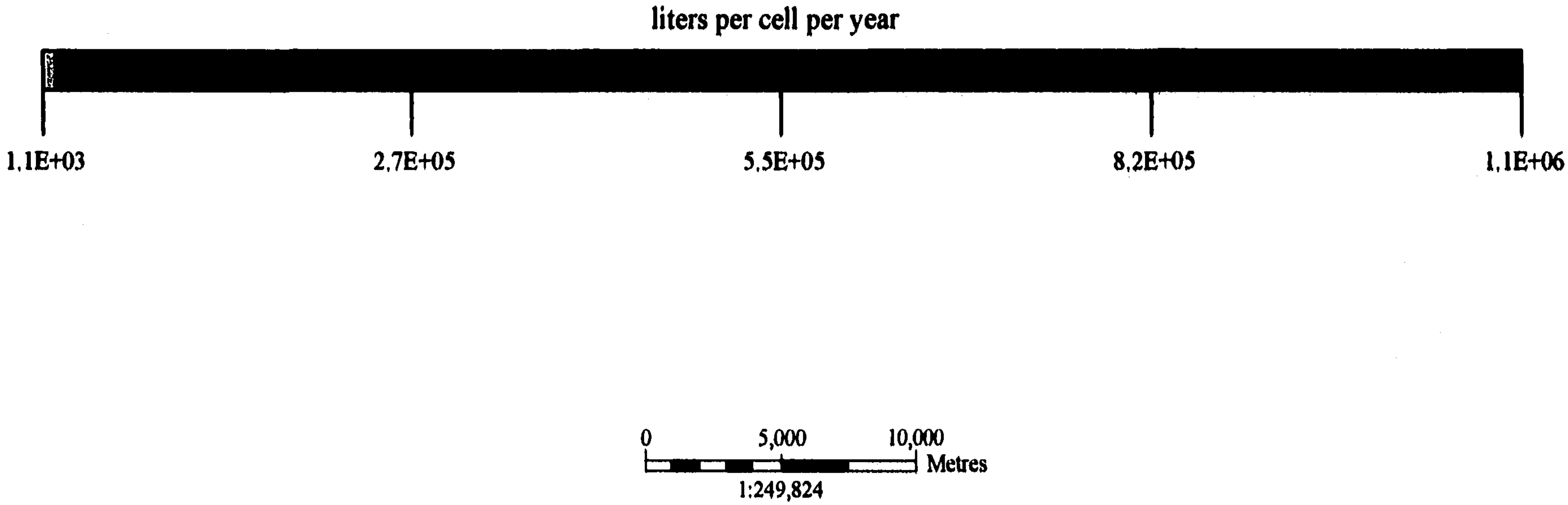
a



b

Figure 3.24. Rank-order graph for water volume exported from each cell in Newnans Lake watershed: a) curve generated by actual data; b) log-log representation of data.

Figure 3.25. Effective watershed, 1950, Newnans Lake. Inner zone exports from 1E4 to 1E6 liters of water per cell per year; middle zone exports on average 6000 l/yr; outer zone exports less than 1000 l/yr.



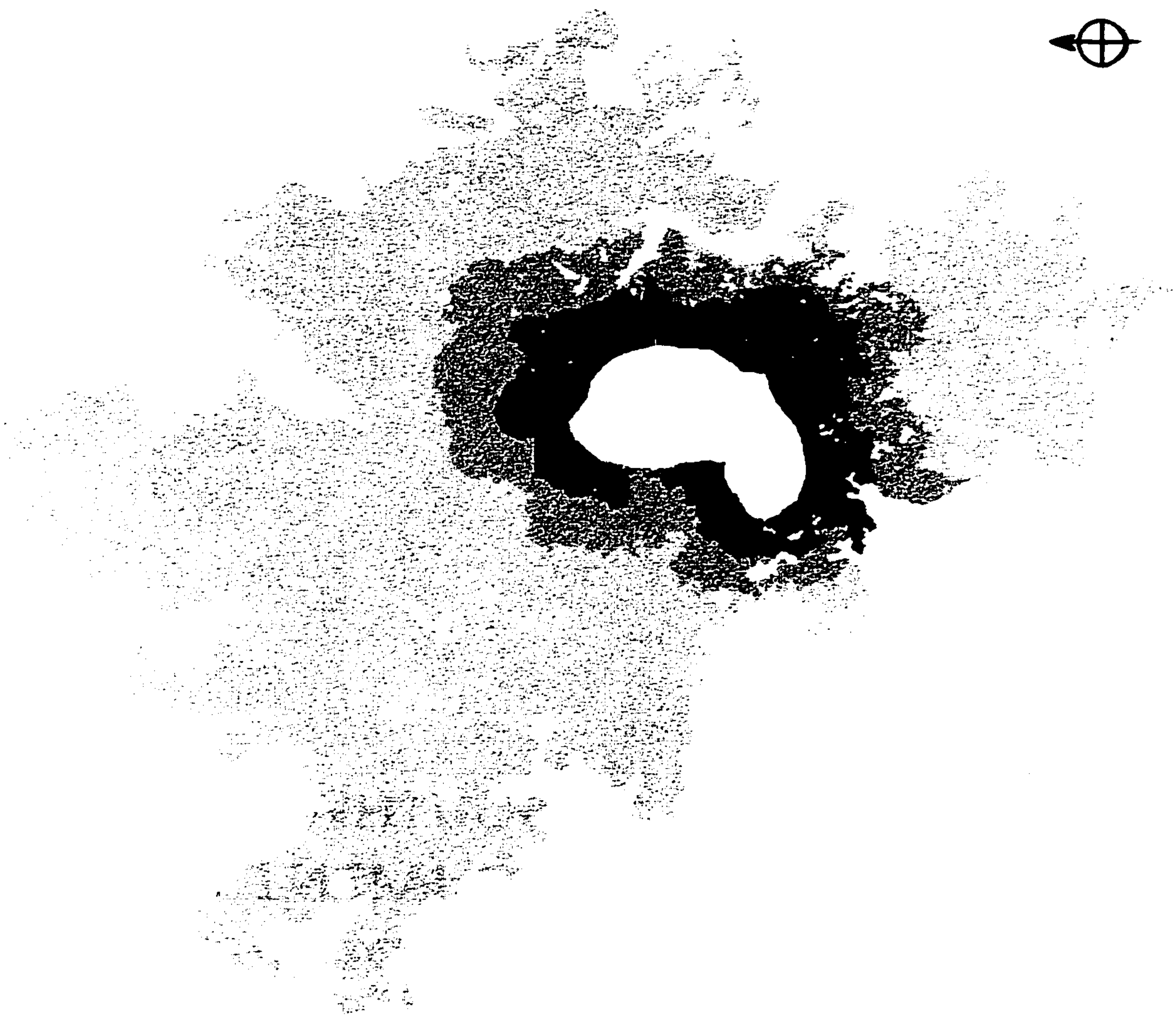
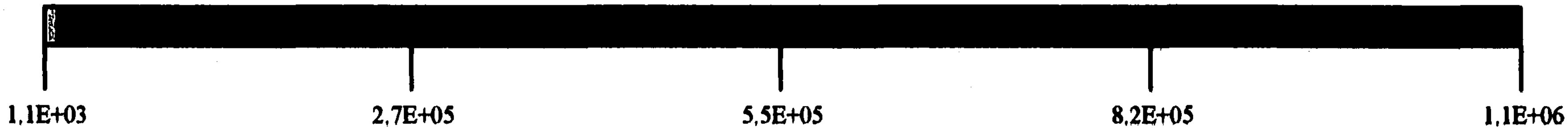


Figure 3.26. Effective watershed, 1970, Newnans Lake. Inner zone exports from 1E4 to 1E6 liters of water per cell per year; middle zone exports on average 6000 l/yr; outer zone exports less than 1000 l/yr.



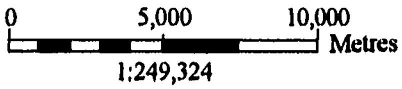


Figure 3.27. Effective watershed, 1990, Newnans Lake. Inner zone exports from 1E4 to 1E6 liters of water per cell per year; middle zone exports on average 6000 l/yr; outer zone exports less than 1000 l/yr.

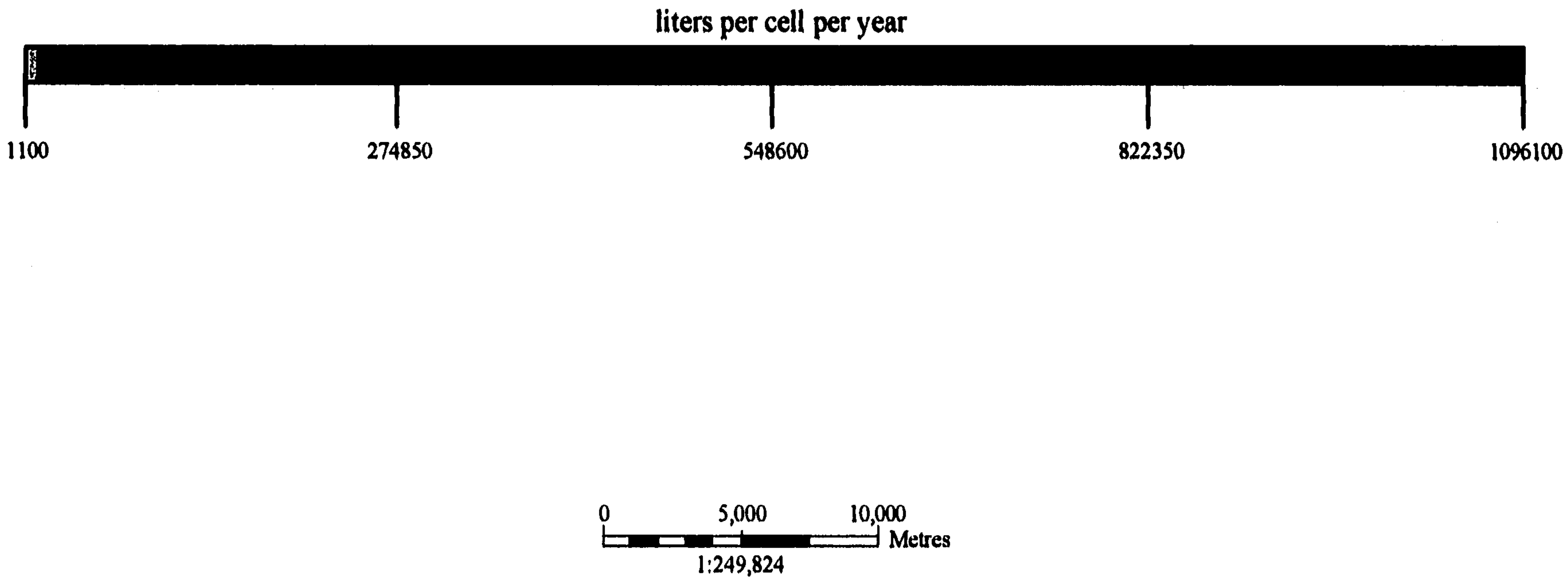


Figure 3.28. Changes in area of watershed contributing stormwater to the lake between1950 and 1970, Newnans Lake watershed. Increases in effective watershed are red to yellow (red being area of highest transport) and coincide with areas having an increase in impervious surface. No change or decrease in transport range from dark green (beneficial change) to light green (little or no change) with beneficial changes coinciding with areas of reforestation.

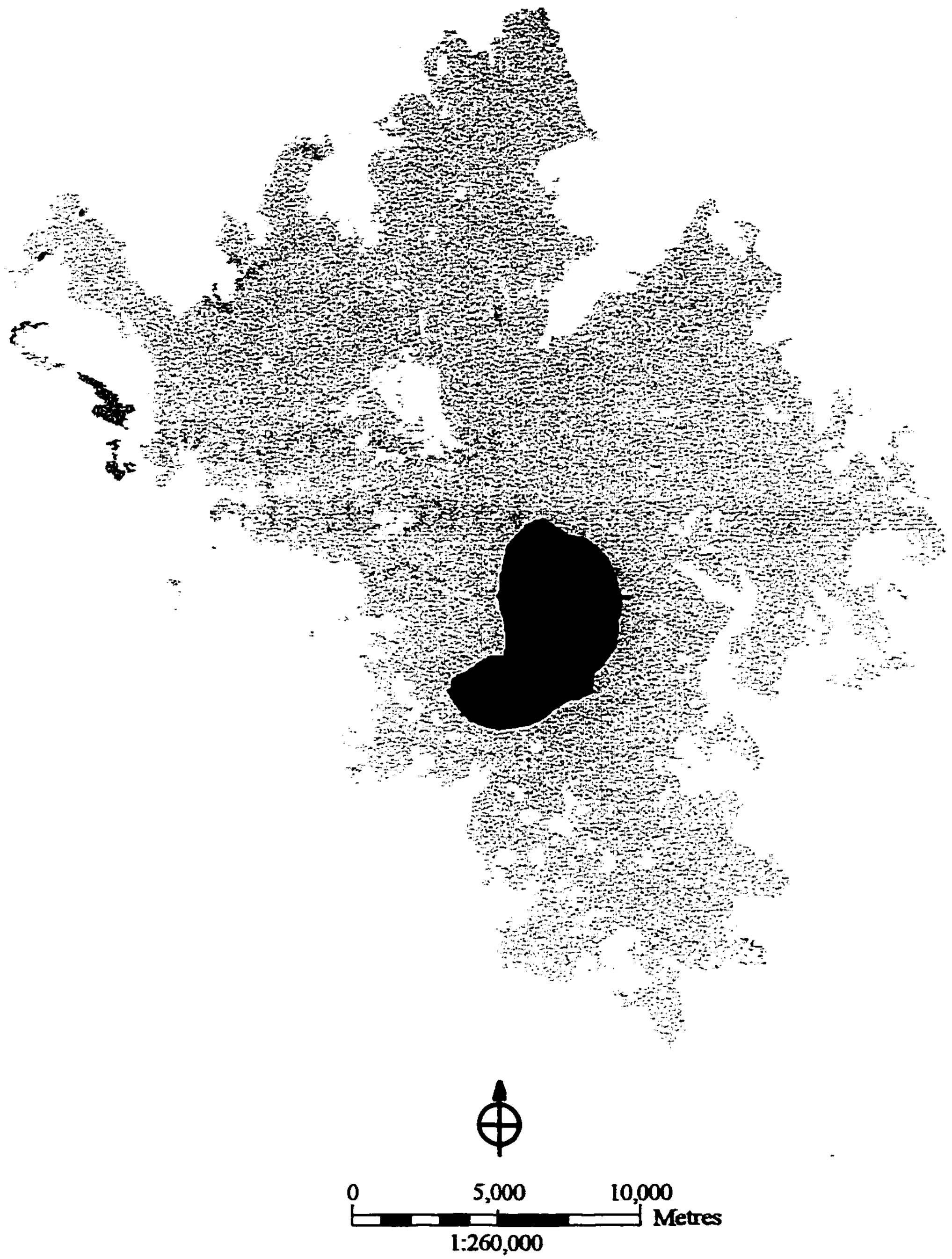
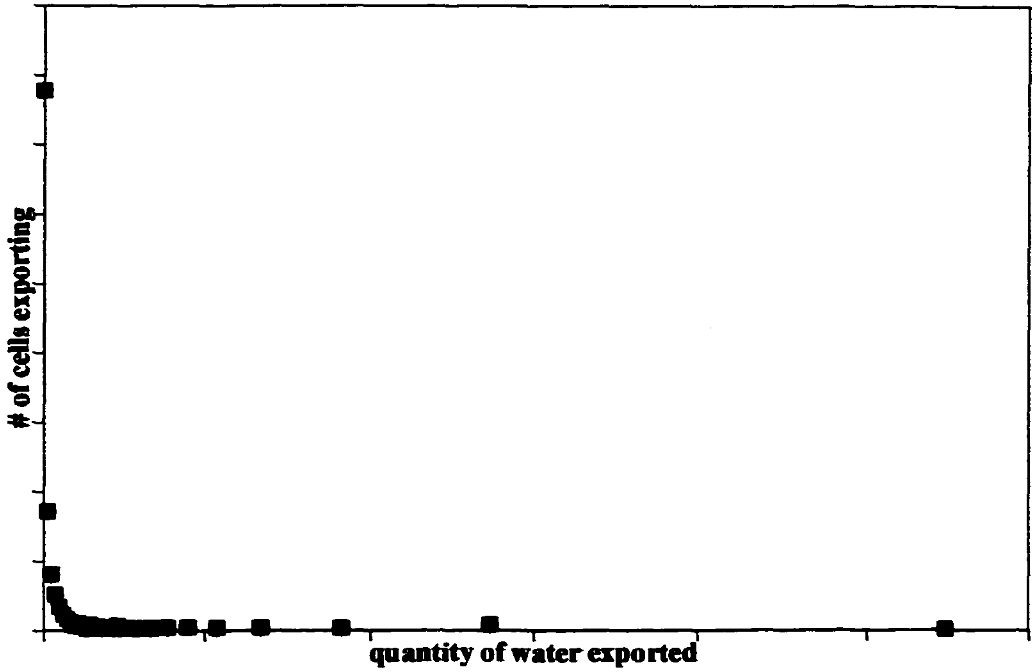
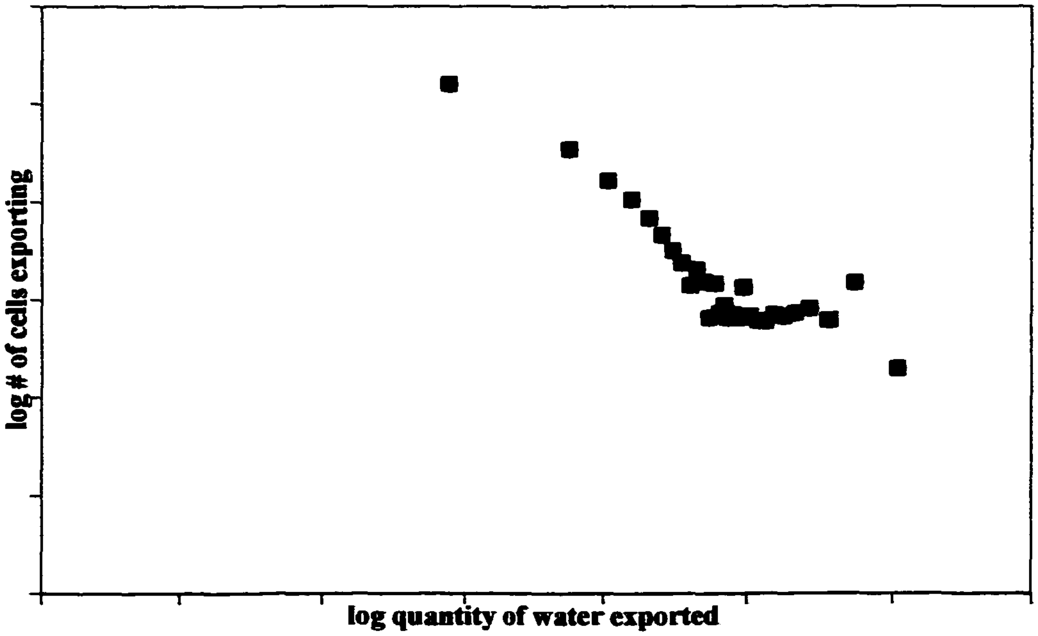


Figure 3.29. Changes in area of watershed contributing stormwater to the lake between1970 and 1990, Newnans Lake watershed. Increases in effective watershed are red to yellow (red being area of highest transport) . No change or decrease in transport range from dark green (beneficial change) to light green (little or no change).



(a)



(b)

Figure 3.30. Rank-order graph for water volume exported from each cell in Lake Weir watershed: a) curve generated by actual data; b) log-log representation of data

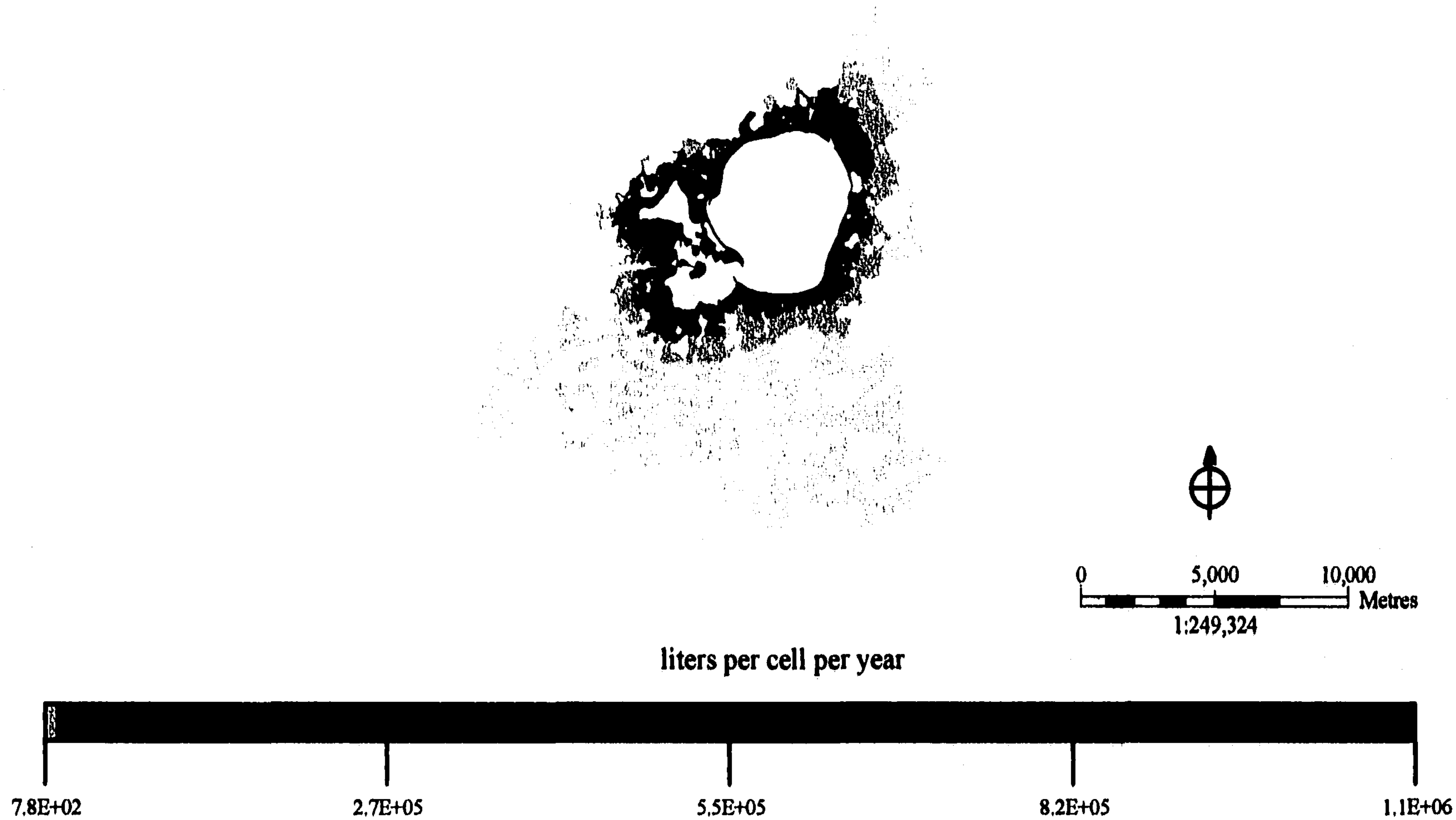


Figure 3.31. Effective watershed, 1950, Lake Weir. Inner zone exports from 1E4 to 1E6 liters of water per cell per year; middle zone exports on average 6000 l/yr; outer zone exports less than 1000 l/yr.

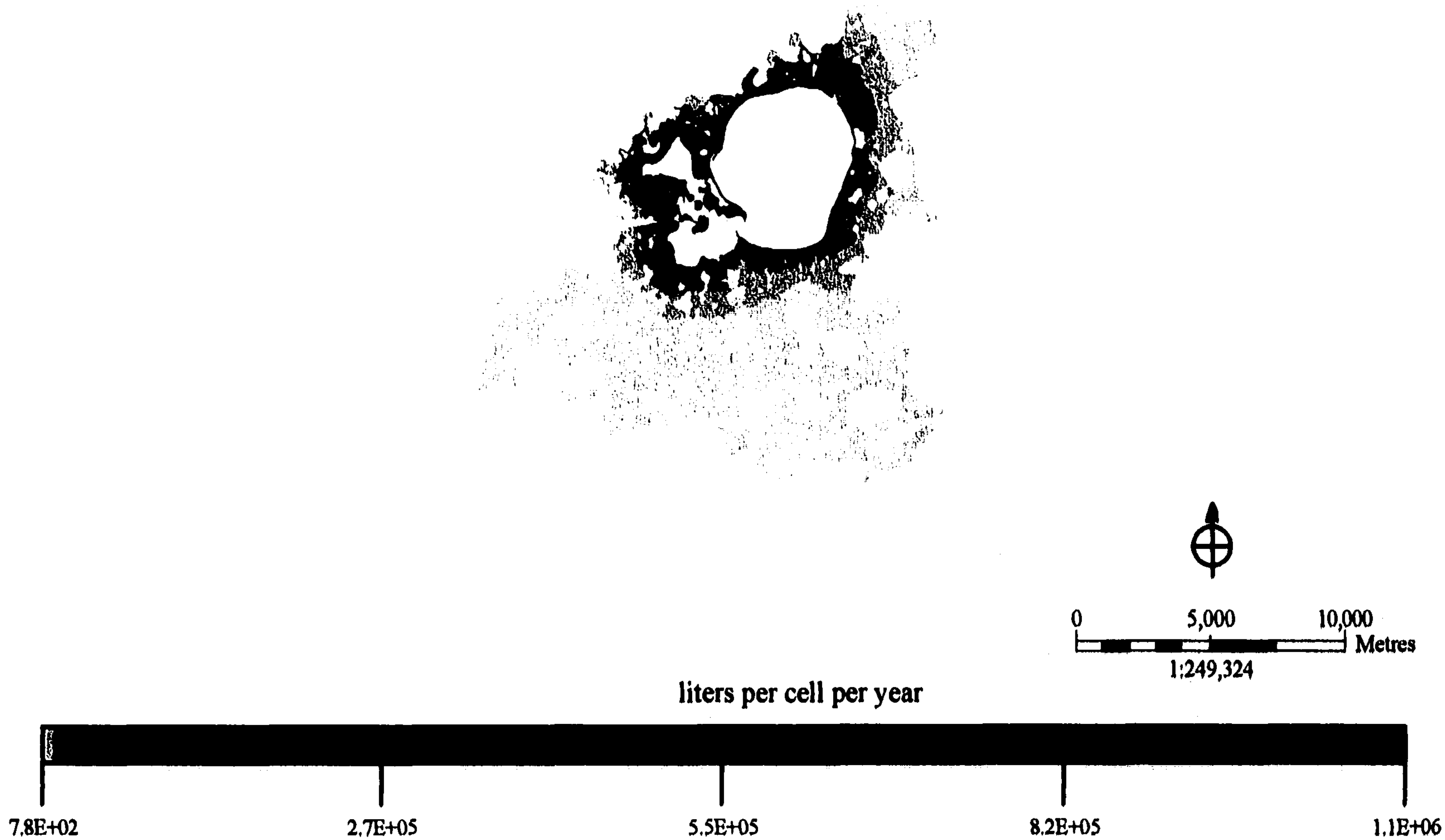


Figure 3.32. Effective watershed, 1970, Lake Weir. Inner zone exports from 1E4 to 1E6 liters of water per cell per year; middle zone exports on average 6000 l/yr; outer zone exports less than 1000 l/yr.

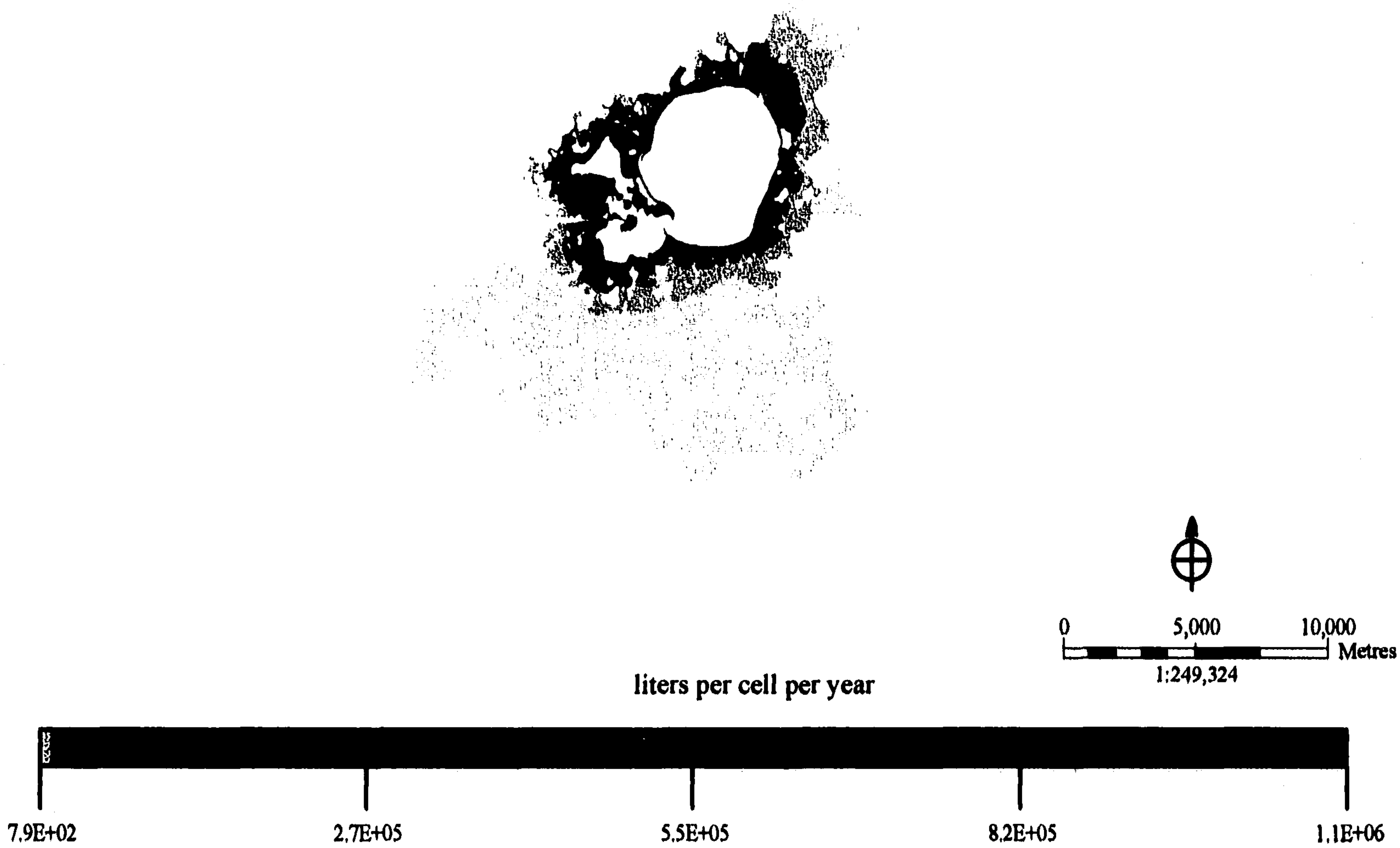


Figure 3.33. Effective watershed, 1950, Lake Weir. Inner zone exports from 1E4 to 1E6 liters of water per cell per year; middle zone exports on average 6000 l/yr; outer zone exports less than 1000 l/yr.

Figure 3.34. Changes in area of watershed contributing stormwater to the lake between 1950 and 1970, Lake Weir watershed. Increases in effective watershed are red to yellow (red being area of highest transport) . No change or decrease in transport range from dark green (beneficial change) to light green (little or no change).

Figure 3.35. Changes in area of watershed contributing stormwater to the lake between 1970 and 1990, Lake Weir watershed. Increases in effective watershed are red to yellow (red being area of highest transport) . No change or decrease in transport range from dark green (beneficial change) to light green (little or no change).

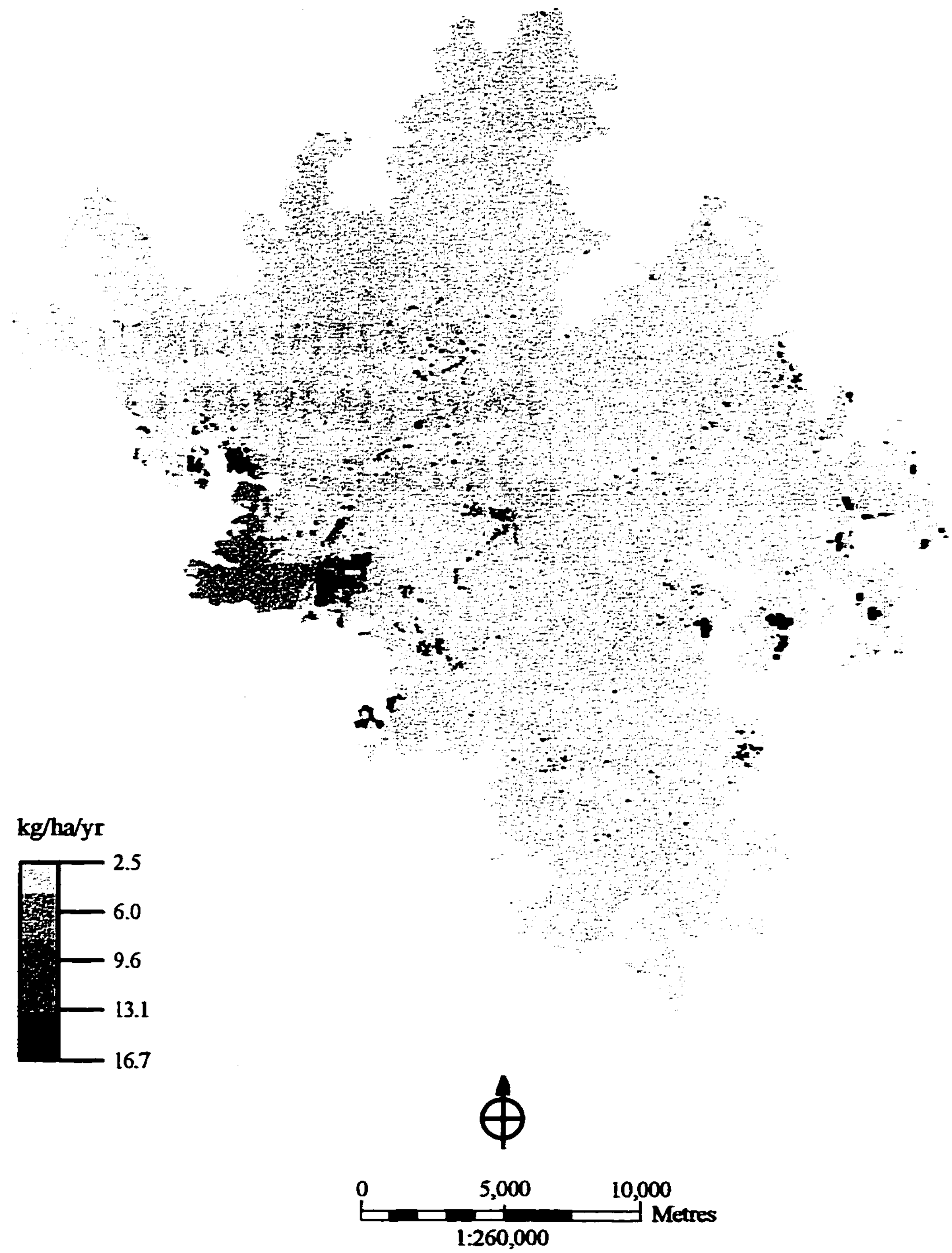


Figure 3.36. Estimated phosphorus deposition, 1950, Newnans Lake watershed.

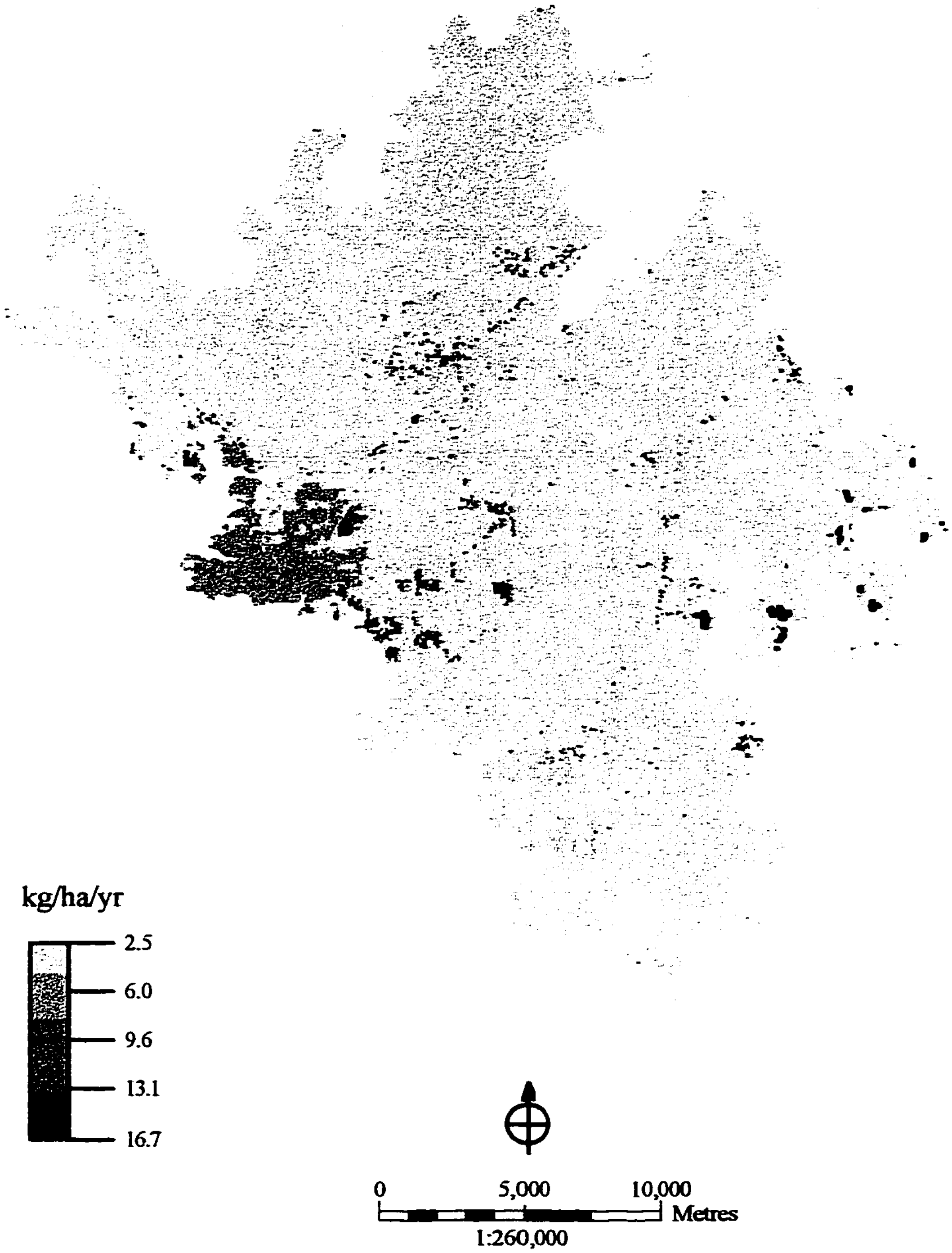


Figure 3.37. Estimated phosphorus deposition, 1970, Newnans Lake watershed.

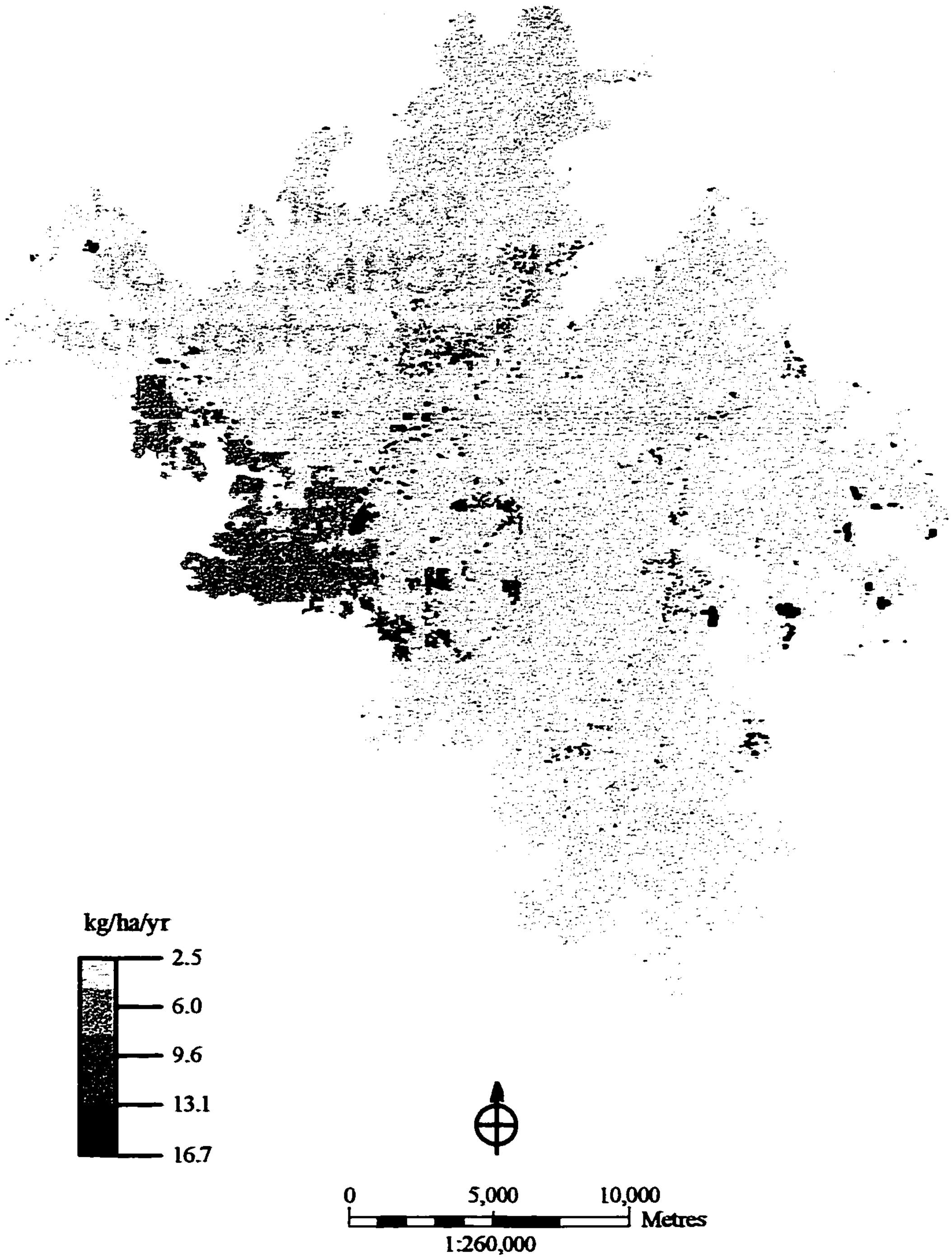


Figure 3.38. Estimated phosphorus deposition, 1990, Newnans Lake watershed.

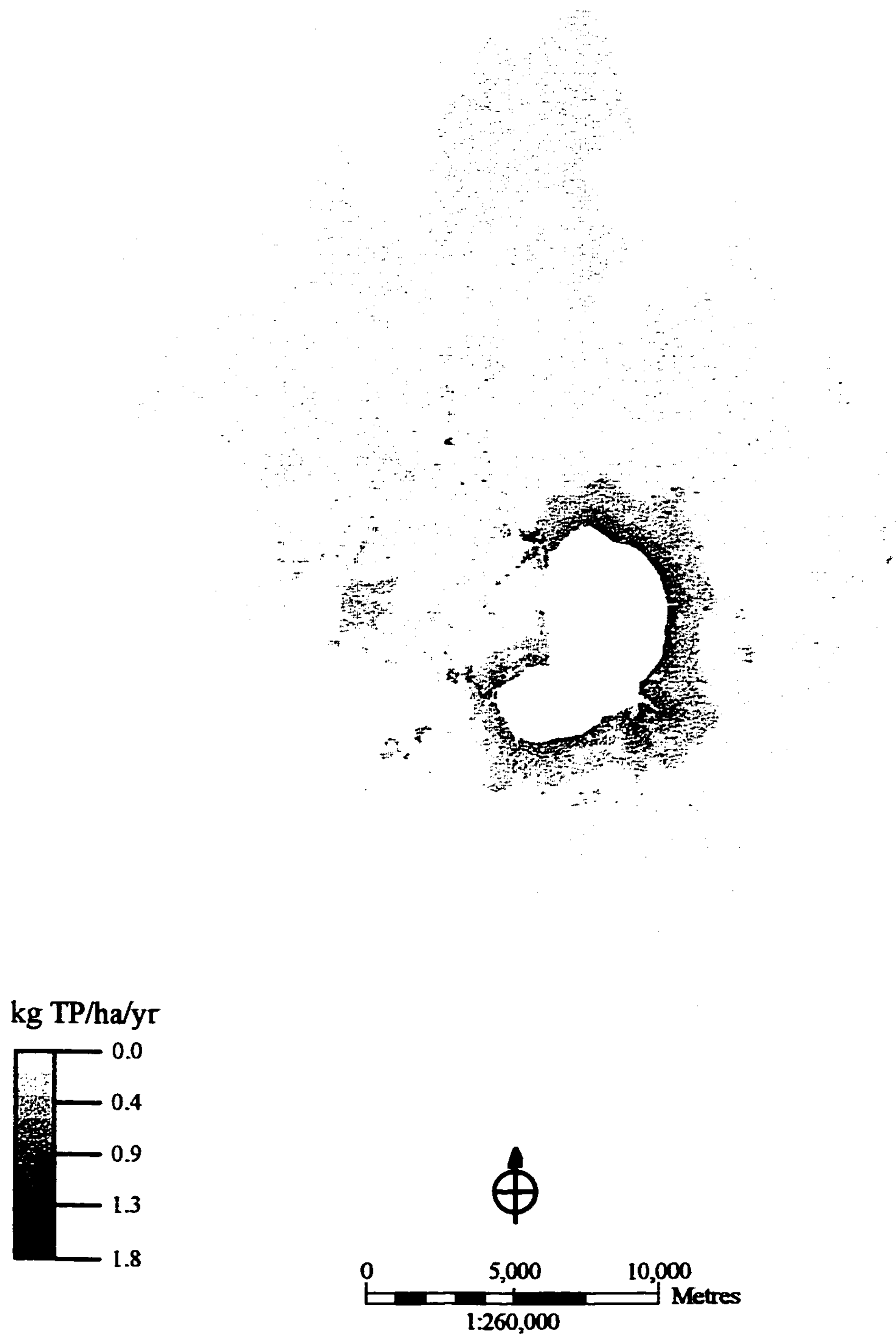


Figure 3.39. Estimated total phosphorus (TP) export profile for 1950, Newnans Lake. Each band represents 20kg TP/ha/yr exported from that area and reaching the lake.

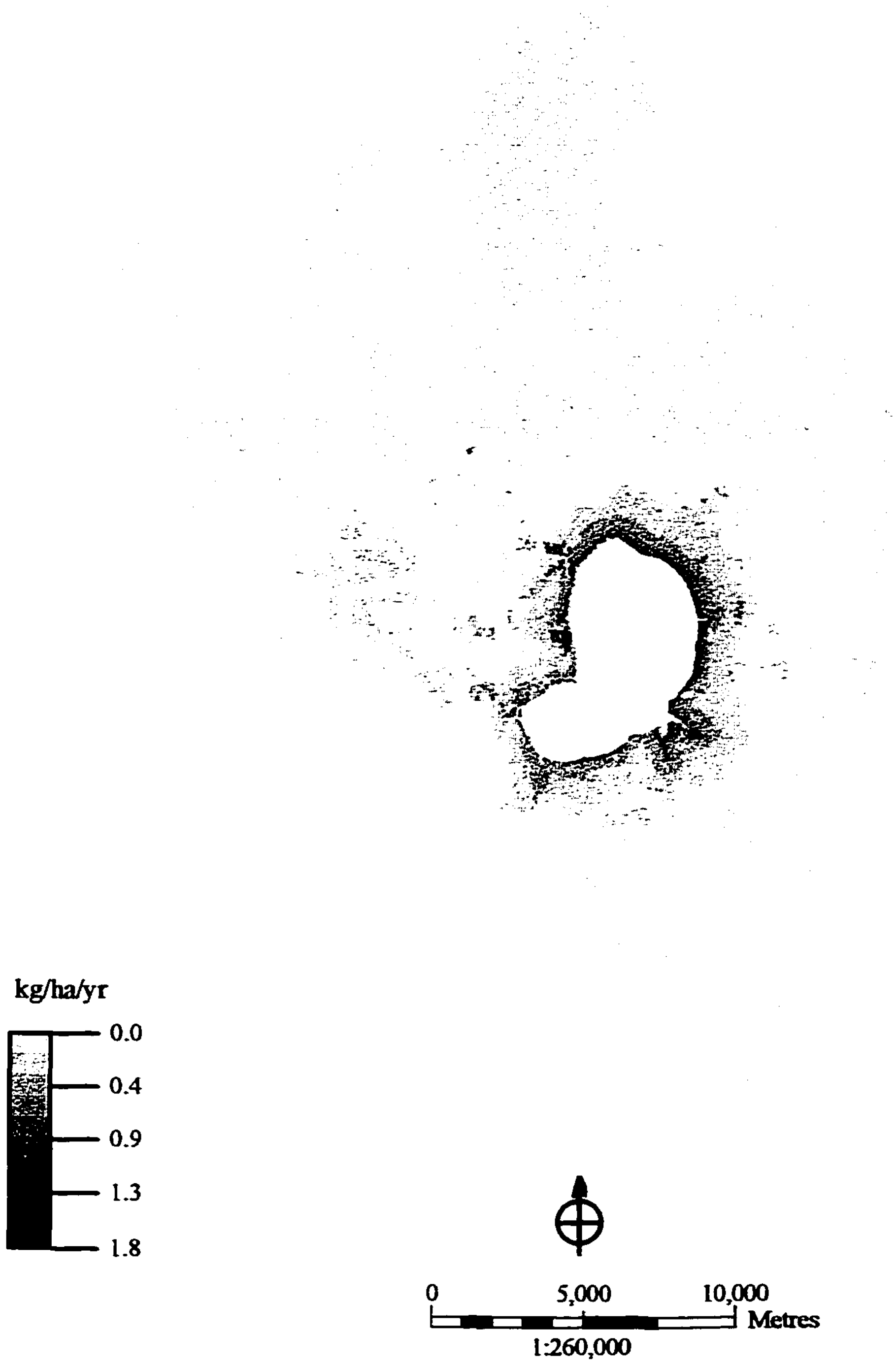


Figure 3.40. Estimated total phosphorus (TP) export profile for 1970, Newnans Lake. Each band represents 20kg TP/ha/yr exported from that area and reaching the lake.

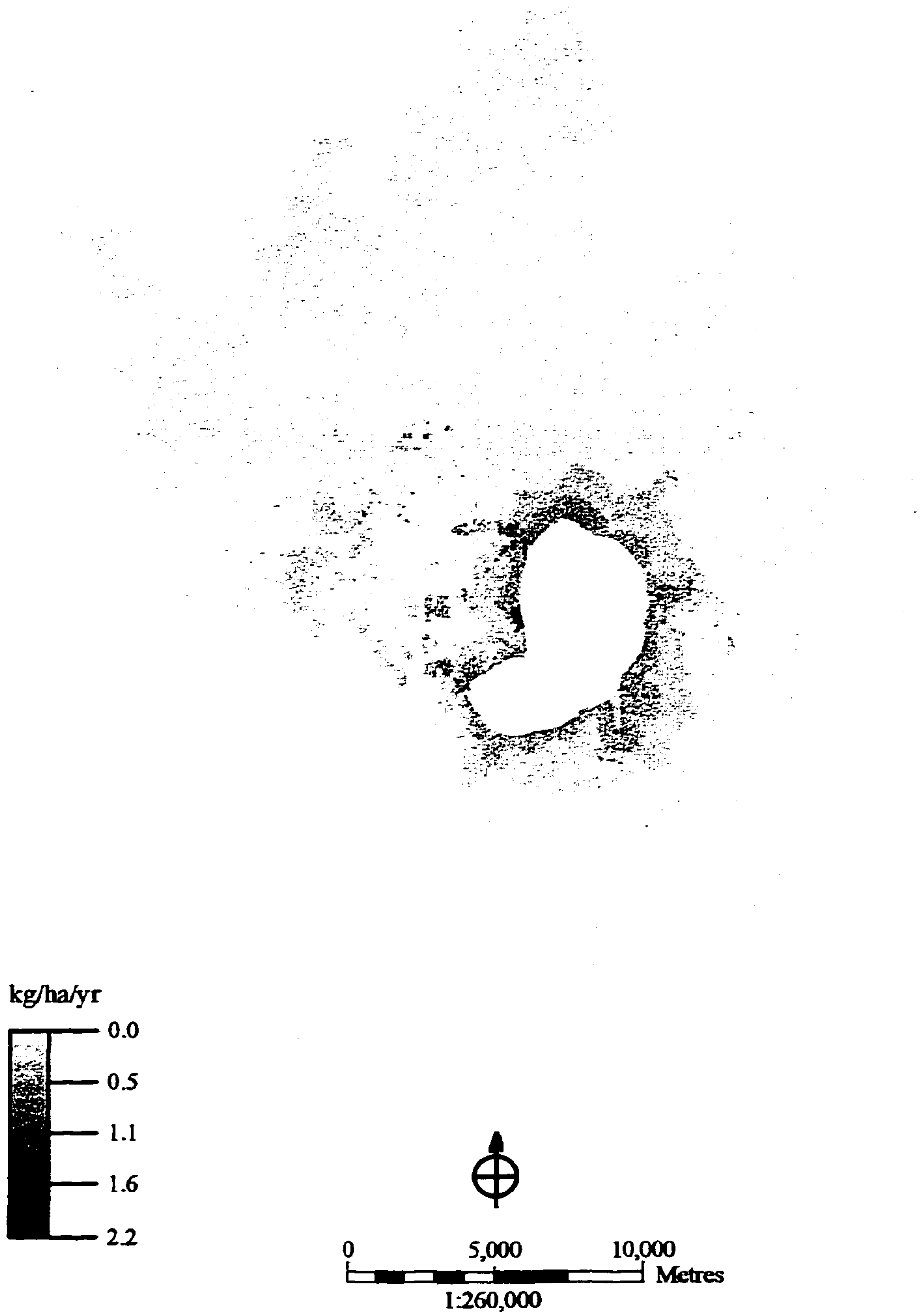


Figure 3.41. Estimated total phosphorus (TP) export profile for 1990, Newnans Lake. Each band represents 20kg TP/ha/yr exported from that area and reaching the lake.

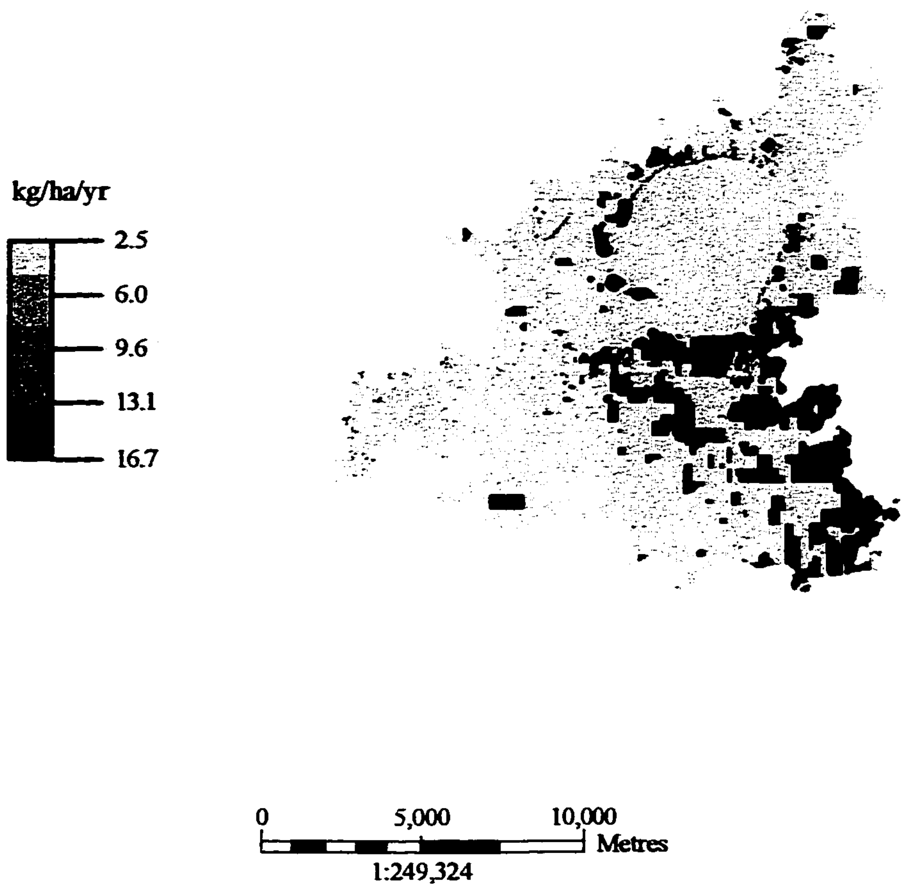


Figure 3.42. Estimated phosphorus deposition, 1950, Lake Weir watershed.

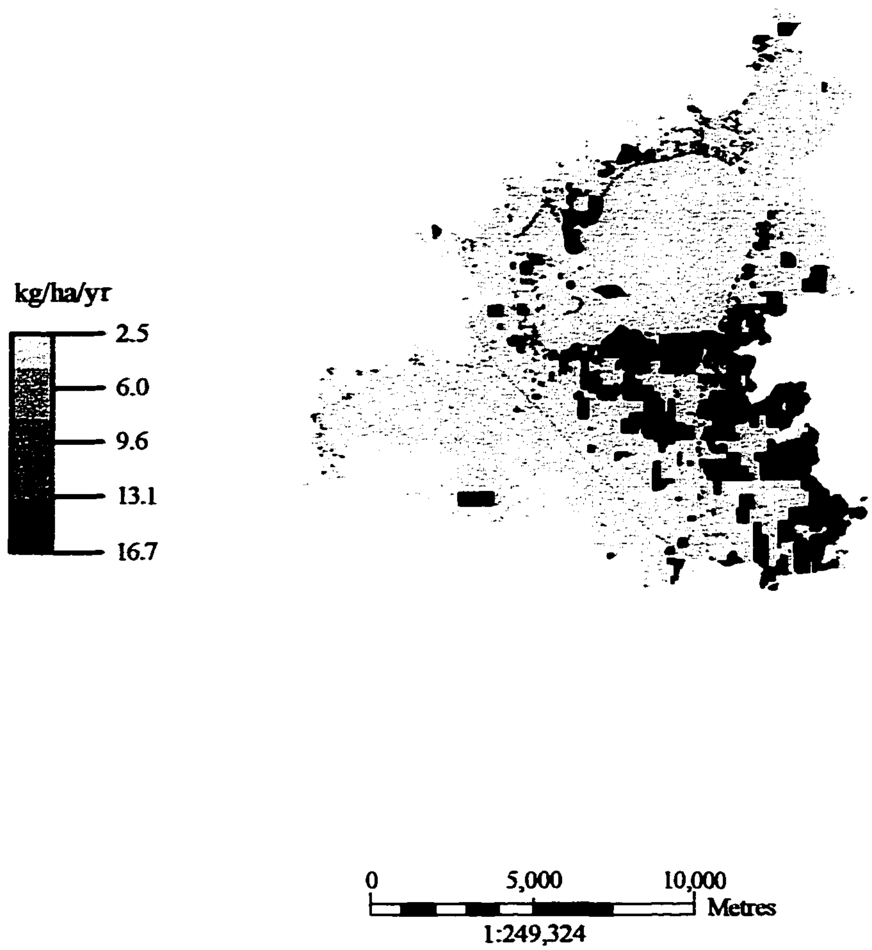


Figure 3.43. Estimated phosphorus deposition, 1970, Lake Weir watershed.

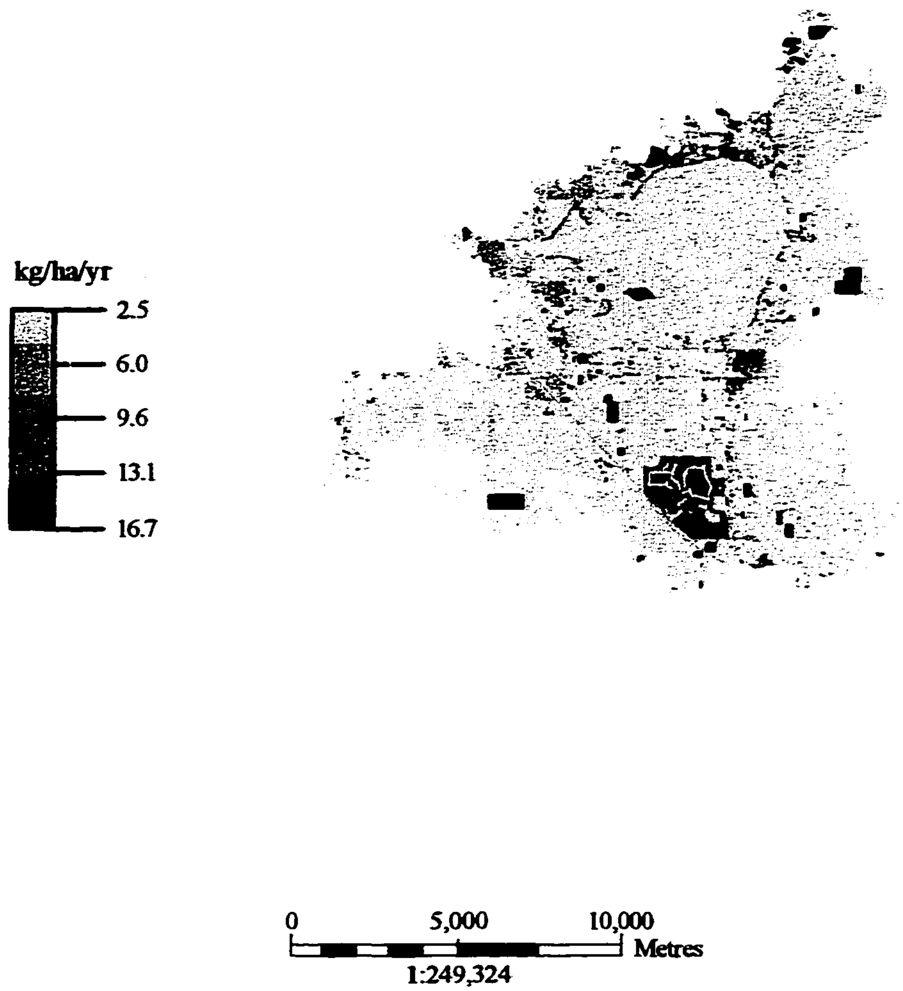


Figure 3.44. Estimated phosphorus deposition, 1990, Lake Weir watershed.

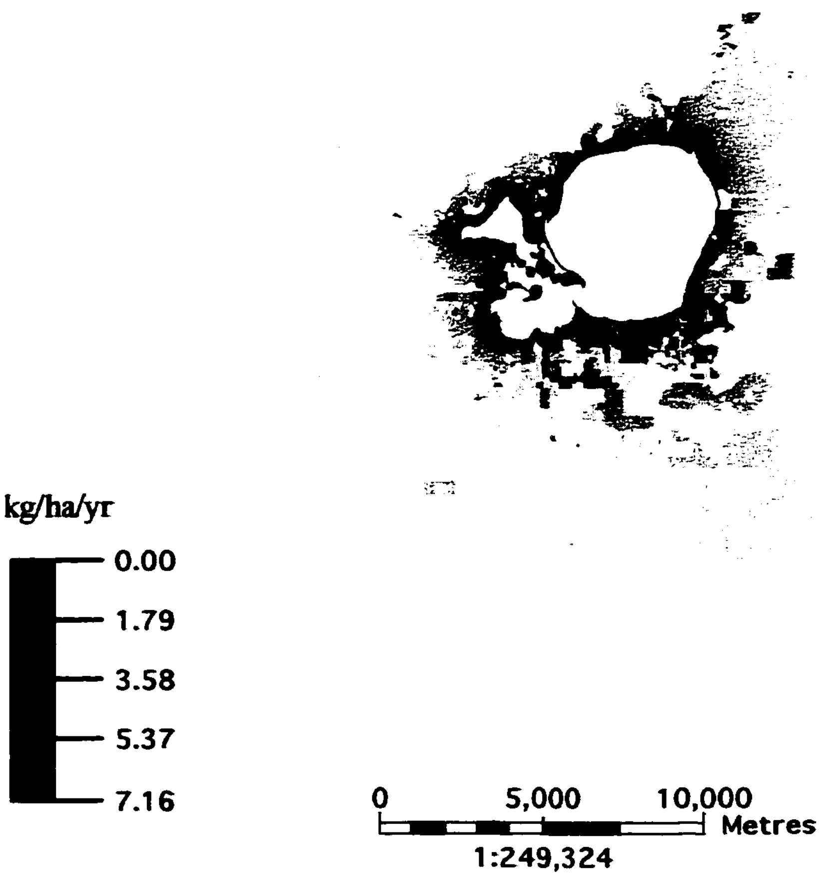


Figure 3.45. Estimated total phosphorus (TP) export profile for 1950, LakeWeir. Each band represents 20kg TP/ha/yr exported from that area and reaching the lake.

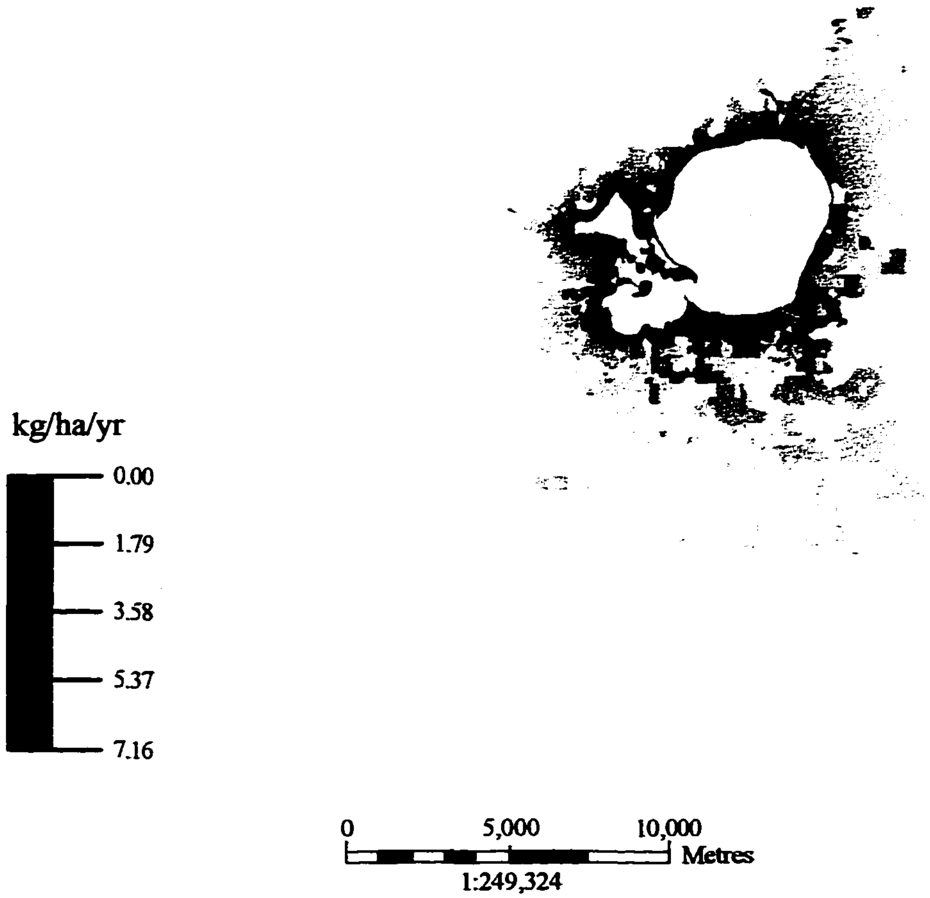


Figure 3.46. Estimated total phosphorus (TP) export profile for 1970, LakeWeir. Each band represents 20kg TP/ha/yr exported from that area and reaching the lake

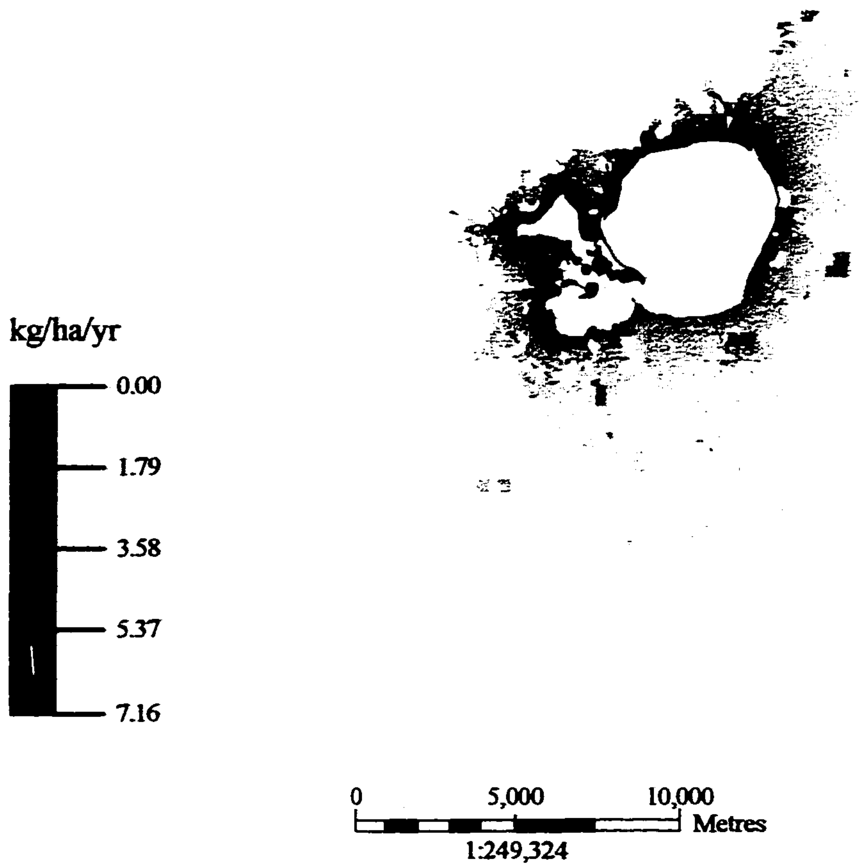


Figure 3.47. Estimated total phosphorus (TP) export profile for 1990, LakeWeir. Each band represents 20kg TP/ha/yr exported from that area and reaching the lake

but in Weir's watershed the difference is less evident than in Newnans'. This is due to the much higher overall phosphorus deposition in Lake Weir's basin.

Results: Emergy Patterns

Aerial Emergy Flux, Newnans Lake

Figures 3.48 - 3.50 illustrate the amount of emergy flow on an aerial basis for the years 1950, 1970 and 1990, respectively. These maps show two main areas of emergy concentration within the watershed - the Gainesville urban area and Newnans Lake.

In 1950, smaller clusters of concentration were evident where roads intersect and near roads leading to the lake. By 1970, existing clusters had expanded, especially the urban Gainesville area and those near the intersection of Waldo Road and Hatchett Creek. A new point of concentration on the lakes midwestern shore developed. A similar pattern of existing cluster expansion continued to 1990, with biggest changes further from the lake.

Aerial Emergy Flux, Lake Weir

Unlike Newnans Lake watershed, Lake Weir's basin did not show a concentrated pattern of hierarchy in the 1950 or 1970 empower density maps (Fig. 3.51 and 3.52). Patches of agricultural areas with empower density slightly lower than the lake extended from the southern lake edge to the southeastern edge of the basin. Residential areas with higher emergy inputs than the lake were concentrated in three main areas: the northern lake perimeter, the middle of the eastern lake edge and southeast of the lake between two areas of agricultural production.

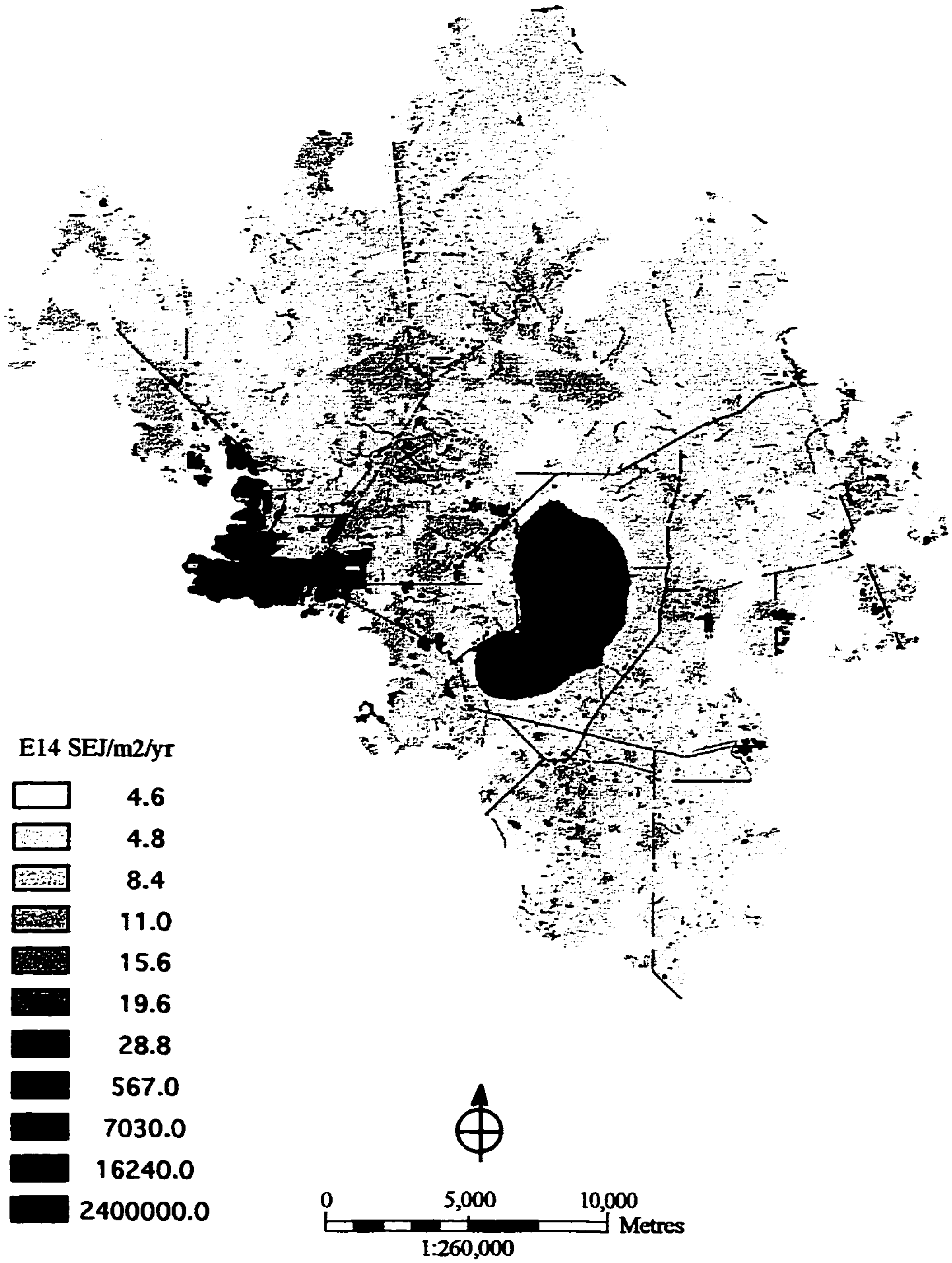


Figure 3.48. Empower density (E14 SEJ/m2/yr) distribution in Newnans Lake watershed in 1950. Black is highest density, progressively lighter areas have decreasing densities.

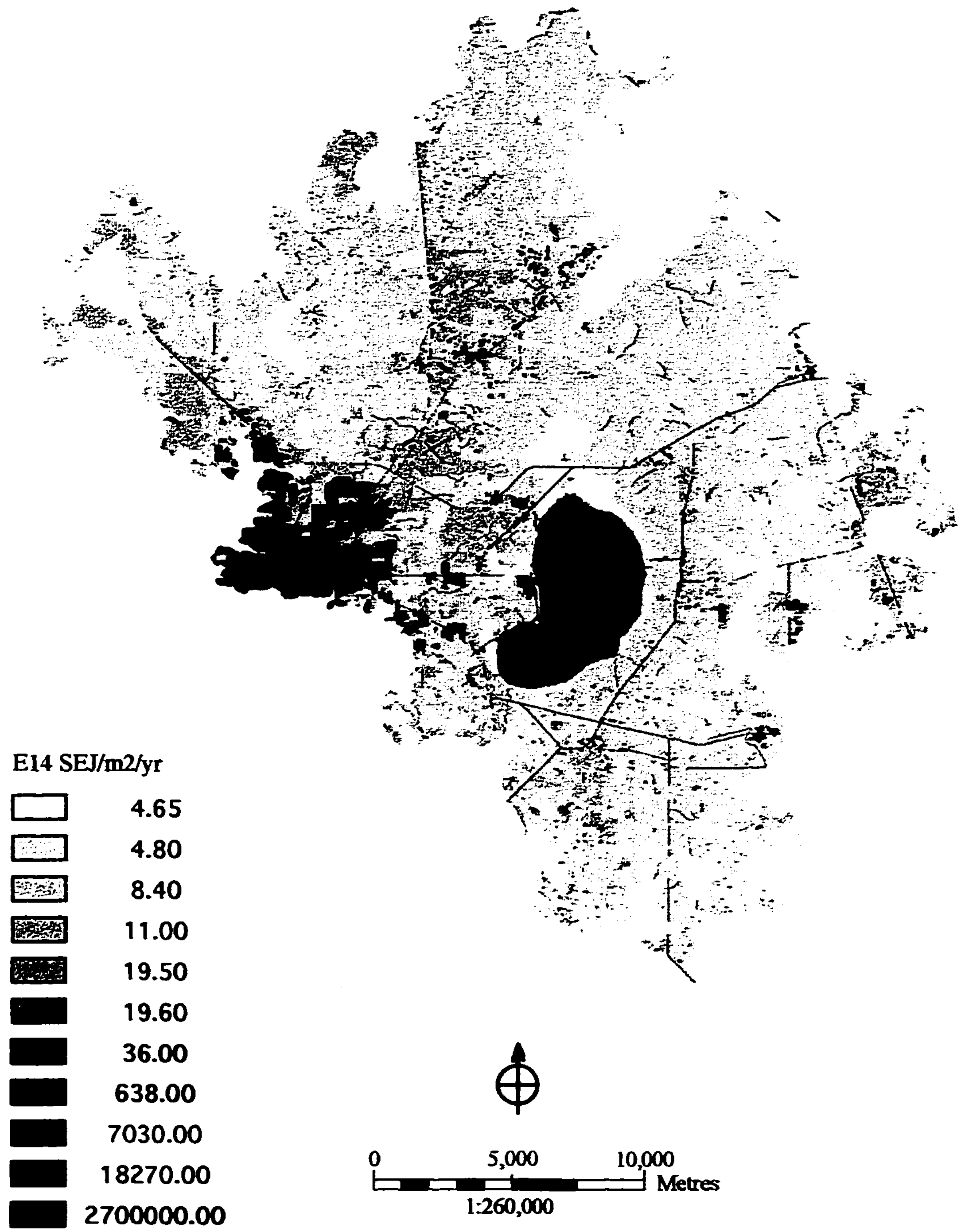


Figure 3.49. Empower density (E14 SEJ/m2/yr) distribution in Newnans Lake watershed in 1970. Black is highest density, progressively lighter areas have decreasing densities

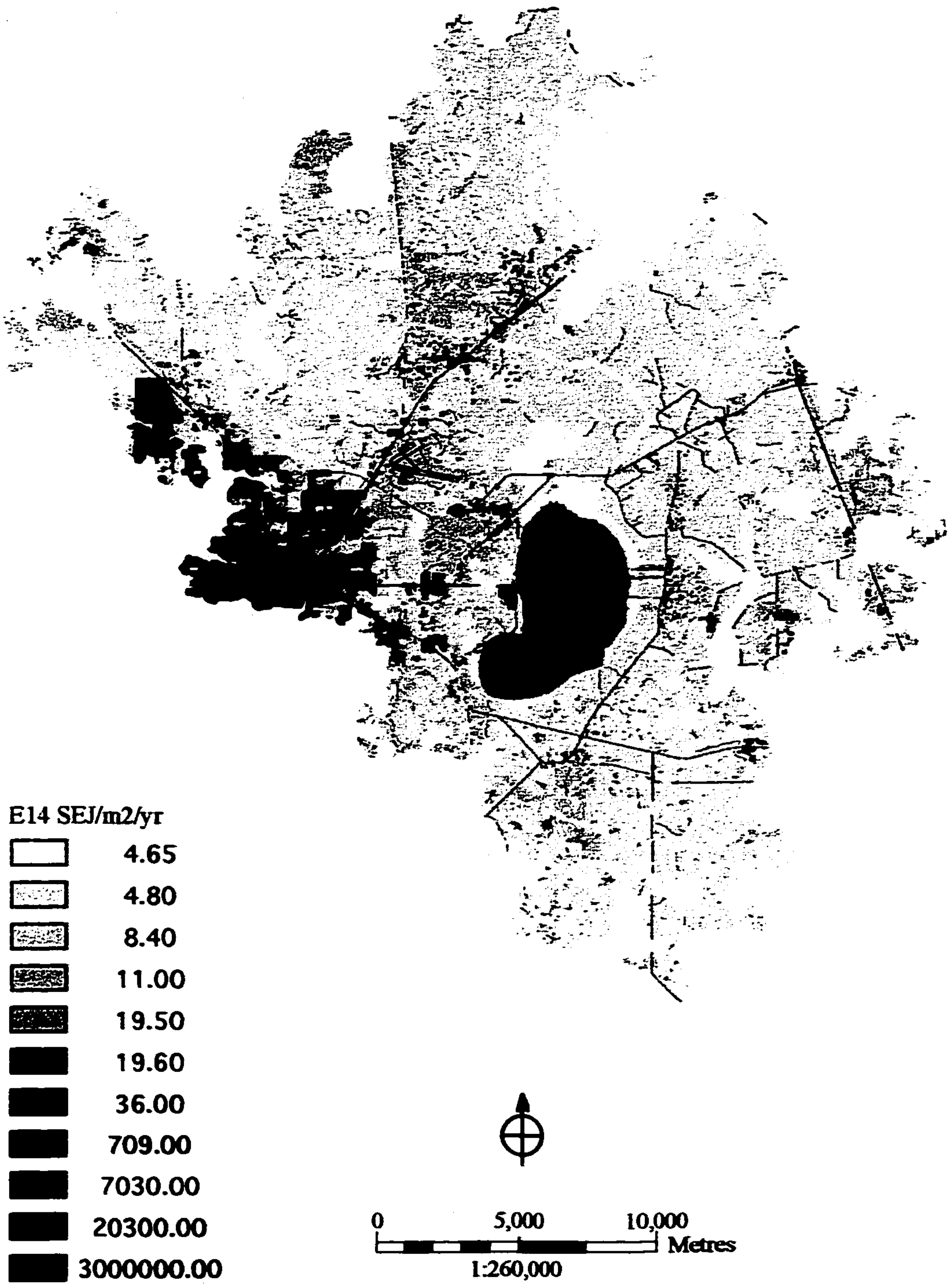


Figure 3.50. Empower density (E14 SEJ/m2/yr) distribution in Newnans Lake watershed in 1990. Black is highest density, progressively lighter areas have decreasing densities

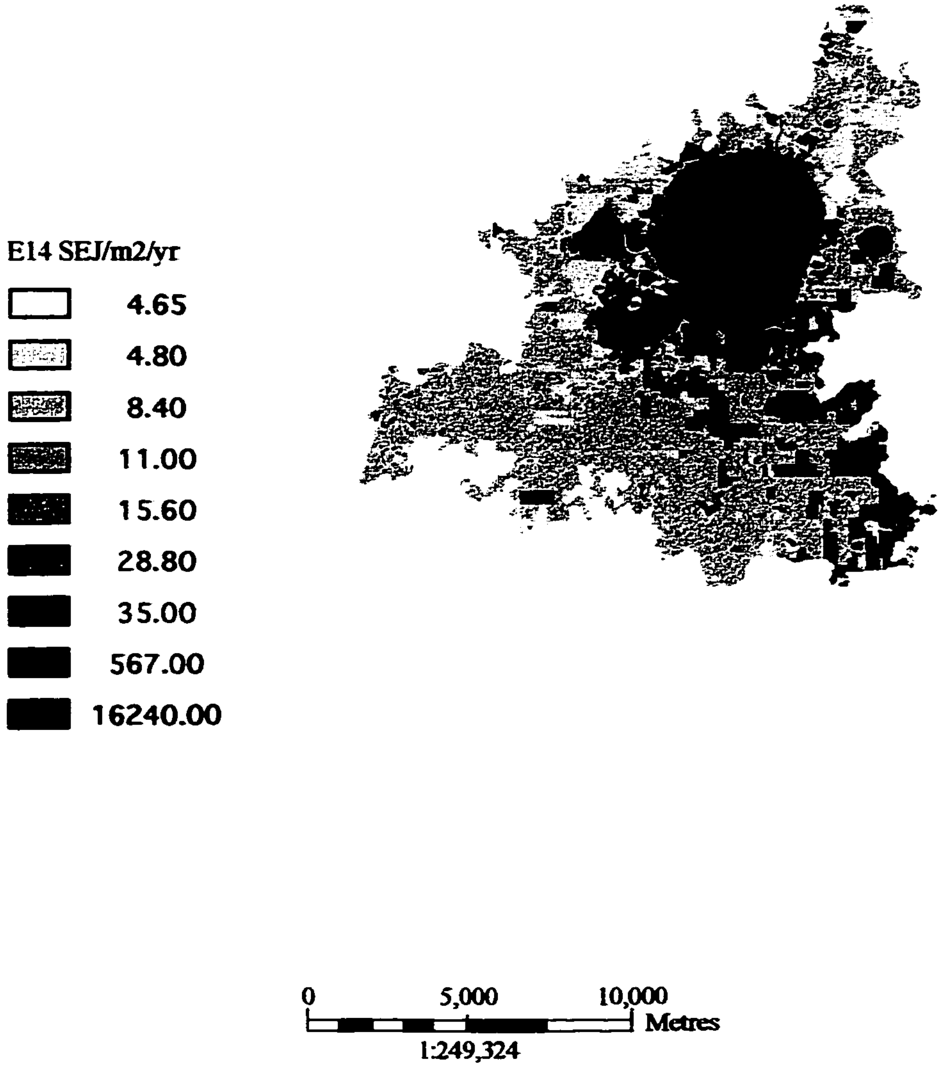


Figure 3.51. Empower density (E14 SEJ/m2/yr) distribution in Lake Weir watershed in 1950. Black is highest density, progressively lighter areas have decreasing densities.

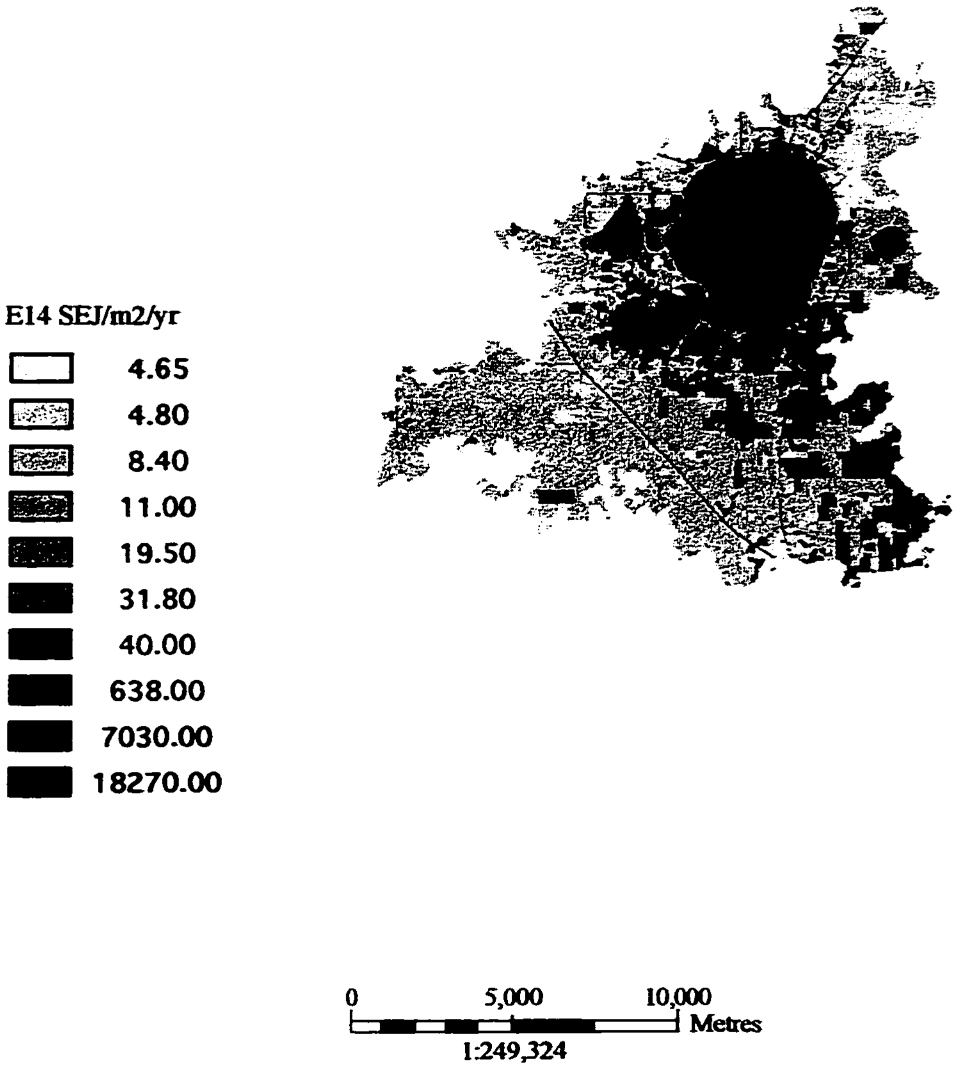


Figure 3.52. Empower density (E14 SEJ/m2/yr) distribution in Lake Weir watershed in 1970. Black is highest density, progressively lighter areas have decreasing densities.

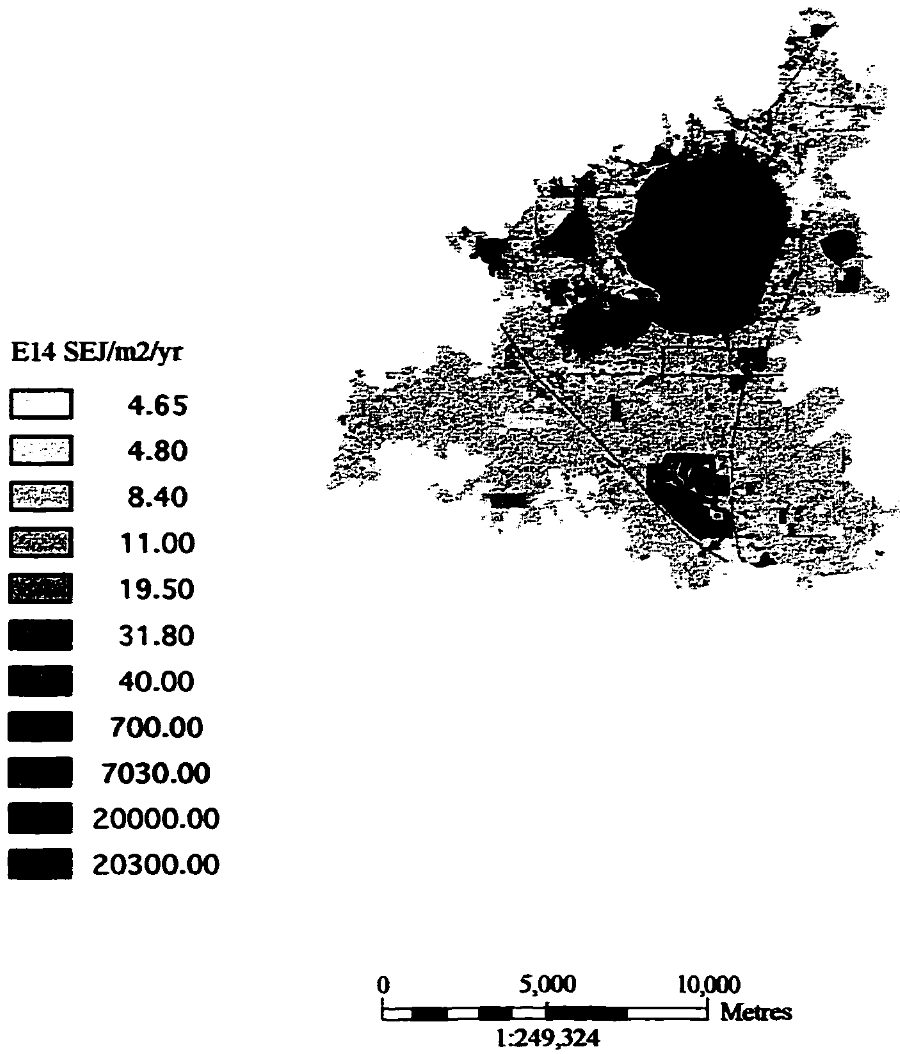


Figure 3.53. Empower density (E14 SEJ/m2/yr) distribution in Lake Weir watershed in 1990. Black is highest density, progressively lighter areas have decreasing densities.

By 1990, however, two main areas of convergence, the lake and a residential area, were apparent, a pattern similar to Newnans' watershed (Figure 3.53). Again, emergy inputs have increased in the area immediately surrounding the lake because of high emergy residential growth, and the main areas of convergence are separate from each other.

Emergy Accumulation Profiles

Cumulative emergy distribution for stormwater in Newnans Lake show several areas of high accumulation in the steeper areas of the watershed to the northwest (Fig. 3.54), but a fairly evenly distributed network throughout the basin. Weir, on the other hand, shows high areas of accumulation throughout the watershed, but patchier networks (Fig. 3.55).

Cumulative emergy distributions for phosphorus have different patterns of accumulation in both watersheds than delineated for the water profiles. Newnans Lake watershed has areas of high accumulation in a widely scattered pattern, mostly dependent on deposition (Figure 3.56). Accumulation networks in Weir's basin are more complex than Newnans' (Fig. 3.57), with areas of high accumulation all along the southern edge of the lake.

PART 2: DYNAMIC LAKE SIMULATION MODEL

Table 3.13 presents definitions of terms describing interactions and flows used in diagramming the lake system at different levels of aggregation.

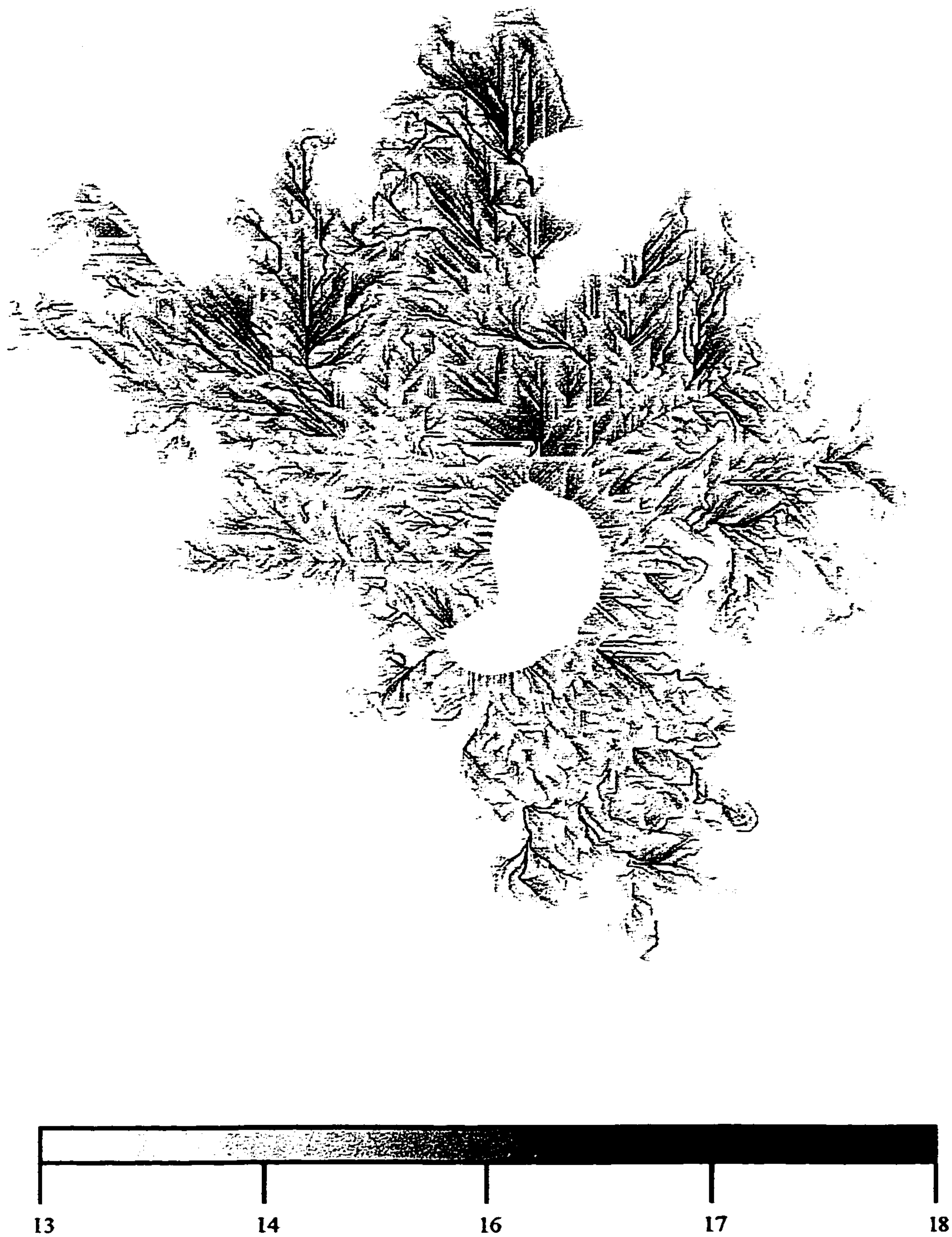


Figure 3.54. Water drainage network, post-development in Newnans Lake watershed, cumulative emergy, log sej.

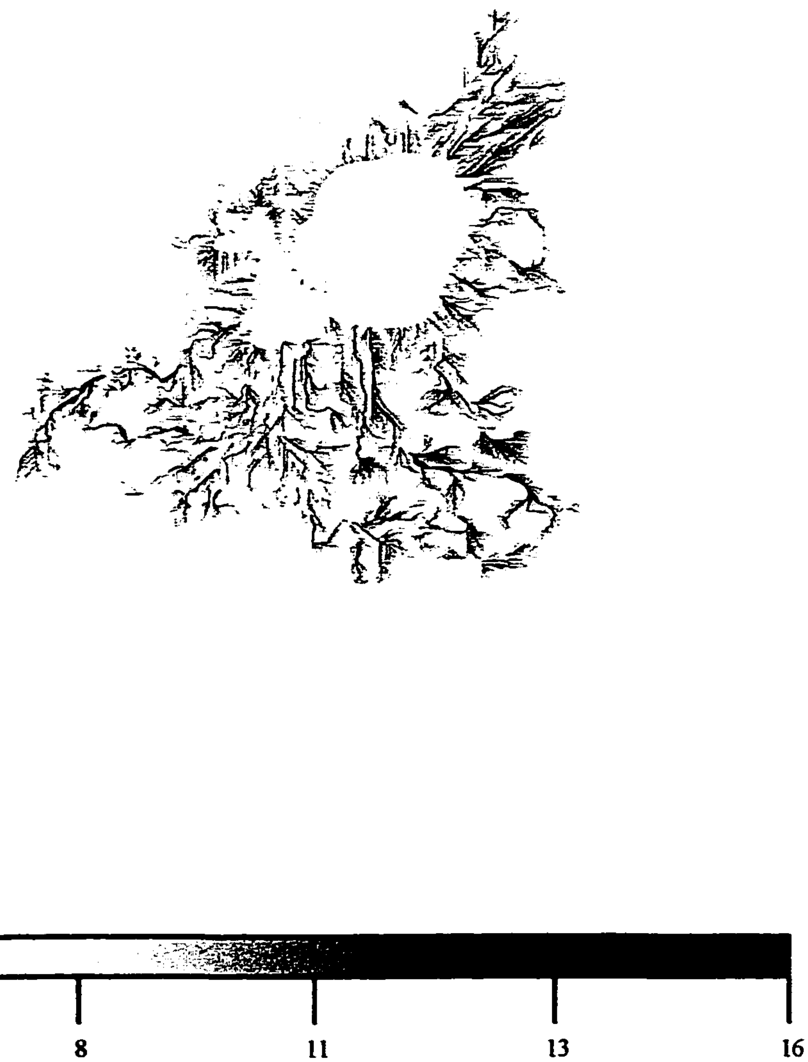


Figure 3.55. Water drainage network, post development in Lake Weir watershed, cumulative emergy, log sej.

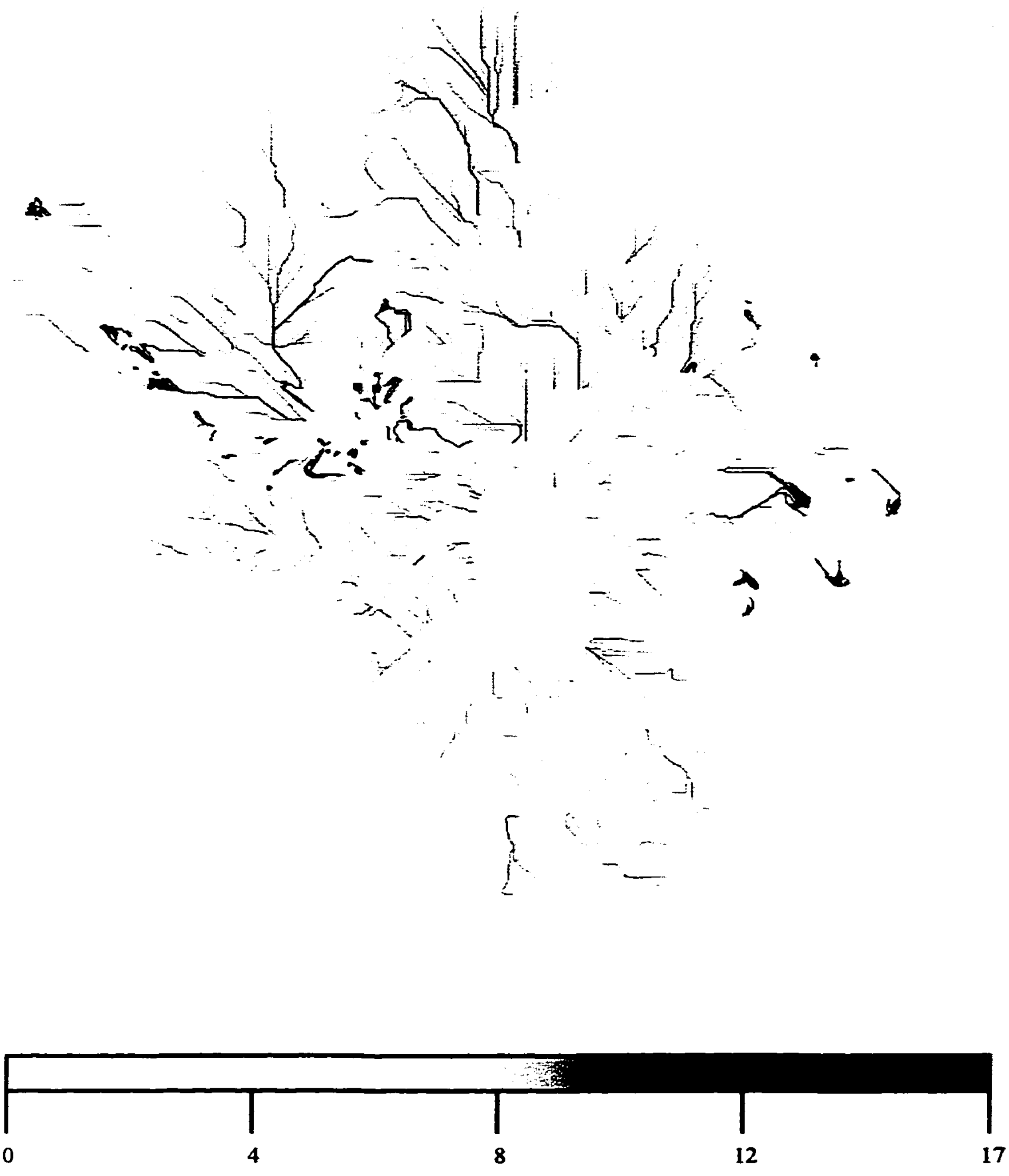


Figure 3.56. Post-development phosphorus emergy drainage network, Newnans Lake, log sej/g.

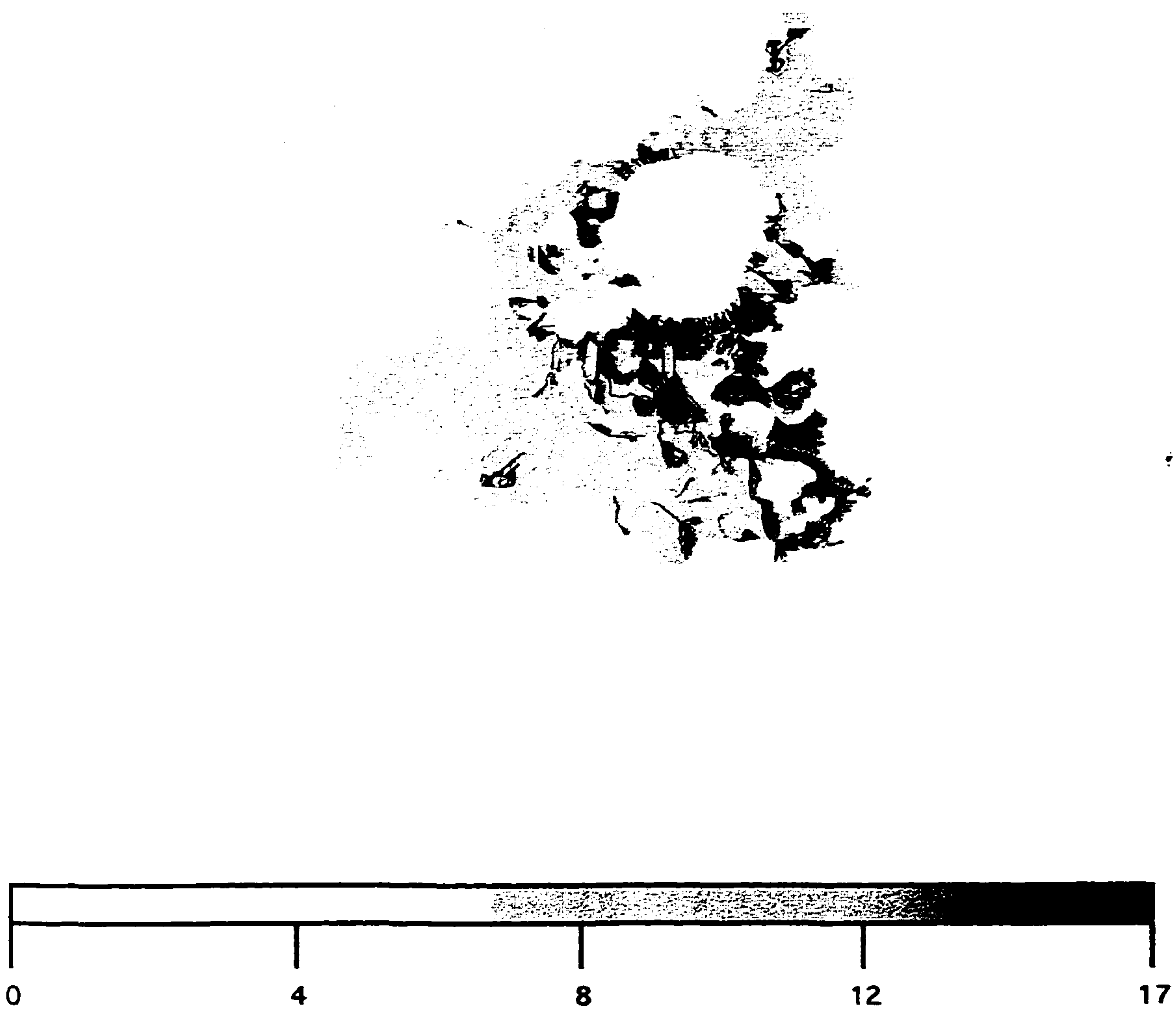
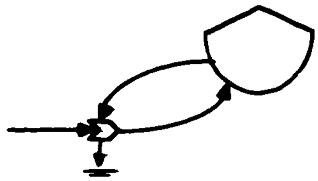
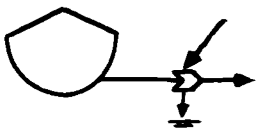
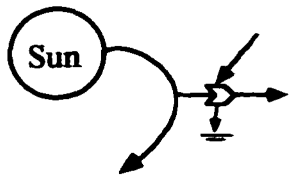
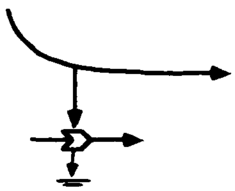


Figure 3.57. Phosphorus emergy networks post-development in Lake Weir watershed, log sej/g

Table 3.13. **Definitions of terms describing interactions and flows relevant to simulations.**

Term	**Definition**	**Symbol**
Autocatalytic unit	A unit within a system that stores enough energy to internally feedback energy to increase its own energy consumption. Example: a fish expending energy to find higher quality food sources	
Calibration coefficients	The proportion of the interactive flows used on any particular path and designated by k	
Drain	Any interaction promoting loss from a tank	
Flow limited source	A source delivering a regulated flow to a system that varies with the energy available to use that flow, but that cannot exceed the maximum regulated flow	
Flow limited path	A material with rapid turnover times, relative to other storages in the system, is often treated as a flow whose delivery to system components is limited by availability and competition	

Development

This in-lake simulation explored the hierarchy of control among trophic levels within the lake. A system diagram for a lake contains a complex network of interactions and food web hierarchy (Fig 3.58). This simulation model includes components considered to be most impacted by watershed nutrient inflow and most important to long-term functional changes within the lake. Figure 3.59 presents an aggregated diagram, with letters used to describe pathways in the following section. Figure 3.60 provides mathematical equations and pathway coefficients used in the computer simulation. Various trophic state indices (TSI) were calculated based on different measures of component productivity, such as biomass storage and net productivity (A).

Aggregation and Interactions

Phytoplankton were aggregated with epiphytic algae (Pl); submergent, emergent and floating leaf macrophytes were aggregated with floating macrophytes (M). Bacteria was modeled as a flow without storage (B). Benthic invertebrates were aggregated with zooplankton (Z), and all fish (F) were incorporated into a single compartment. These divisions were based primarily on turnover times and similarity of main energy sources.

Organic matter (Org) and phosphorus (P) in the water column were aggregated with sedimentary components, ultimately passing outside the system boundaries (H). A fraction of the detrital organic matter was both converted to phosphorus and resuspended on a regular basis (C) with the amount dependent on lake geometry and trophic status. Organic matter in the water column was modeled as a use of sunlight prior to availability to all producers except macrophytes (D). All producers were considered autocatalytic.

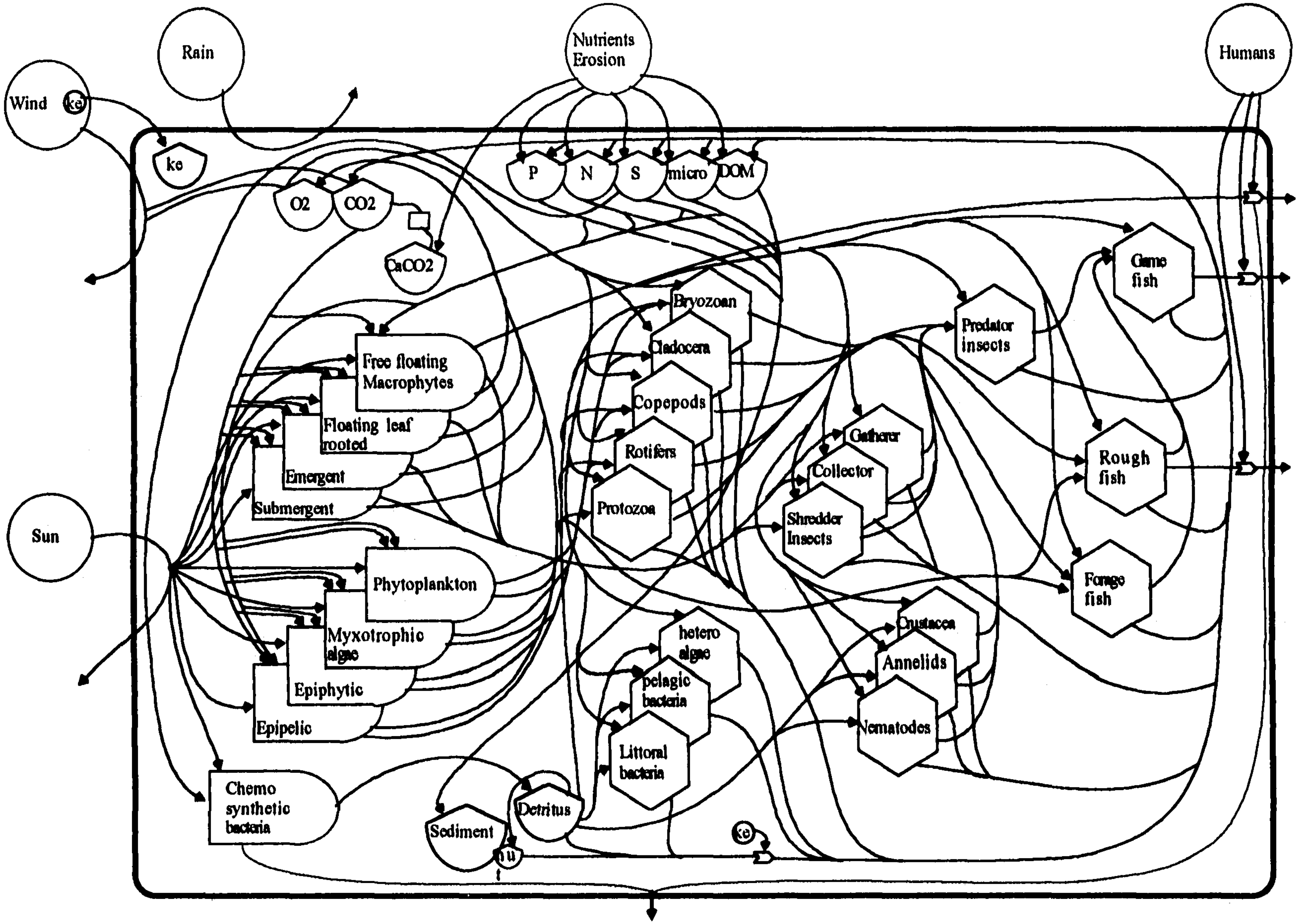


Figure 3.58. Lake diagram illustrating complexity of interactions and food web hierarchy.

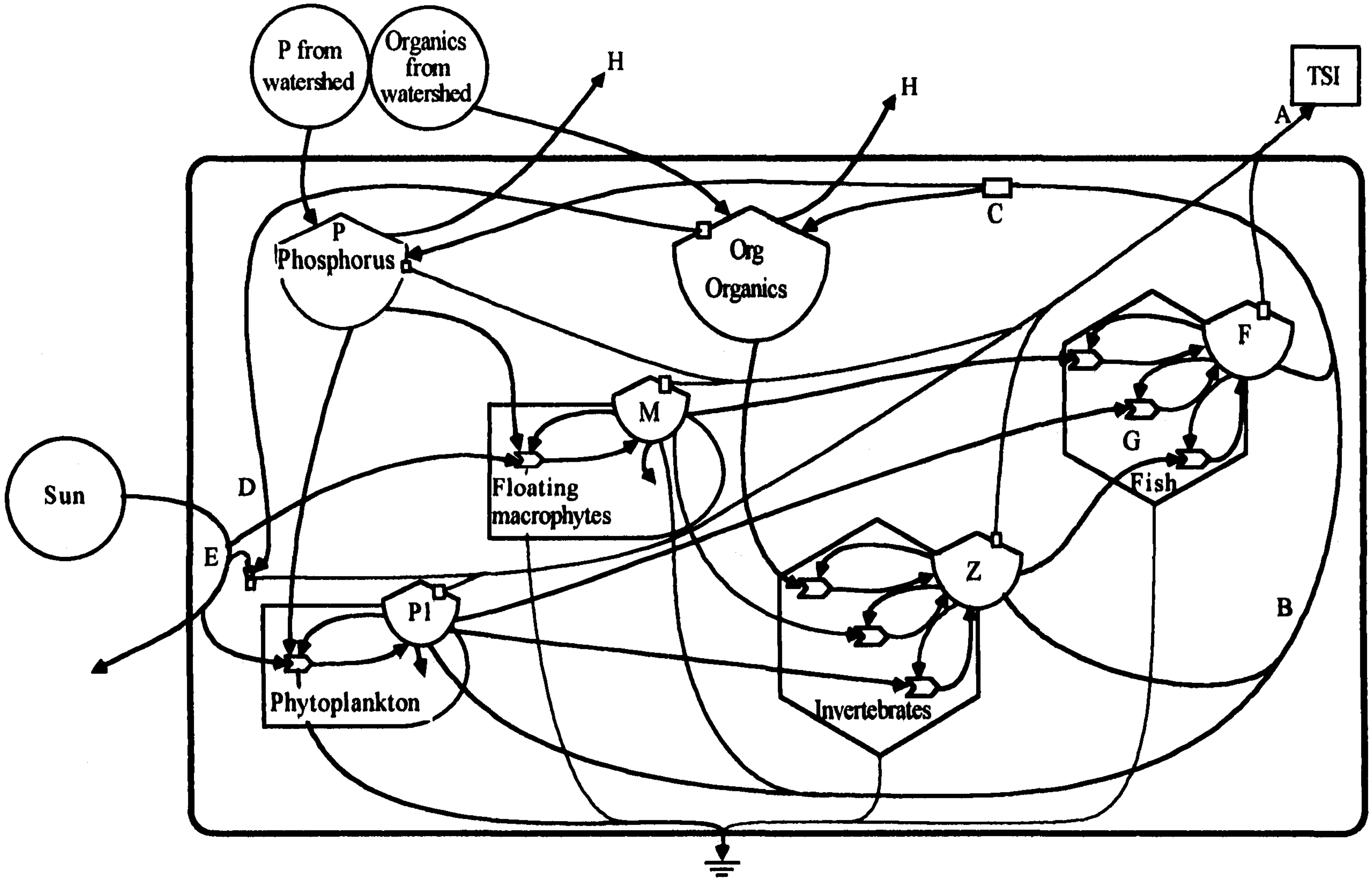


Figure 3.59. An aggregated in-lake energy systems diagram with components and pathways included in the simulation of lake responses to changing phosphorus loads and determination of dynamic trophic state indices.

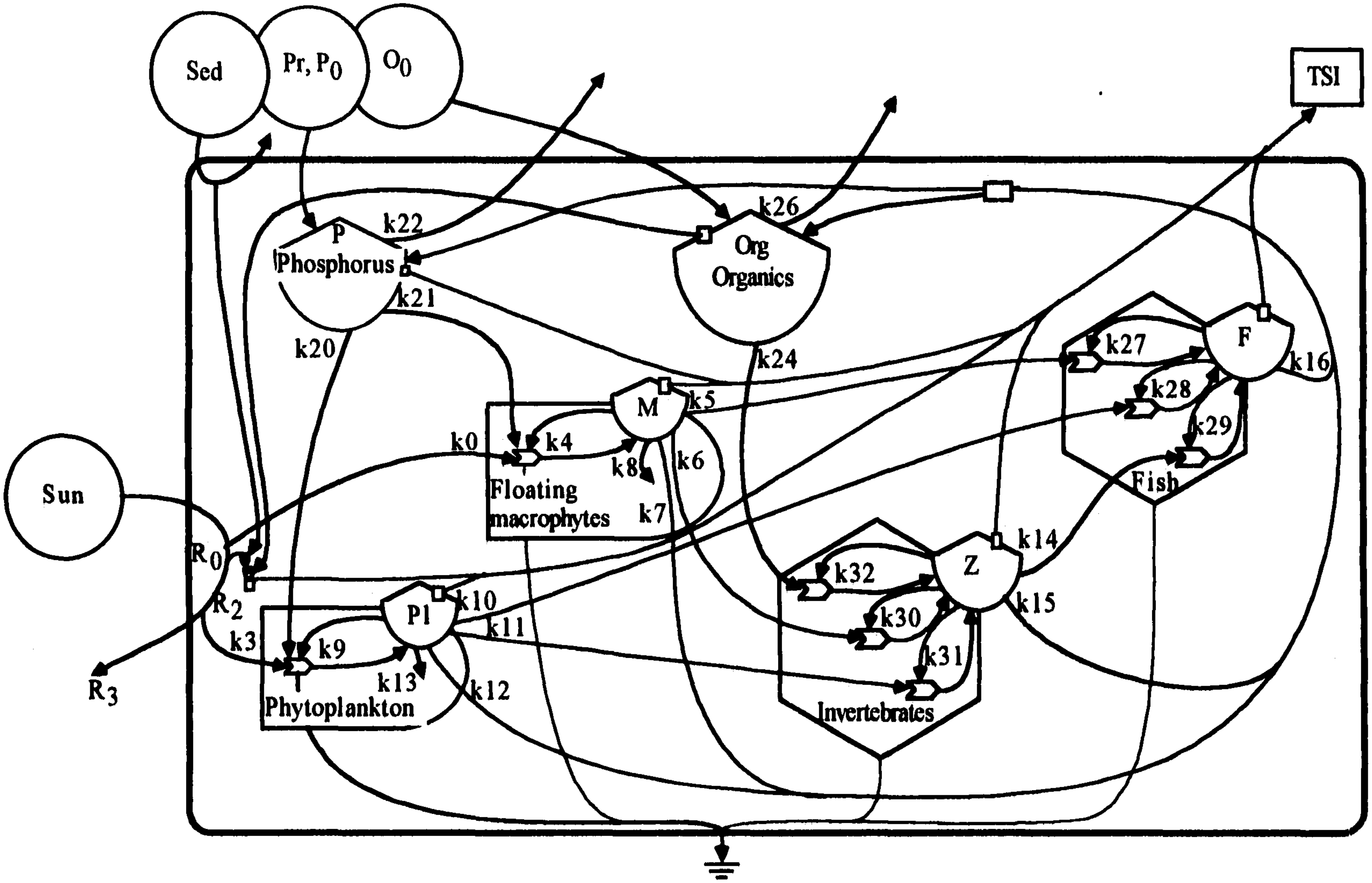
Figure 3.60. In-lake energy systems diagram and equations used to simulate response to changing watershed inputs.

Rates and concentrations

Light energy remaining after use by floating vegetation	$R0 = I/(1+k0*P*M)$
Light energy remaining after dispersion by organics	$R2 = R1/(1+k2*Org)$
Light available for periphyton and phytoplankton	$R3 = R2/(1+k3*P*Pl)$
Concentration of phosphorus and organics once in lake	$P0 = Pc*runin*1000/h20$ $O0= Oc*runin*1000/h20$ $Pr = rainlk*.167/h20$

Mass/energy balances

Floaters	$dM = k4*R0*P*M -k5*F*M - k6*Z*M - k7*M - k8*M$
Phytoplankton	$dPl = k9*R3*P*Pl-k10*Pl*F - k11*Pl*Z -k12*Pl - k13*Pl$
Zooplankton	$dZ = k32 *Org*Z + k30*Z*M + k31 * Pl*Z - k14*Z*F - k15*Z$
Fish	$dF = k27*F*M + k28*F*Pl + k29*F*Z - k16*F$
Phosphorus	$dP = phin - phout$ $phin = P0+fr*(k7*M + k12*Pl + k15*Z + k16*F)$ $phout = k20*P*Pl + k21*P*M + k22*P$
Organics	$dOrg = orgin - k24*Org - k26*Org$ $orgin = O0 + frorg*(k7*M + k12*Pl + k15*Z + k16*F)$


Sed
Pr, P_0
O_0
TSI
Sun
P
Phosphorus
k22
k21
k20
Org
Organics
k26
k24
M
k5
k4
k0
k8
k6
k7
Floating
macrophytes
R_0
R_2
R_3
k3
P1
k10
k11
k9
k13
k12
Phytoplankton
Z
k14
k15
k32
k30
k31
Invertebrates
F
k16
k27
k28
k29
Fish

Since consumers aggregated in Z and F expend different amounts of energy in locating and ingesting different food sources, each was represented with separate autocatalytic interactions (G) within a single compartment. The energy fraction allotted to each of these three uptake interactions was based on estimates of the percentage that each food source contributed to the total intake.

Trophic State Simulation

Trophic state indices were calculated four different ways for comparison of early responses. Curves of instantaneous values are presented along with other system parameters in each simulation graph. Long term averages were calculated for the length of each simulation.

1. Gross productivity for all organisms, both autotrophs and heterotrophs, was calculated from the inflow to each individual storage
2. Net productivity was calculated from the inflow to each organism minus the metabolic portion of the outflow.
3. Biomass was calculated by summing the storages throughout the simulation.
4. A Huber TSI was calculated using the log transformation equations for Secchi disc, chlorophyll and phosphorus in the water column (Huber et al., 1982). Secchi depths were calculated from the amount of light remaining after use by the phytoplankton. A straight-line equation was derived from the relationship of remaining light in the oligotrophic simulation to an average Secchi depth for Weir and the same relationship from the eutrophic simulation and Newnans.

Calibration Data

Numbers associated with production rates, biomass storage and turnover times were collected from the literature and actual data for the two lakes in this study. Lakes with similar trophic states or characteristics were selected for inclusion in average values for calibration of simulation coefficients (Table 3.14).

Data from the literature were both averaged and adjusted to account for balancing of material flows between the components in the model. Most adjustments were made using life cycle turnover times and some basic assumptions about divisions of flows. For example, an assimilation efficiency of 10% was used to value flows through each successive trophic level. Table 3.15 presents a summary of these flows after they had been averaged and normalized for use as calibration points for the simulations.

Figure 3.61 presents the flow and storage values used to calibrate this model for initial simulations. Calculation of coefficients for this and for all other simulations are given in Appendix G.

Simulation Results

Each lake was simulated using averaged data for oligotrophic, eutrophic and hypereutrophic conditions to demonstrate the impact of changing watershed inputs. The pulsing responses resulting from the hypereutrophic simulation were used to explore the cause of the pulse and the hierarchy of pulse control.

Simulations Comparing Responses to TP Loading

There were four main differences between calibrations for oligotrophic and eutrophic simulations. First, flows and storages were altered to reflect the levels present in empirical data (Table 3.15). Second, because the oligotrophic simulation was meant as a representation of Lake Weir, the lake volume was increased and the watershed area decreased from the eutrophic parameters, in proportion to the differences between Weir and Newnans. Third, the amount of nutrient resuspension was

Table 3.14. Productivity, storage, turnover times and uptake rates from various literature sources.

Organism	Comments	Production/ units	Biomass/ units	Turnover/ units	Source
Algae	eutrophic	1000mgC/m2/d	300mgC/m3	-	Likens (1975)
		1564mgC/m2/d	-	-	Wetzel (1966)
	mesotrophic	250-1000mgC/m2/d	100-300mgC/m3	-	Likens (1975)
		438mgC/m2/d	-	-	Goldman & Wetzel (1963)
	oligotrophic	99.3mgC/m2/d	-	-	Wetzel (1966)
		50-300mgC/m2/d	20-100mgC/m3		Likens (1975)
Macrophytes (aquatic)	broad leaf	500-1100g/m2/yr	-	-	Kvet & Husak (1978)
	grasses	3450g/m2/yr	-	-	Klopatek (1974)
	submergent	4.6g/m2/d	-	-	Wetzel (1983)
	emergent	2-7g/m2/d	2200g/m3	-	ibid
	floating	4-12g/m2/d	630-1500g/m3	-	ibid
Zooplankton	eutrophic	0.11-9.15g/m3/d	0.35g/m3	9.2-25d	Winberg (1970)
	mesotrophic	1.12-3.09g/m3/d	.07-.14g/m3	9.1-14.3d	Kajak (1970)
	oligotrophic	.94-3.02g/m3/d	.136-.43g/m3	22-29d	Moskatenko & Votinsev (1970)
Fish	eutrophic	-	134-614kg/ha	-	Champeau (1997)
	mesotrophic	-	18-61 kg/ha	-	Champeau (1997)

Table 3.15. Summary data used as guide for initial simulations.

	Production g/m2/day	Biomass g/m3	Turnover days
Pelagic algae	2-4	>0.6	2-10
Epiphytic Algae	0.12-34	1-177	10-60
Average	1.1-18	80	-
Submergent macrophytes	4.6	-	-
Emergent macrophytes	2-7	2200	-
Floating macrophytes	4-12	630-1500	-
Average	5.5	1500	245
Zooplankton	0.11-9.15	0.35	9-25
Fish	0.0025	13-60(g/m2)	1825

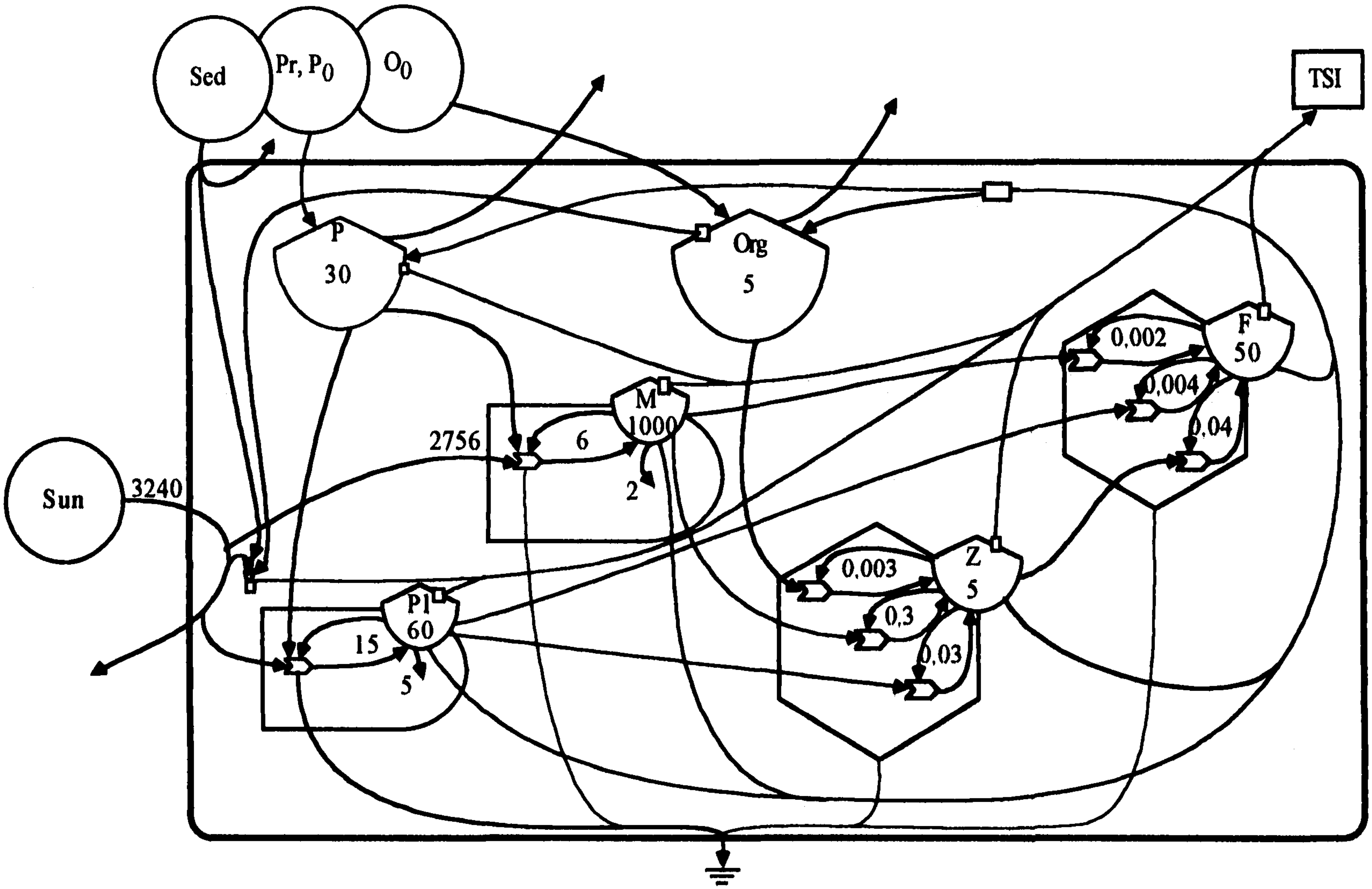


Figure 3.61. Steady state flows and storages for eutrophic simulation.

decreased in the oligotrophic model to simulate increased depth. Fourth, the phosphorous runoff coefficient from the watershed to the lake was 1/4 the input to the eutrophic lake.

There was one main difference in calibration between the eutrophic and hypereutrophic simulations. A switch to blue-green algae as the dominant phytoplankton species often accompanies this increase in eutrophic conditions (Brenner et al., 1998; Wetzel, 1983), and this group is not a favored food by zooplankton, nor is assimilation by fish as high as other algal species. Consequently, organic material becomes a more important food source. The hypereutrophic simulation has the algae consumption coefficient lowered and the organic consumption higher to reflect these conditions.

The simulation using calibration values within eutrophic ranges exhibited a small increase in total biomass with increasing TP loading from the watershed, with macrophytes and fish showing the earliest response (Fig 3.62). The average Huber TSI before increased TP loading was 78 and 82 after loading.

The hypereutrophic simulation exhibited a pulse in fish and zooplankton populations, but showed very little response to increased TP loading (Fig 3.63) The average Huber TSI before increased TP loading is 96 and is 98 after loading.

The oligotrophic simulation showed the greatest change in conditions following TP load increases, with fish and phytoplankton showing early responses (Fig 3.64). The average Huber TSI before loading is 36 and jumps to 48 after loading.

Gross and net productivity showed less than a 10% difference between all three simulation conditions, and was insensitive to TP loading. Average biomass was 1188 for hypereutrophic, 1000 for eutrophic and 548 for oligotrophic. Instantaneous biomass curves showed a fast response to TP loading. While the Huber TSI showed high variability dependent on seasonal fluctuations in TP inputs, overall sensitivity to increased loading was mixed.

Pulsing Simulation

When the primary path of zooplankton productivity was switched from a balanced ingestion of phytoplankton and organic matter, a pulsing pattern between fish and zooplankton developed. Several sources and interactions in the simulation were varied to determine if the pulse was exogenous or endogenous.

Figures 3.65 - 67 present results from simulating different levels of available solar energy. Neither sun nor rain inputs are oscillating, and all other inputs are held constant. Figure 3.65 illustrates a pulsing response in fish and zooplankton for the first 3000 days, with decreasing amplitude and period. Macrophytes grow to a high level in the beginning but slowly decline to a much lower equilibrium level in about 25 years. Figure 3.66, presenting results from higher solar input, exhibits a similar pulse in fish and zooplankton, but taking twice as long to reach equilibrium. Macrophytes exhibit a more pronounced oscillation and reach a high equilibrium level after about 18 years. Figure 3.67 shows results from lower solar input. Again, fish and zooplankton develop a pulsing pattern, with initially higher amplitude and longer period than the two higher input simulations. Macrophytes increase initially but drop to an extremely low equilibrium level. Equilibrium for all components is reached in about 3 years.

To determine the components interacting to create the pulsing behavior apparent in fish and zooplankton, the base model was simulated holding some components constant, while allowing others to vary. Phosphorus and organic tanks were always allowed to accumulate or drain, as they have no interactive inputs. Components allowed to vary were added one at a time in a step-wise progression, beginning with phytoplankton. Figures 3.68 and 3.69 illustrate that phytoplankton and macrophytes, alone or together, do not pulse. Addition of zooplankton (Fig 3.70) as a varying component exhibits a single pulse. When fish are allowed to vary, the repeated pulsing pattern occurs, with fish and zooplankton as the pulsing pair (Fig 3.71).

PART 3. WATERSHED CLASSIFICATION AND MANAGEMENT

Various ratios of material flows and emergy values were calculated to compare and contrast the two watersheds in this study. Predicted non-point source runoff, both water and phosphorous, were compared to water quality, physical characteristics of each lake and trophic state indices from other sources. Summary emergy values and changing emergy per mass ratios for these material flows are also presented.

Predevelopment watershed simulations were also run to provide a basic understanding of watershed loads characteristic of long-term geomorphic parameters. Two key assumptions were used to create these land use maps. First, the entire watershed was assumed to be covered in forest. Second, areas surrounding water and streams were assumed to be forested wetlands if forested wetlands were still present nearby in any of the years included in this study.

Material Loads and Ratios

Loads and ratios of phosphorus and water exports from the watershed to the lake were calculated to put these values into a format familiar to lake management. They are also compared to water quality data collected as close to the periods of simulation as possible. Three different concentration ratios are presented. Runoff phosphorus

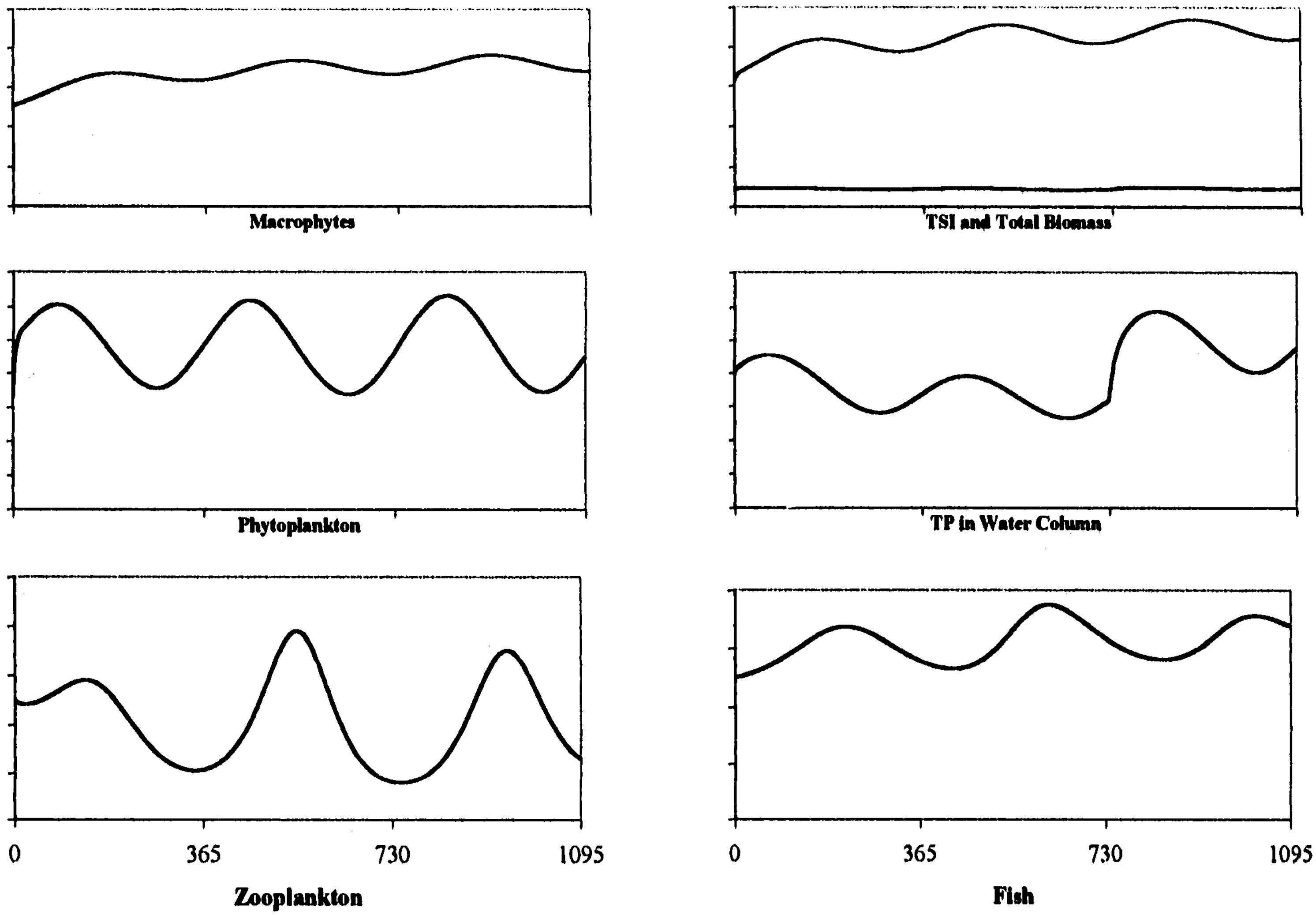


Figure 3.62. Simulation of eutrophic conditions with runoff increase after 2 years.

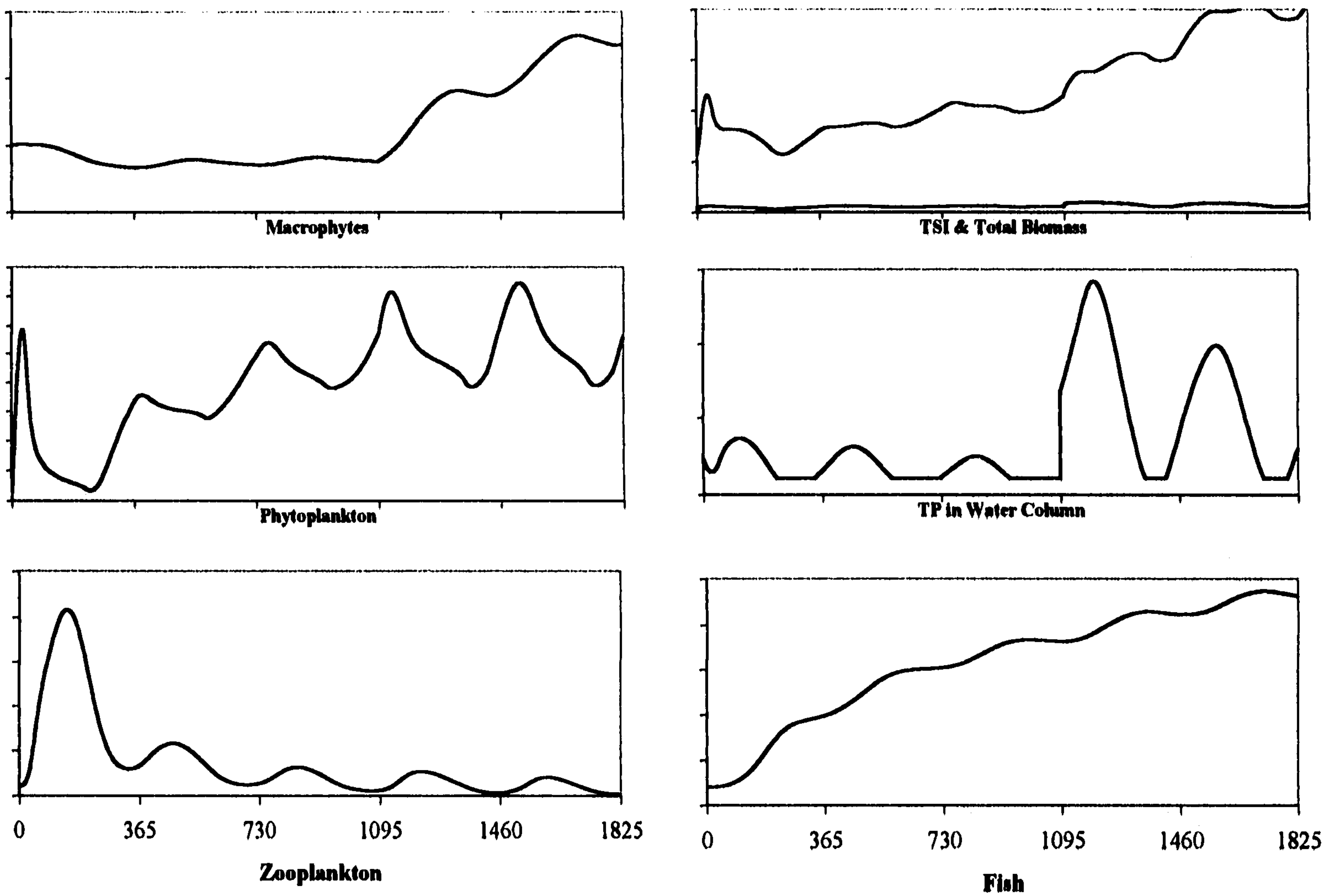


Figure 3.63. Simulation of oligotrophic conditions with runoff increase after 3 years.

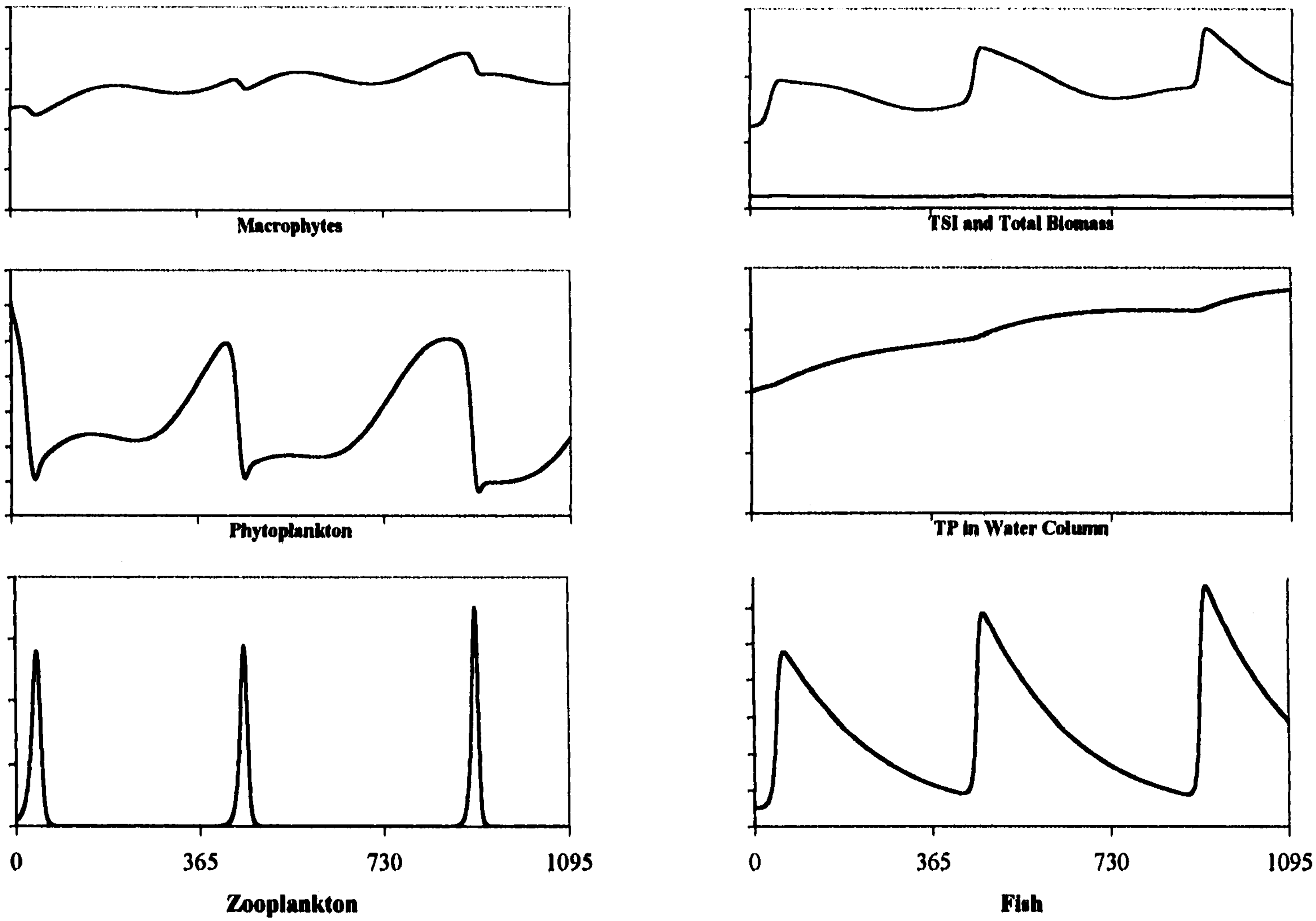


Figure 3.64. Simulation of hypereutrophic conditions with zooplankton using less phytoplankton

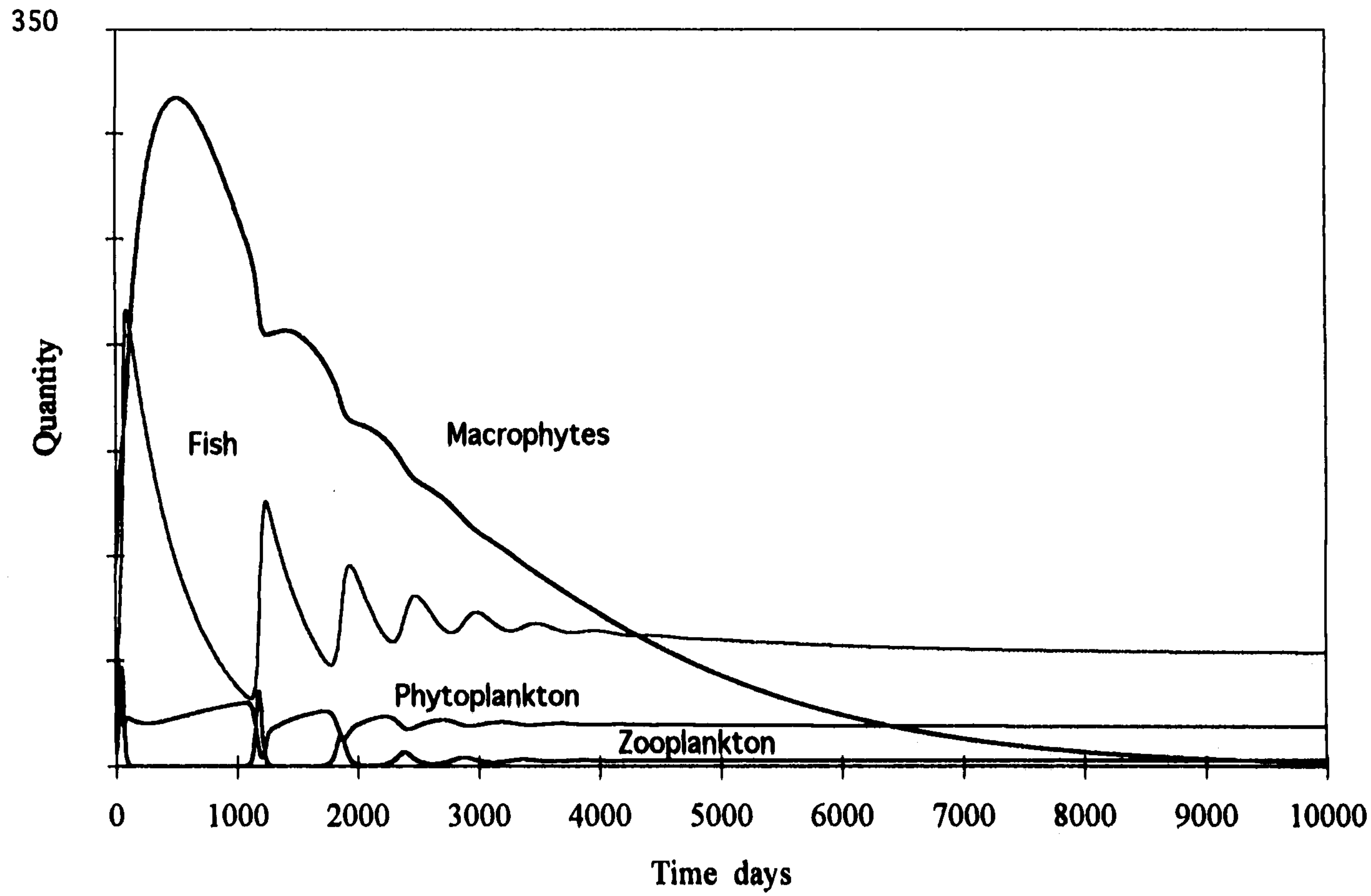


Figure 3.65. In-lake simulation using averaged eutrophic conditions for several lakes worldwide with averaged environmental sources. No perturbations occur in inputs and the model is run for about 30 years.

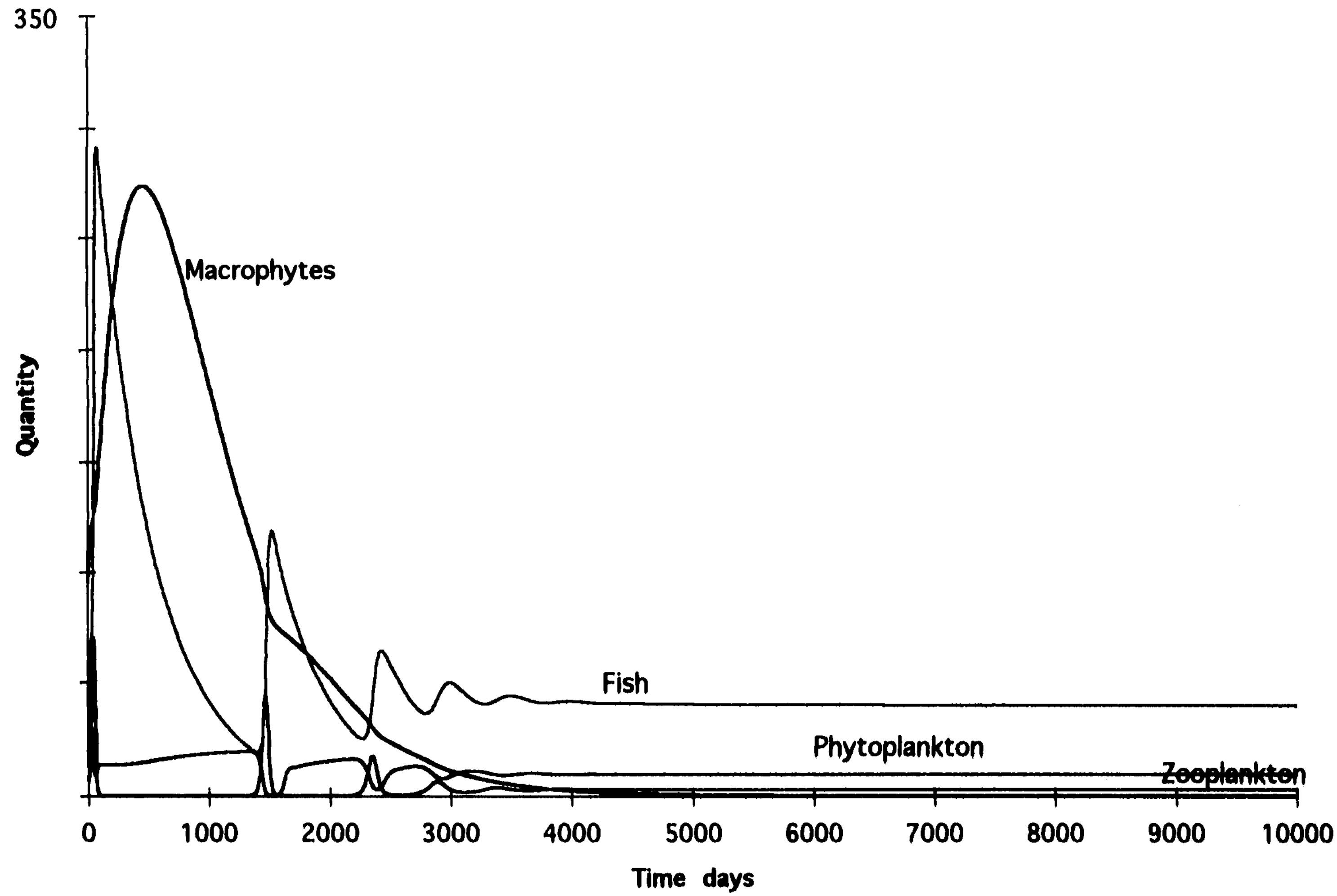


Figure 3.66. In-lake simulation using averaged eutrophic conditions for several lakes worldwide with lower environmental sources than shown in Figure 3.65.

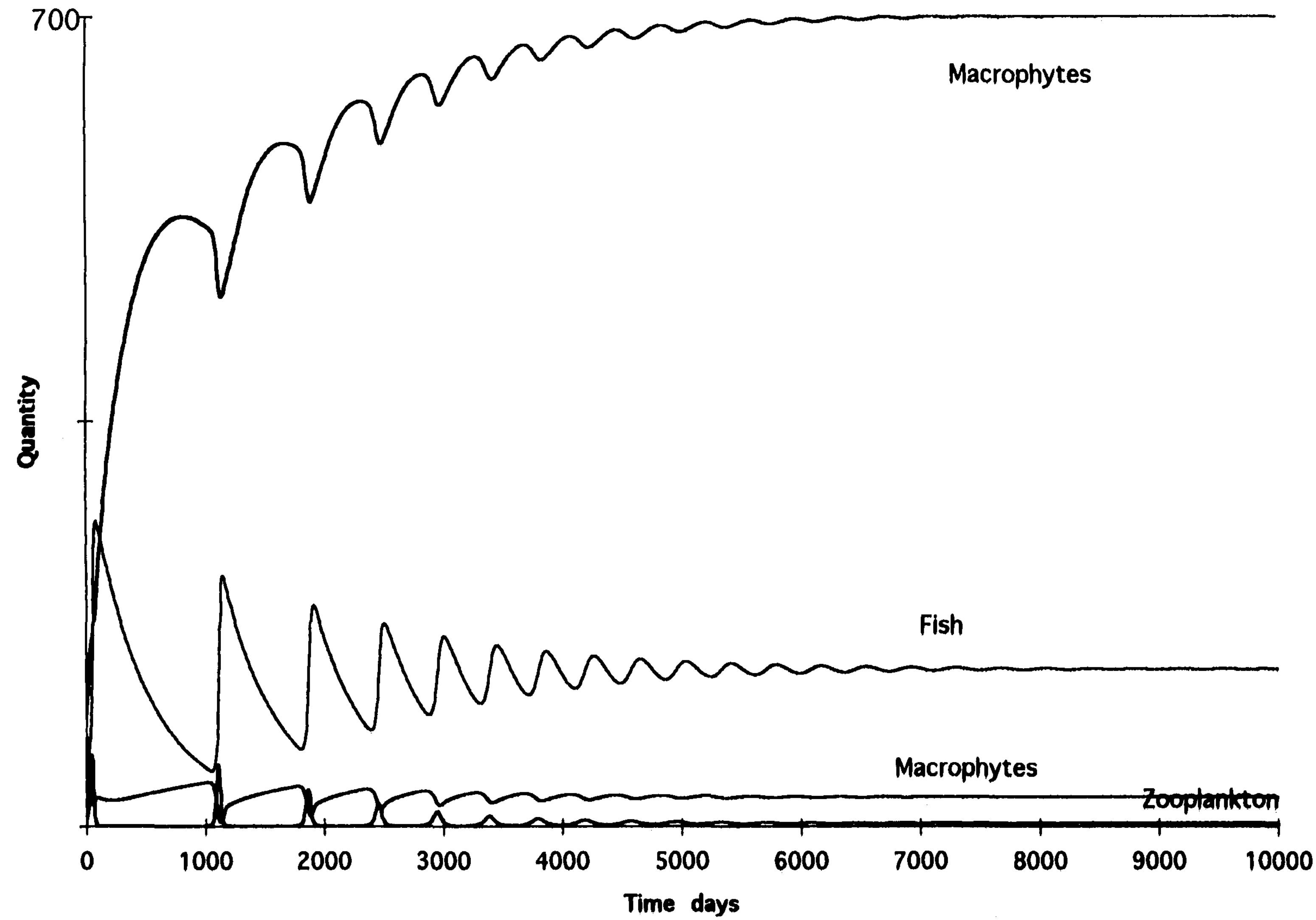


Figure 3.67. In-lake simulation using averaged eutrophic conditions for several lakes worlwide, but with higher environmental sources than shown in Figure 3.65.

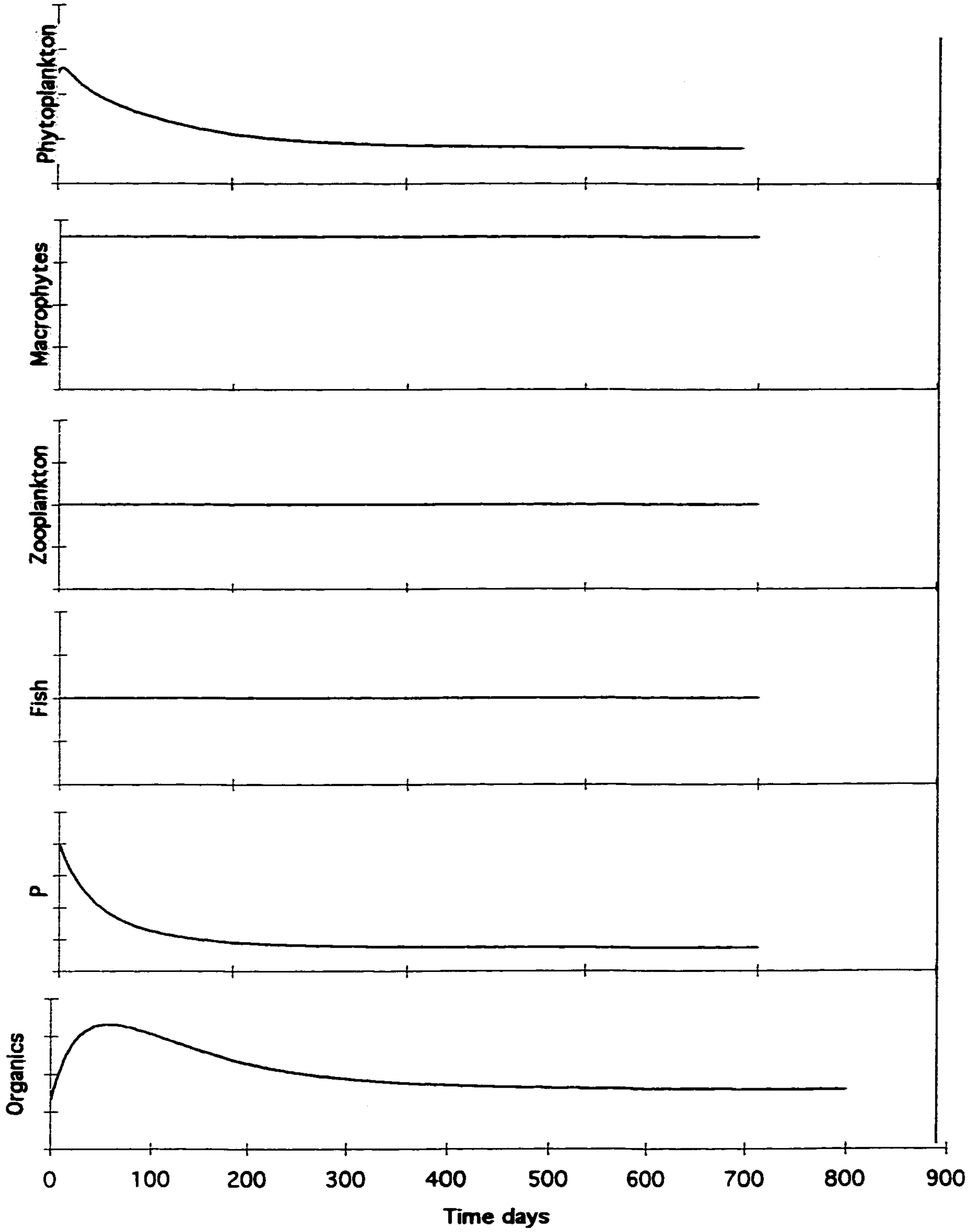


Figure 3.68. **Using in-lake simulation to explore hierarchy of pulsing control. Phytoplankton storage is allowed to vary. All other variables higher in the chain are held constant.**

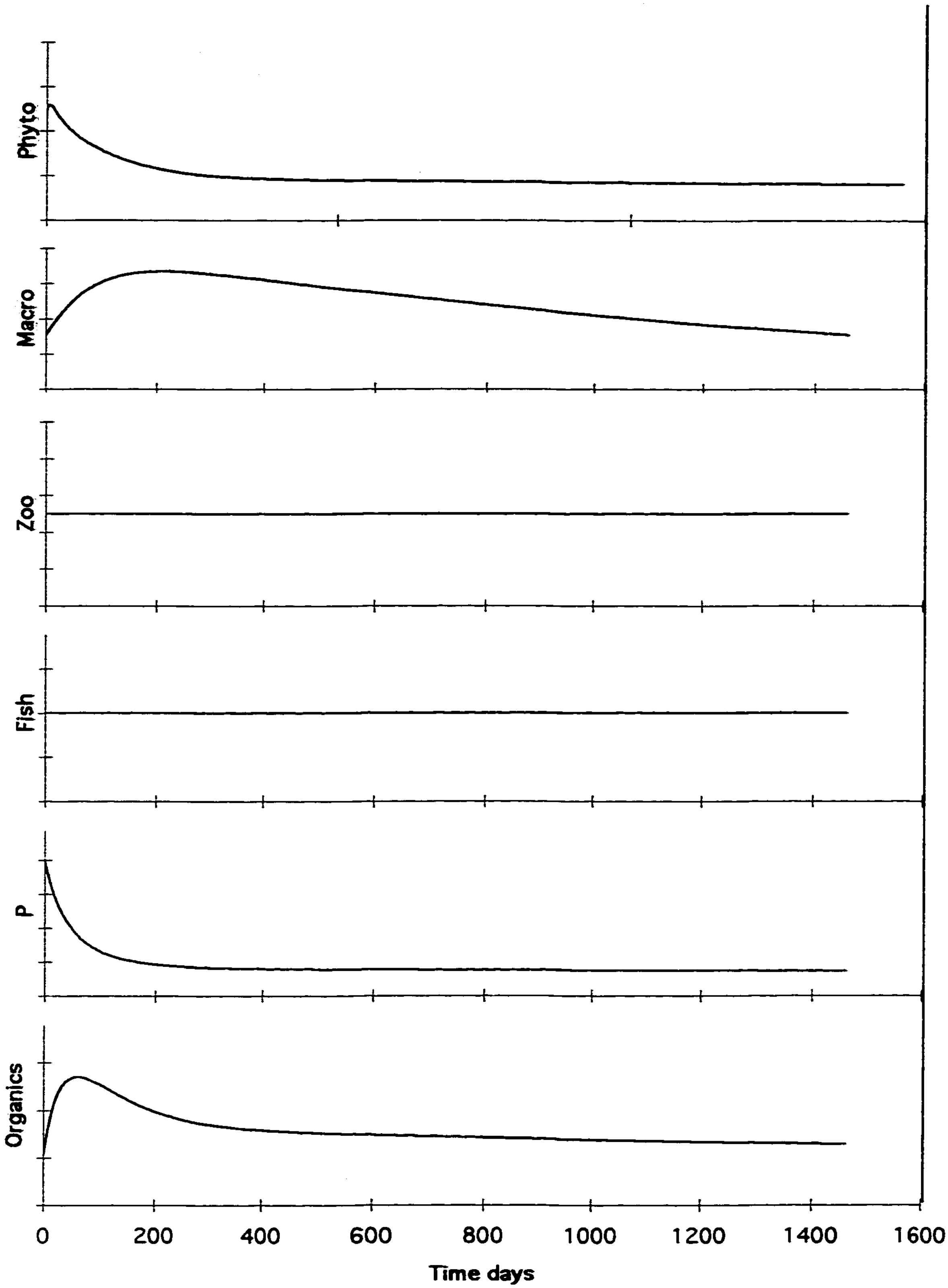


Figure 3.69. Using in-lake simulation to explore hierarchy of pulsing control. Producer storages are allowed to vary. All other variables higher in the chain are held constant.

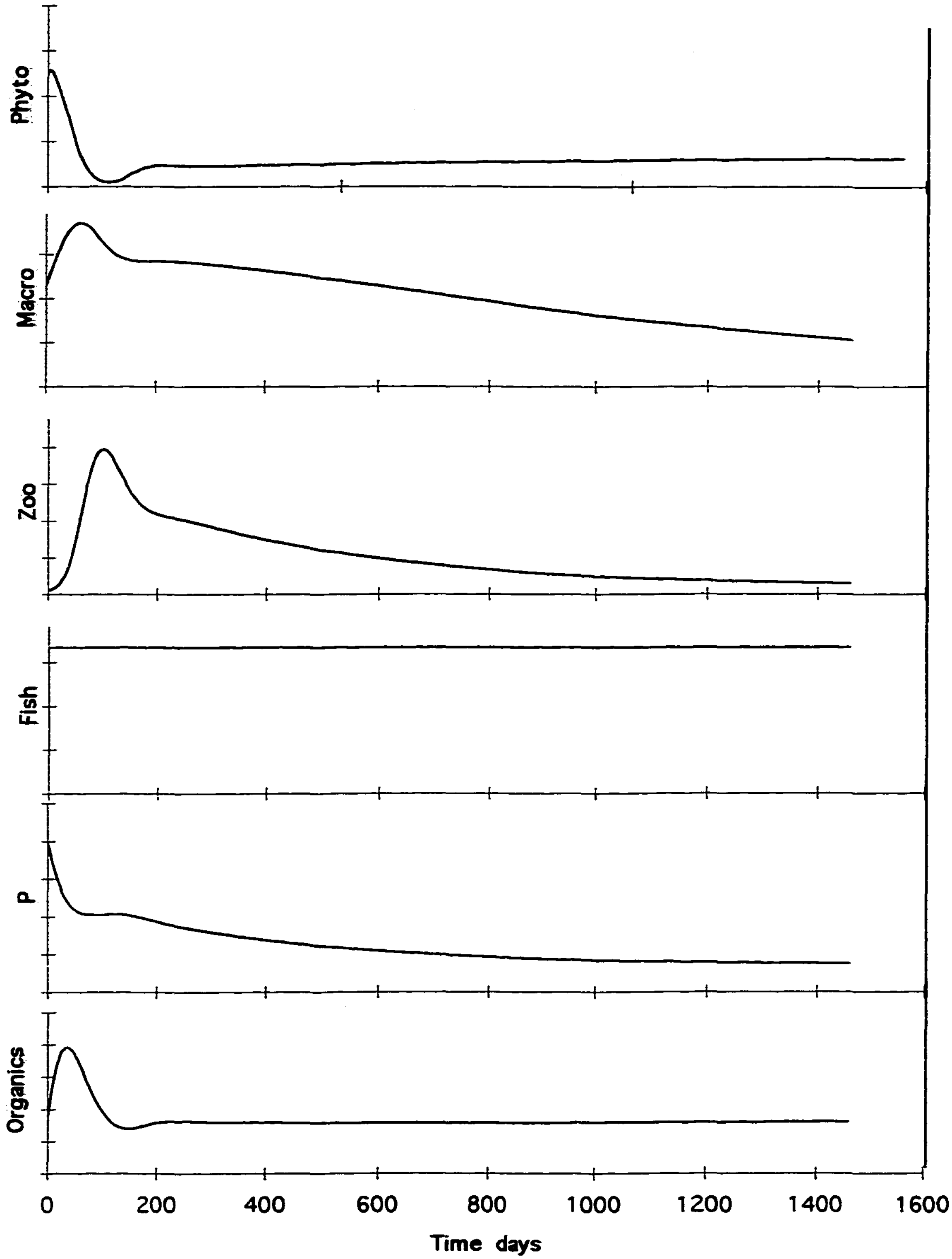


Figure 3.70. Using in-lake simulation to explore hierarchy of pulsing control. Producer storages and zooplankton are allowed to vary. Fish storage is held constant.

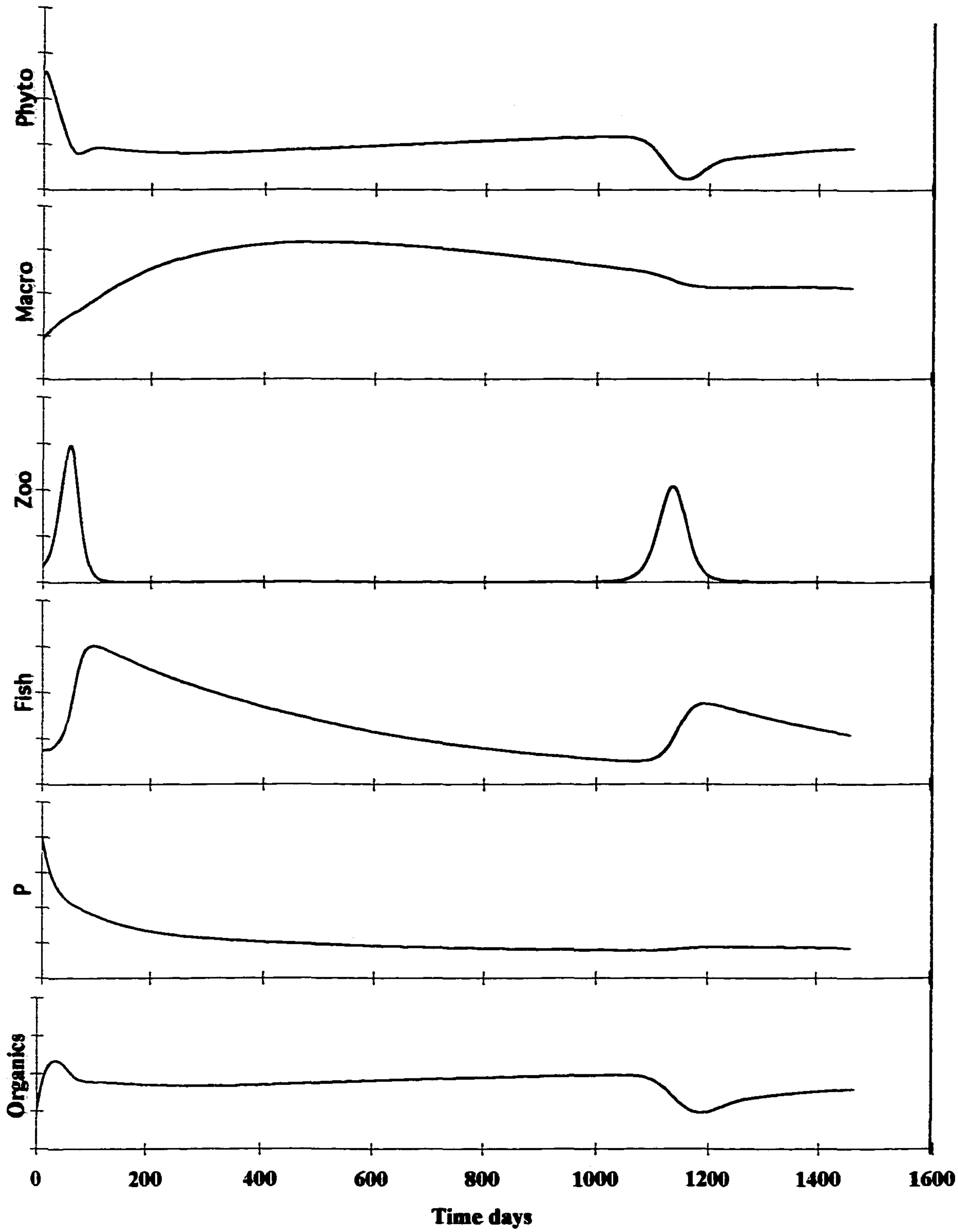


Figure 3.71. Using in-lake simulation to explore hierarchy of pulsing control; all variables are fully interacting.

concentrations in mg/l can be used in Vollenweider's loading equations. Phosphorus to lake volume ratios can be compared to water column TP. Phosphorus to sediment ratios are commonly used in characterizing TP in sediment records.

Newnans Lake

Overall loading changes simulated from pre-development through 1990 are shown in Tables 3.16 for Newnans Lake. Newnans Lake shows a steady increase in TP and TP concentration ratios (Fig 3.72). Water showed a temporary drop in 1970 due to reforestation north of the lake, but was higher overall in 1990. These changes are similar to those in water quality data taken from Huber et al. (1982) and from more recent Lakewatch data (1998) (Figure 3.73). Phosphorus to sediment ratios are lower than those from cores taken by Gottgen and Crisman (1993) as expected (Fig 3.73), since stream inputs are greater than non-point source inputs (Table 3. 6).

Lake Weir

Lake Weir simulations show increasing stormwater inputs to the lake, but much lower phosphorus after 1970 (Table 3.17). This is due to replacement of citrus production with range and residential land use. Phosphorus concentrations show a concomitant drop (Figure 3.74). Corresponding water quality data also show a drop in water column TP and overall trophic state index (Figure 3.75).

Emergy Loads and Ratios

Comparison Between Watersheds

A direct comparison of emergy inflows at both the highest point of development and pre-development periods is presented as a means for ranking the two watersheds and comparing emergy to empirical water quality data (Table 3.18). Overall, Newnans Lake has higher emergy flows than Weir except in recreational use.

Two interesting differences and similarities are evident. The emergy per mass in TP runoff is the same in pre-development time periods for both lakes, suggesting a baseline value of 6E4 sej/g for phosphorus. The transformity for runoff water is different for the two watersheds, but the same throughout time for each watershed.

Watershed and lake emergy inputs for both lakes reflect the same relationship as the TSI (Figure 3.76). Log values of emergy flows are presented for better comparison.

Comparison of Simulated Phosphorus Load and Empirical Phosphorus Data

Emergy values for phosphorus runoff are higher for Lake Weir than Newnans Lake in both 1970 and 1990, but predevelopment TP runoff emergy is higher in Newnans (Tables 3.19 and 3.20). The direction of change in emergy values for TP loading are consistent with empirical data (Fig 3.77). Newnans Lake shows a slight increase across both sets of values, and Weir shows a larger decrease.

Emergy Accumulation Patterns

Little difference in the network pattern for phosphorus emergy is apparent between the pre-development era and highest level of development in Newnans Lake watershed (Fig 3.78 and 3.79). However, total emergy flows are five orders of magnitude lower.

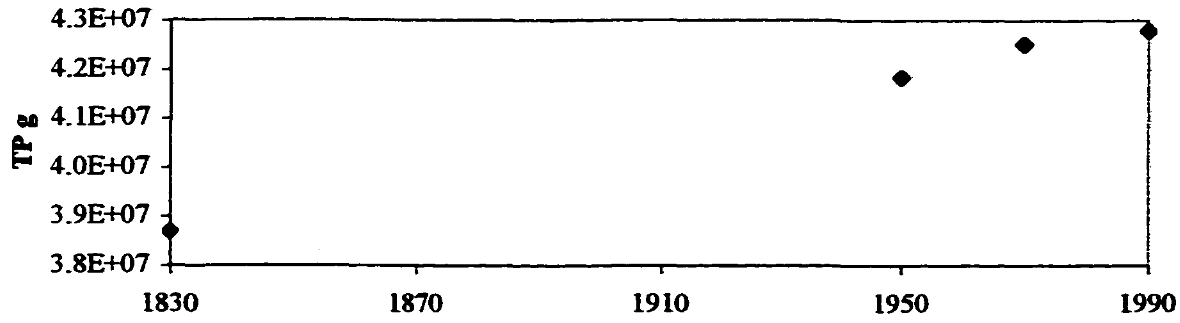
Lake Weir, on the other hand, exhibits less complexity in the pre-development period than in the period of highest phosphorus runoff (Fig 3.80 and 3.81). Total emergy flows are still increased by five orders of magnitude.

Table 3.16. Summary data for watershed loads to Newnans Lake from spatial simulation.

	Pre-development	1950	1970	1990
Phosphorus,g	3.87E+07	4.18E+07	4.25E+07	4.28E+07
Water, m3	2.66E+08	2.68E+08	2.68E+08	2.70E+08
Sediments, kg	2.77E+07	2.79E+07	2.79E+07	2.81E+07
TP/Sed Ratio, mg/g	1.40	1.50	1.53	1.52
Average P Concentration, mg/l	0.145	0.156	0.159	0.158
Runoff, % of total rain	34.50%	34.80%	34.80%	35.10%
TP load/lake volume Ratio, g/m	1.08	1.17	1.19	1.20
TP load/lake area, ug/cm^2/yr	13.05	14.11	14.34	14.47

Table 3.17. Summary data for watershed loads to Lake Weir from spatial simulations.

	Pre-development	1950	1970	1990
Phosphorus,g	2.42E+07	4.97E+07	5.26E+07	3.40E+07
Water, m3	6.61E+07	6.66E+07	6.68E+07	6.71E+07
Sediments, kg	7.59E+06	7.64E+06	7.66E+06	7.70E+06
TP/Sed Ratio, mg/g	3.19	6.50	6.87	4.42
Average P Concentration, mg/l	0.37	0.75	0.79	0.51
Runoff, % of total rain	30.21%	30.43%	30.51%	30.66%
TP load/lake volume Ratio, g/m	0.13	0.26	0.27	0.18
TP load/lake area, ug/cm^2/yr	10.40	21.35	22.61	14.62



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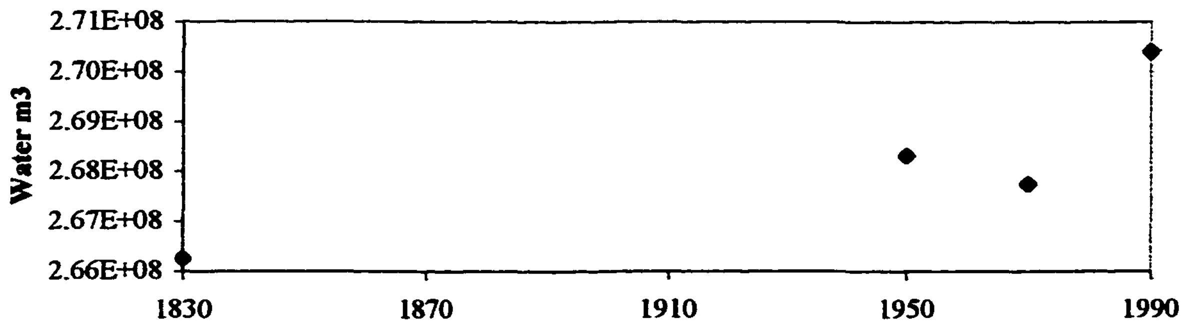

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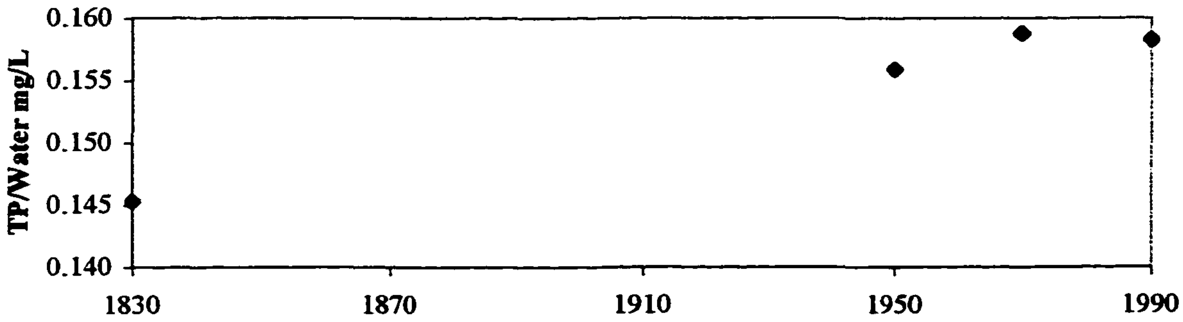

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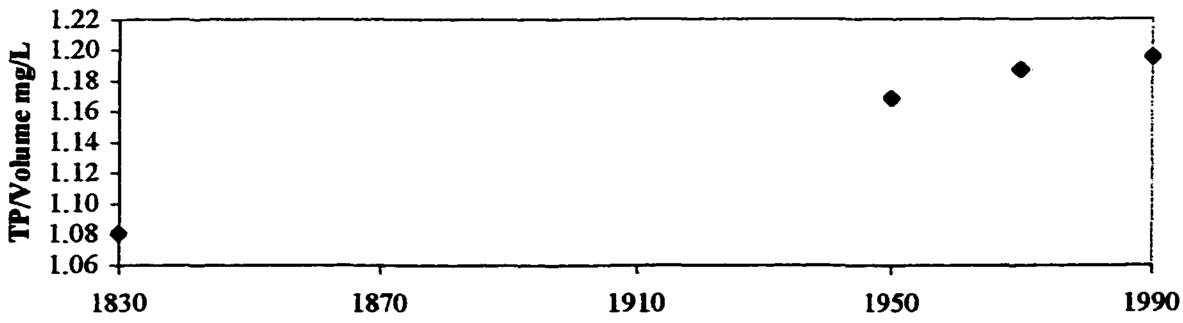
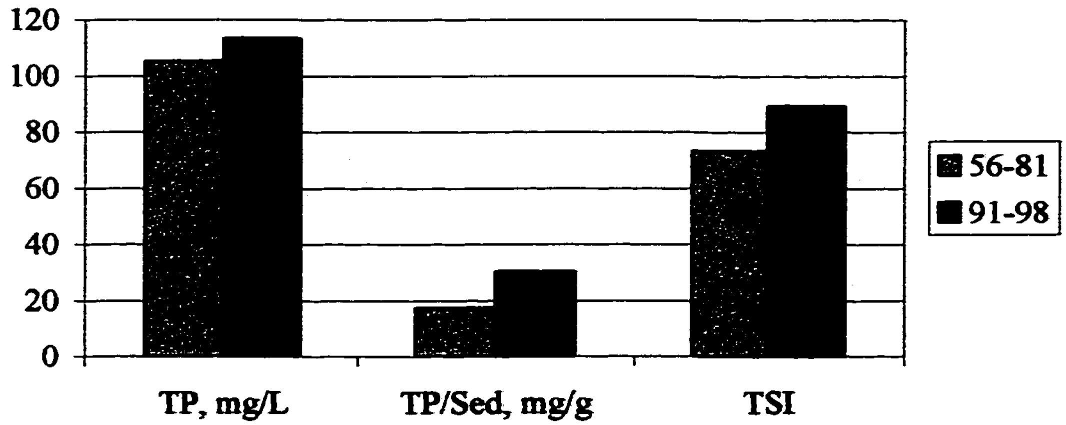


(d)

Figure 3.72. Phosphorus and water loads to Newnans Lake from the watershed; a) TP loading, g; b) water, m3; c) TP concentration, mg/l; d) TP to lake volume ratio,g/m3.



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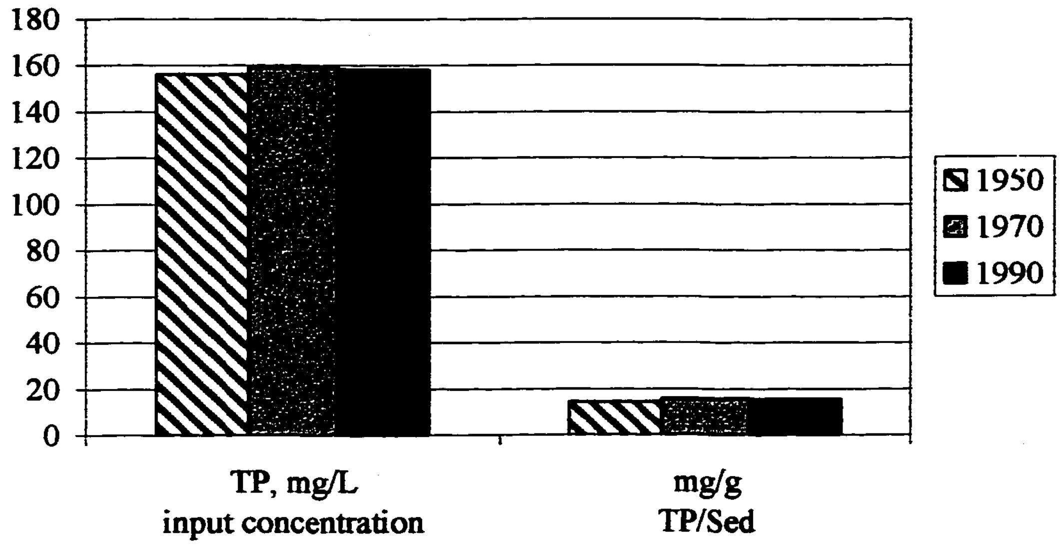


(b)

Figure 3.73. Comparison of simulated TP loading and water quality data for Newnans Lake; a) TP and TSI data from Huber (1982) and Lakewatch (1998), TP/sediment ratios from Gottgens & Crisman (1993); b) simulation values.

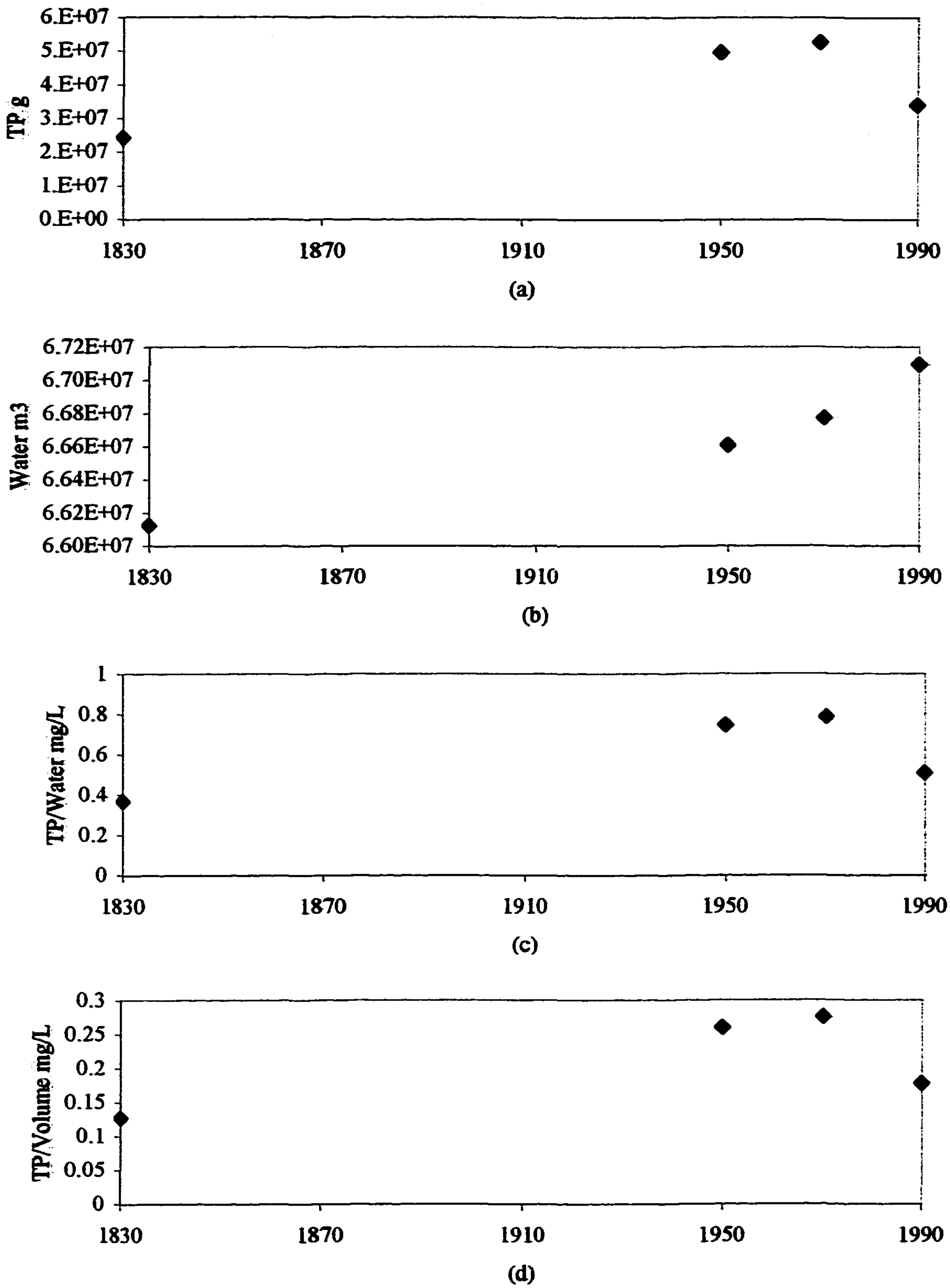
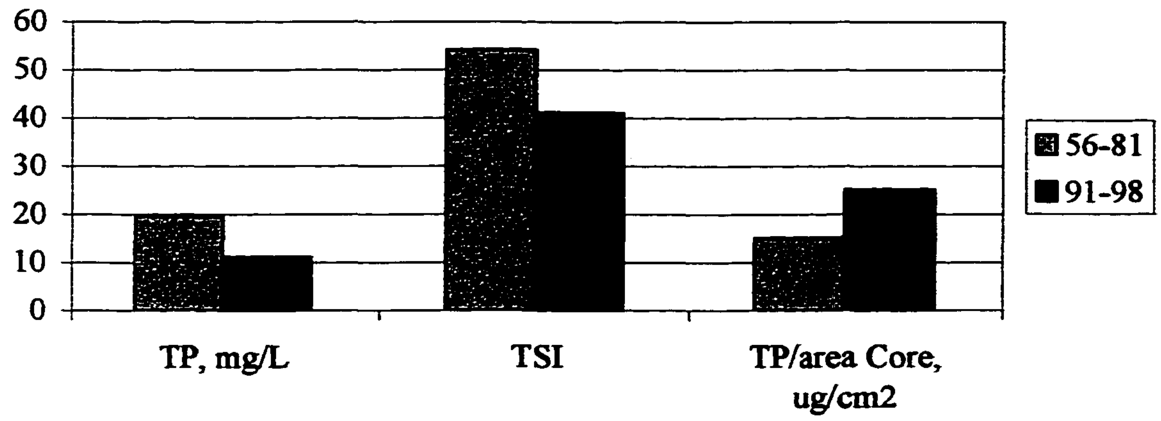


Figure 3.74. Phosphorus and water loads to Lake Weir from the watershed; a) TP, g; b) water, m3; c) TP concentration, mg/l; d) TP to lake volume ratio,g/m3



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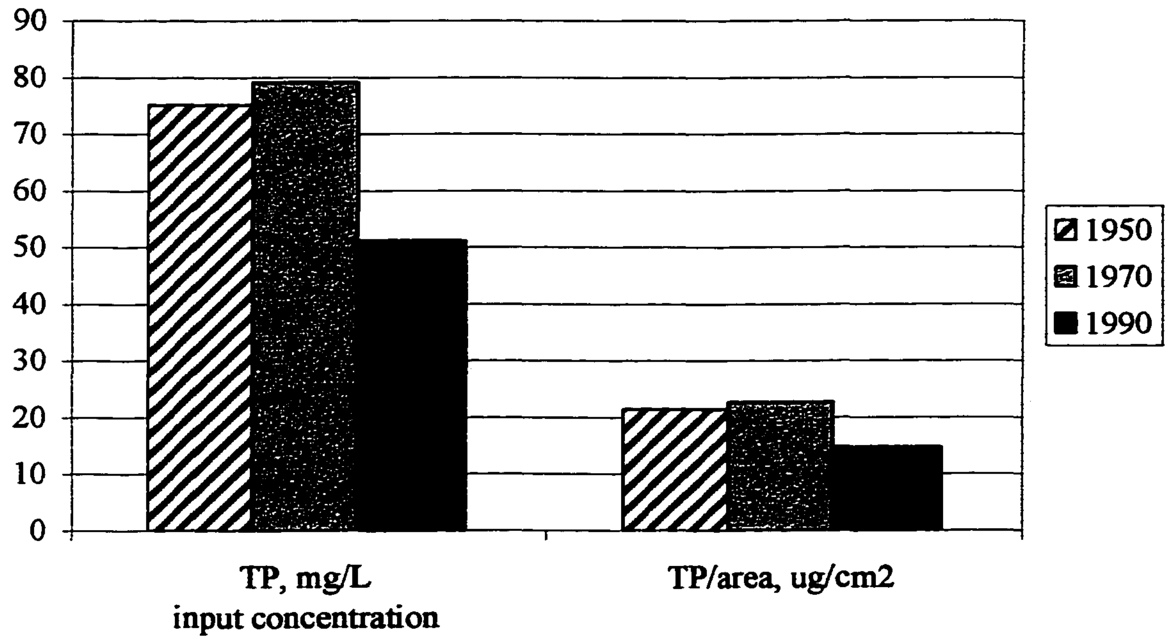


Figure 3.75. Comparison of simulated TP loads and empirical water quality data, Lake Weir; a) TP and TSI data from Huber (1982) and Lakewatch (1998), TP/sediment ratios from Crisman et al. (1992); b) simulation values.

Table 3.18. Comparison of watershed emergy classification parameters.

	Newnans	Weir
Maximum Development		
Watershed emergy used, sej/yr	2.49E+22	9.24E+20
Average empower density, sej/ha/yr	4.28E+17	7.64E+16
Emergy input to lake, sej/yr	1.09E+20	1.02E+19
Emergy/perimeter lake, sej/m/yr	3.33E+15	2.01E+14
Emergy/area lake, sej/ha/yr	3.60E+16	4.00E+15
Emergy/mass TP lake, sej/g	8.31E+10	1.46E+09
Emergy/mass runoff TP, sej/g	6.85E+09	1.27E+10
Transformity lake water, sej/J	6.15E+05	1.08E+04
Transformity runoff water, sej/J	6.31E+04	1.86E+04
Recreational use, sej/yr	2.62E+21	6.92E+21
Pre-Development		
Watershed emergy used, sej/yr	5.80E+19	2.42E+19
Average empower density, sej/ha/yr	9.97E+14	2.00E+15
Emergy/mass runoff TP, sej/g	9.36E+04	9.36E+04
Transformity runoff water, sej/J	6.32E+04	1.88E+04

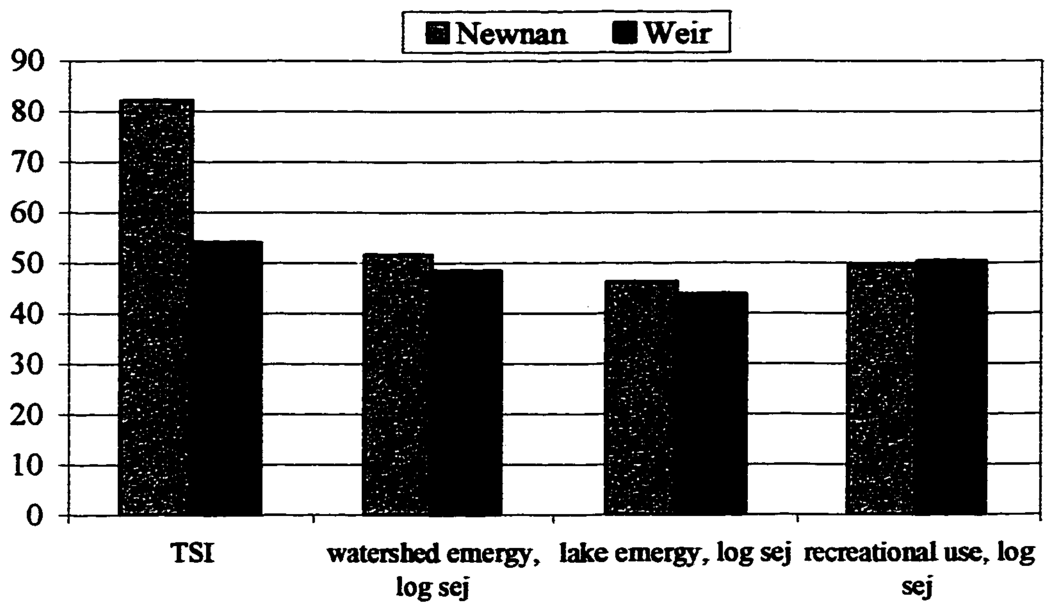


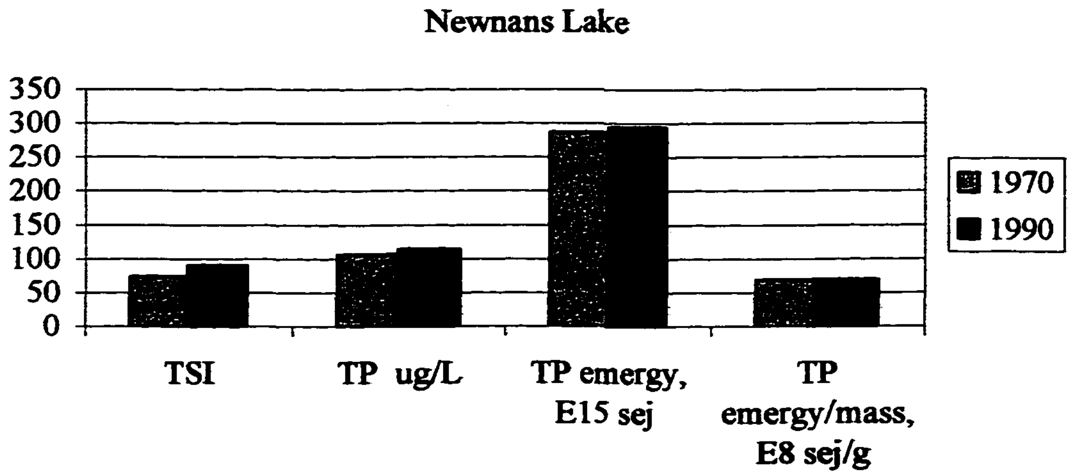
Figure 3.76. Comparison of emergy flows to the watershed and lake with trophic state index for both Newnans Lake and Lake Weir.

Table 3.19. Summary emergy data for runoff to lake, Newnans Lake.

	pre-development	1970	1990
Phosphorus			
Emergy input, sej	3.62E+12	2.86E+17	2.93E+17
Average emergy/mass, sej/g	9.36E+04	6.84E+09	6.85E+09
Water			
Emergy input, sej	8.09E+19	8.15E+19	8.41E+19
Average transformity, sej/J	6.16E+04	6.31E+04	6.40E+04

Table 3.20. Summary emergy data for runoff to lake, Lake Weir.

	pre-development	1970	1990
Phosphorus			
Emergy input, sej	2.26E+12	6.68E+17	4.32E+17
Average emergy/mass, sej/g	9.36E+04	1.27E+10	1.12E+10
Water			
Emergy input, sej	5.94E+18	6.00E+18	6.00E+18
Average transformity, sej/J	1.87E+04	1.86E+04	1.86E+04



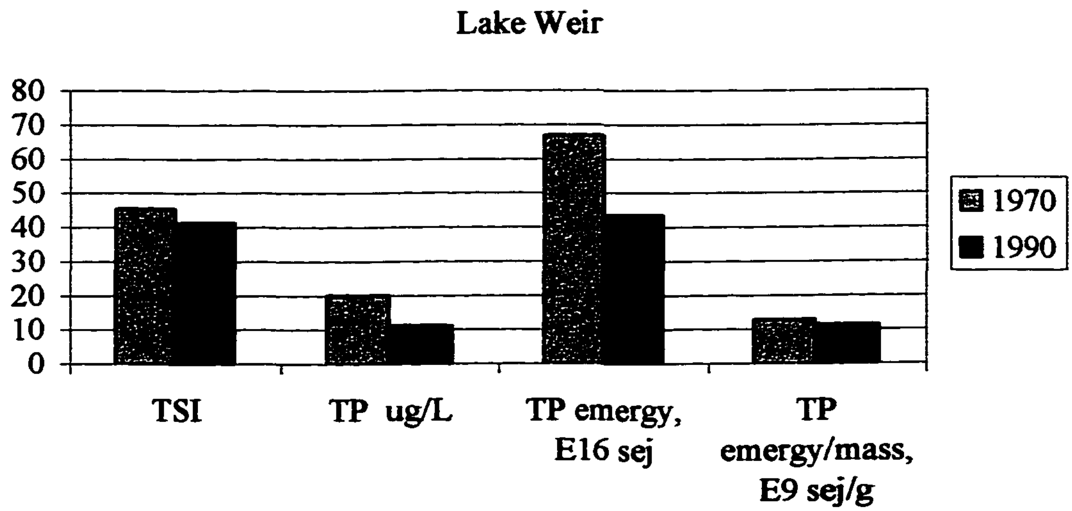


Figure 3.77. Comparison of simulated phosphorus emergy flows over time with empirical water quality from Huber et al. (1982) and Lakewatch (1998).

Intervention Strategies

Remediation of increasing phosphorus inputs was attempted by replacing existing land use in specific areas of each watershed with areas resembling retention ponds in holding capacity. Two strategies were used to optimize placement, and both were compared for amount of area required to reduce current loads to pre-development levels, as well as patterns of placement. One method uses areas of highest cumulative phosphorus loads to pinpoint mitigation sites. The second method uses emergy per mass ratios higher than the ratio found in industrial concentration of phosphorus (> 2E12 sej/g) to pinpoint appropriate holding areas for phosphorus runoff.

Newnans Lake

Using areas of highest drainage for phosphorus as preferred placement requires 385 hectares mitigation area to reduce Newnans phosphorus load to pre-development levels. The placement areas are concentrated along the western lake edge, between the lake and the residential areas (Fig 3.82). These areas are currently cypress swamp and lawn.

The emergy per mass method requires 700 hectares of Newnans watershed, but the areas are scattered throughout the watershed and require few changes in current developed land use (Fig 3.83).

Lake Weir

Using areas of highest drainage for phosphorus as preferred placement requires 280 hectares mitigation area to reduce Lake Weir's phosphorus load to pre-development levels. The placement areas are again concentrated along the lake edge, between the lake and the residential areas (Fig 3.84). However, the sites are more evenly distributed around the lake.

The emergy per mass method requires 560 hectares of Weir's watershed, but, again, the areas are scattered throughout the watershed, mostly near existing agricultural areas (Fig 3.85). They do not appear to require conversion of current developed land use.

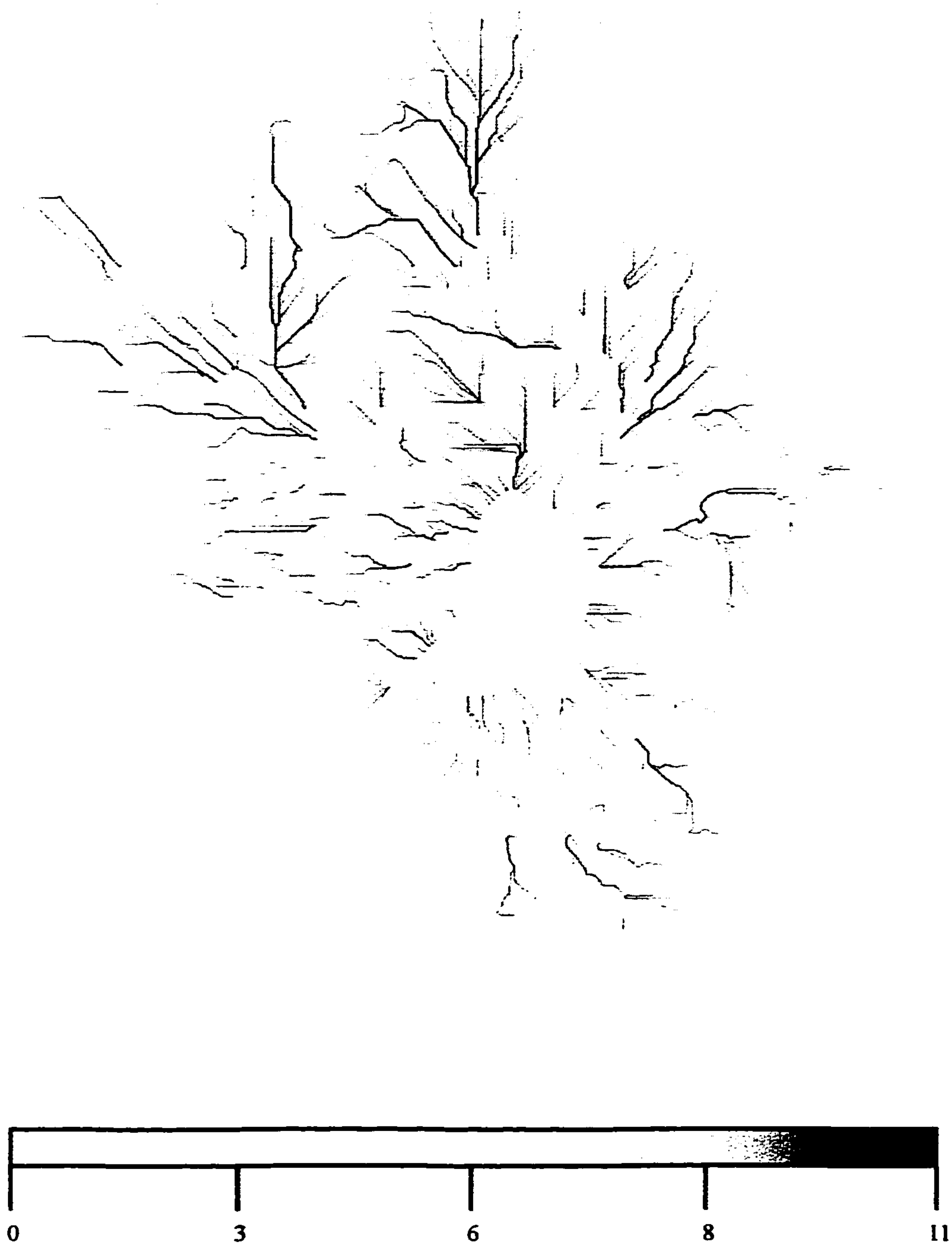


Figure 3.78. Pre-development phosphorus emergy drainage network, Newnans Lake; log sej/g.

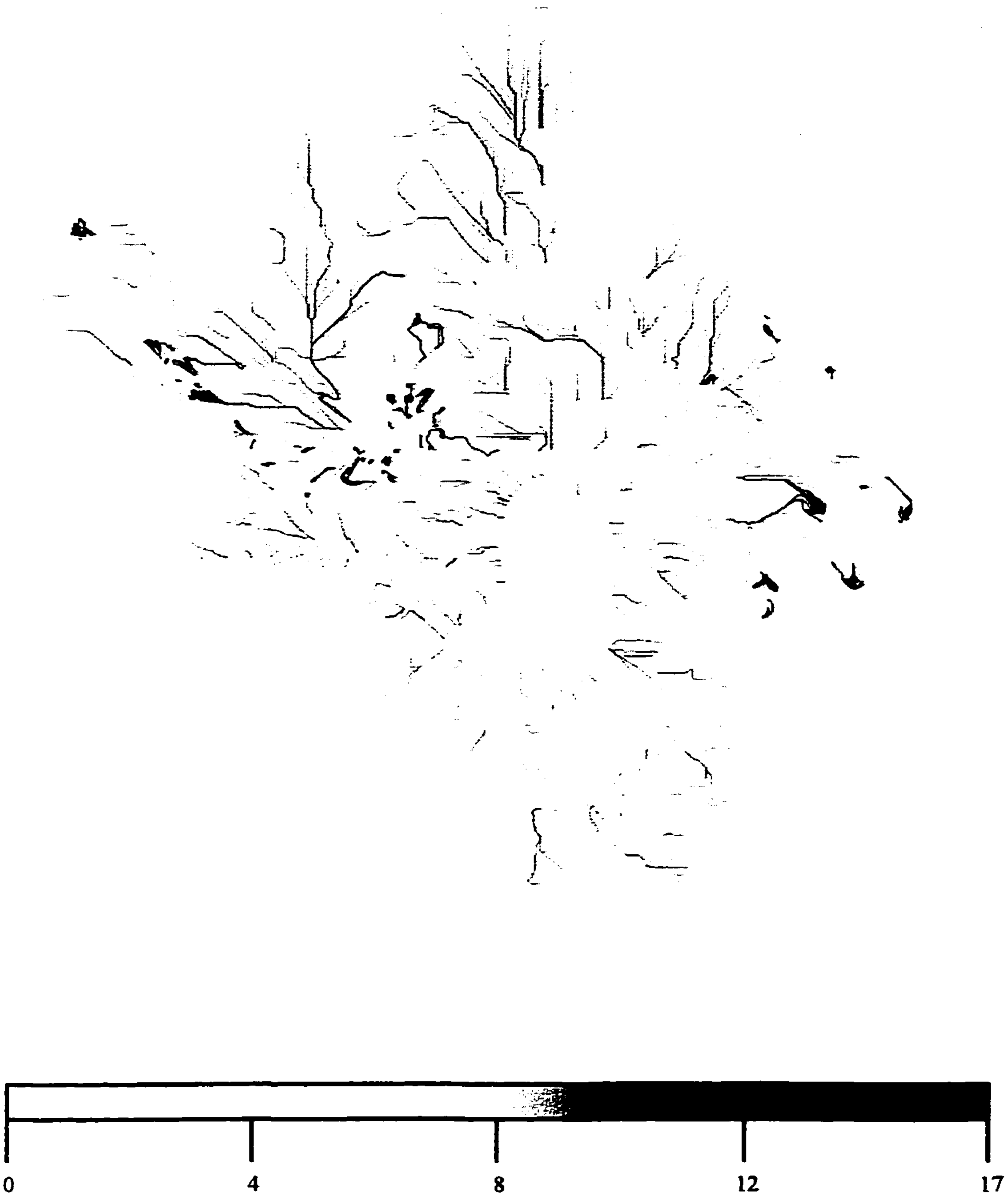


Figure 3.79. Post-development phosphorus emergy drainage network, Newnans Lake, log sej/g.

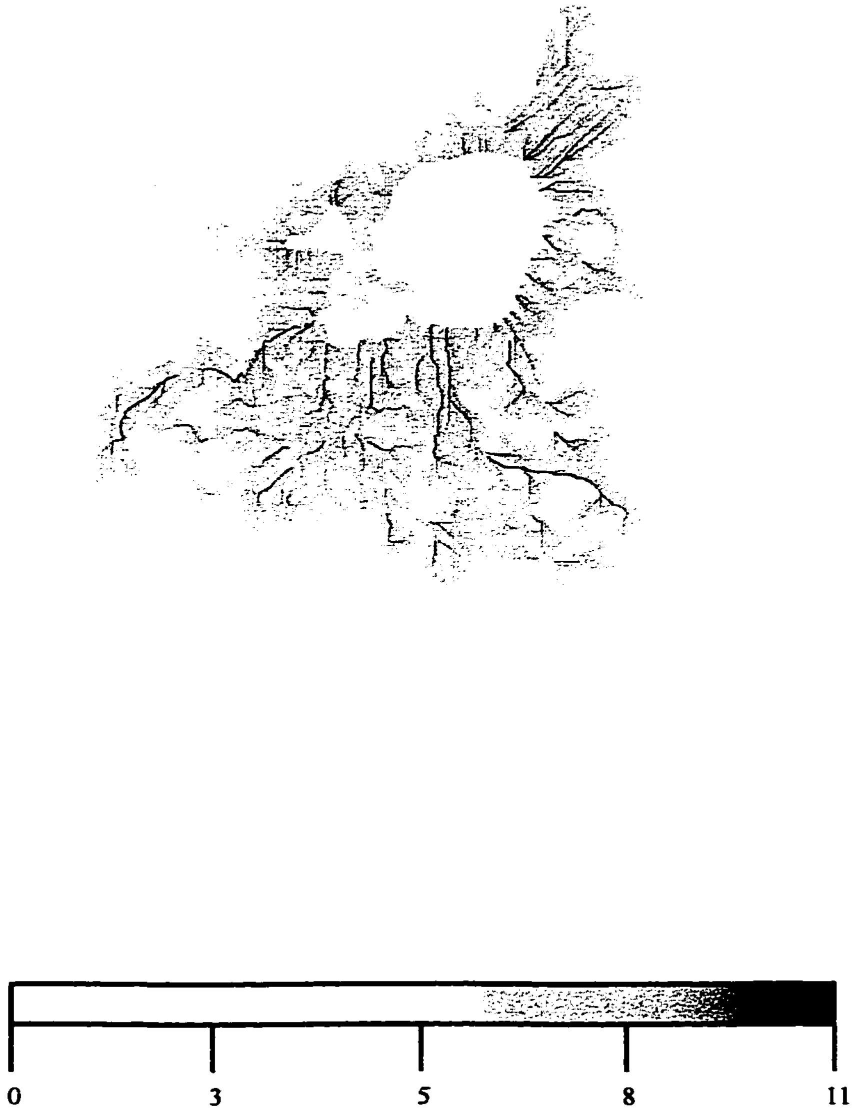


Figure 3.80. Pre-development phosphorus emergy drainage network, Lake Weir; log sej/g.

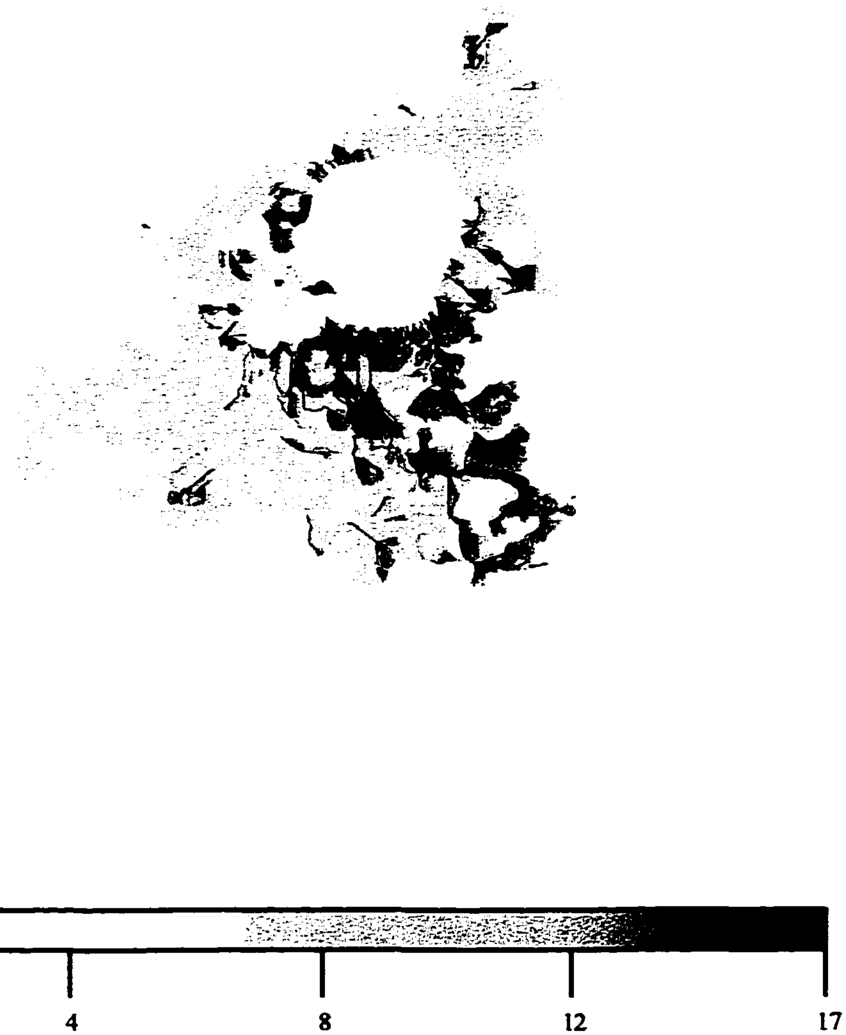


Figure 3.81. Post-development phosphorus emergy drainage network, Lake Weir , log sej/g

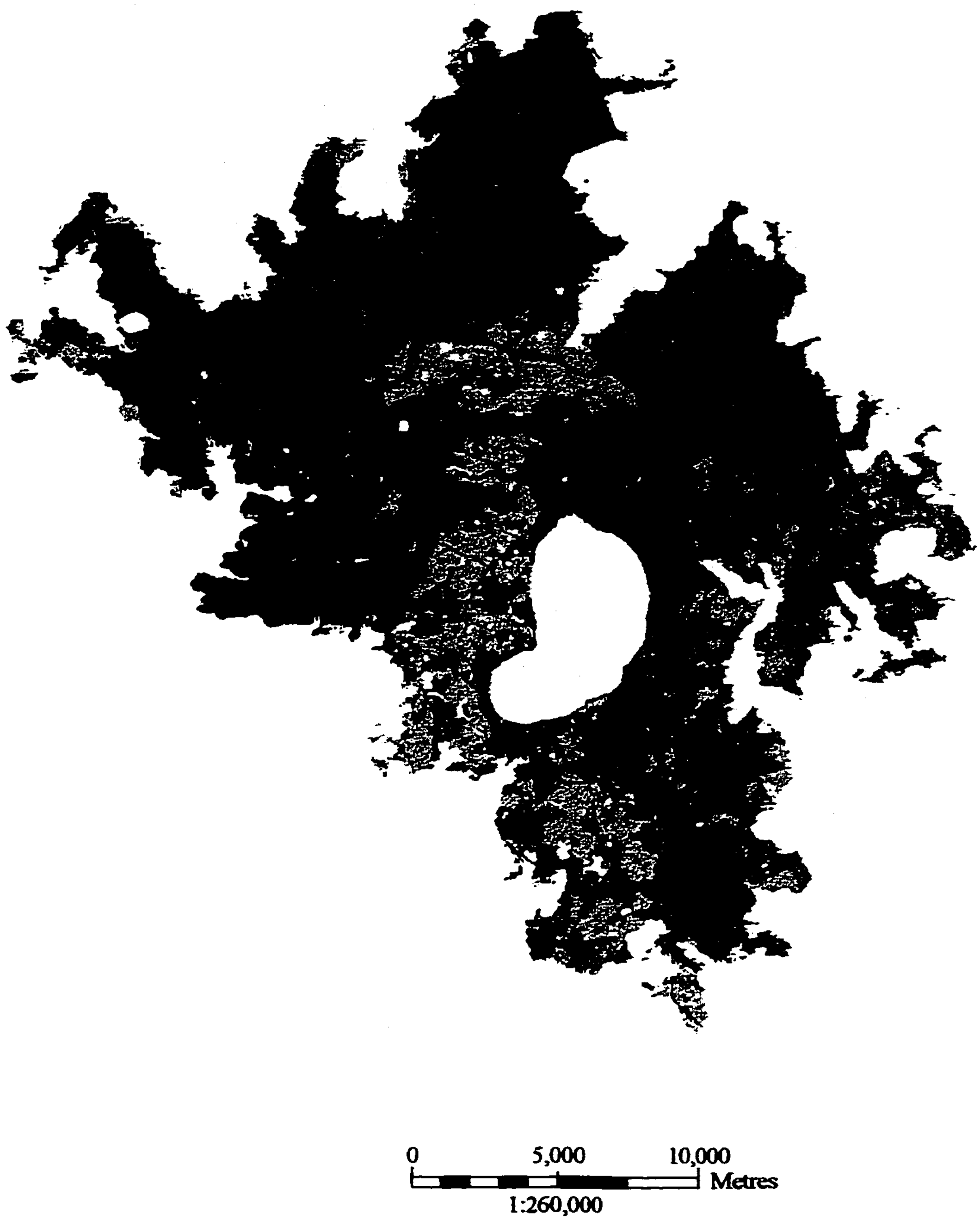


Figure 3.82. Placement of intervention based on points of highest mass loading, Newnans Lake; purple areas indicate best siting.

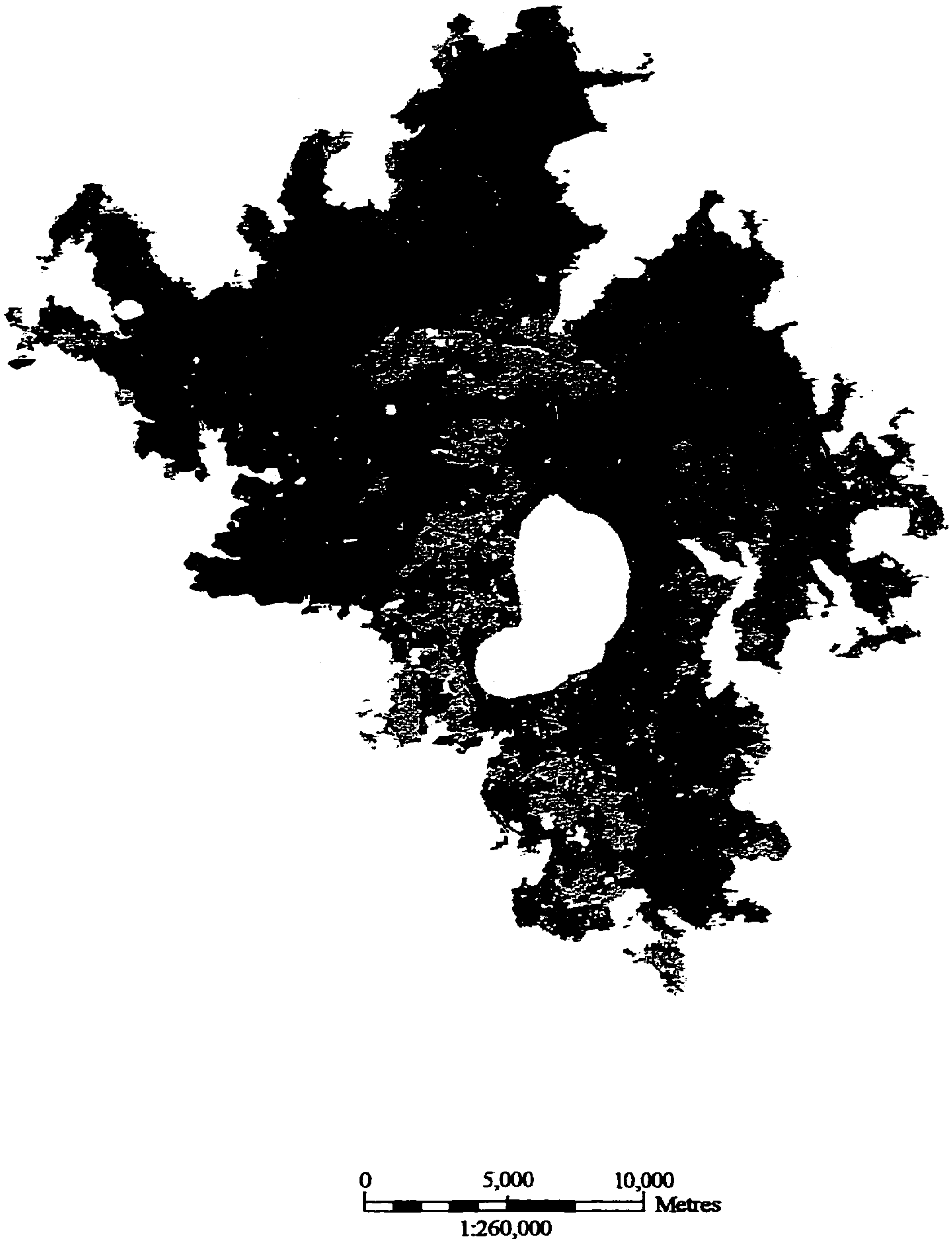


Figure 3.83. Placement of intervention based on points of emergy/mass greater than 2E12 sej/g, Newnans Lake; purple areas indicate best siting.

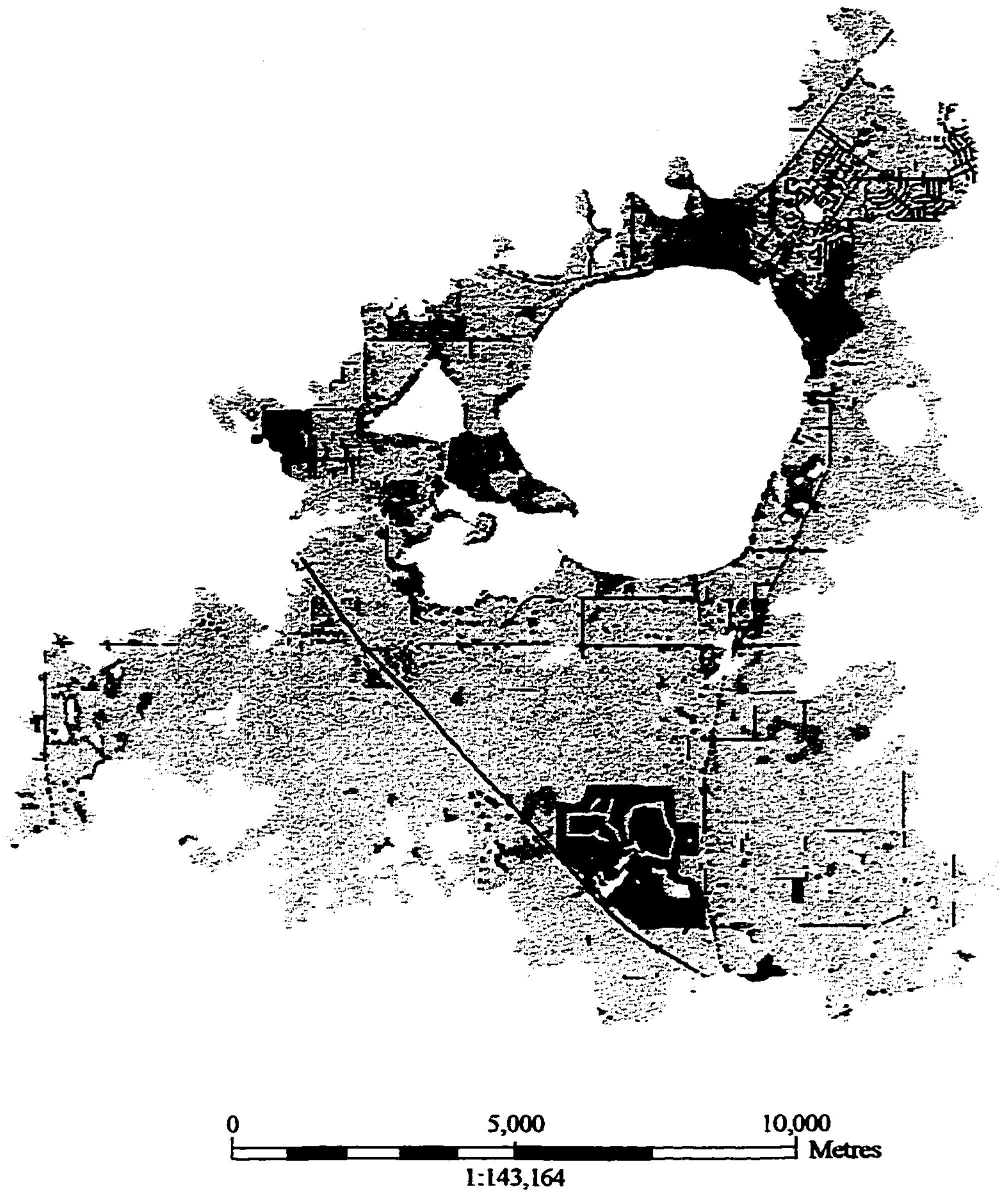


Figure 3.84. Placement of intervention based on points of highest mass loading, LakeWeir; purple areas indicate best siting.

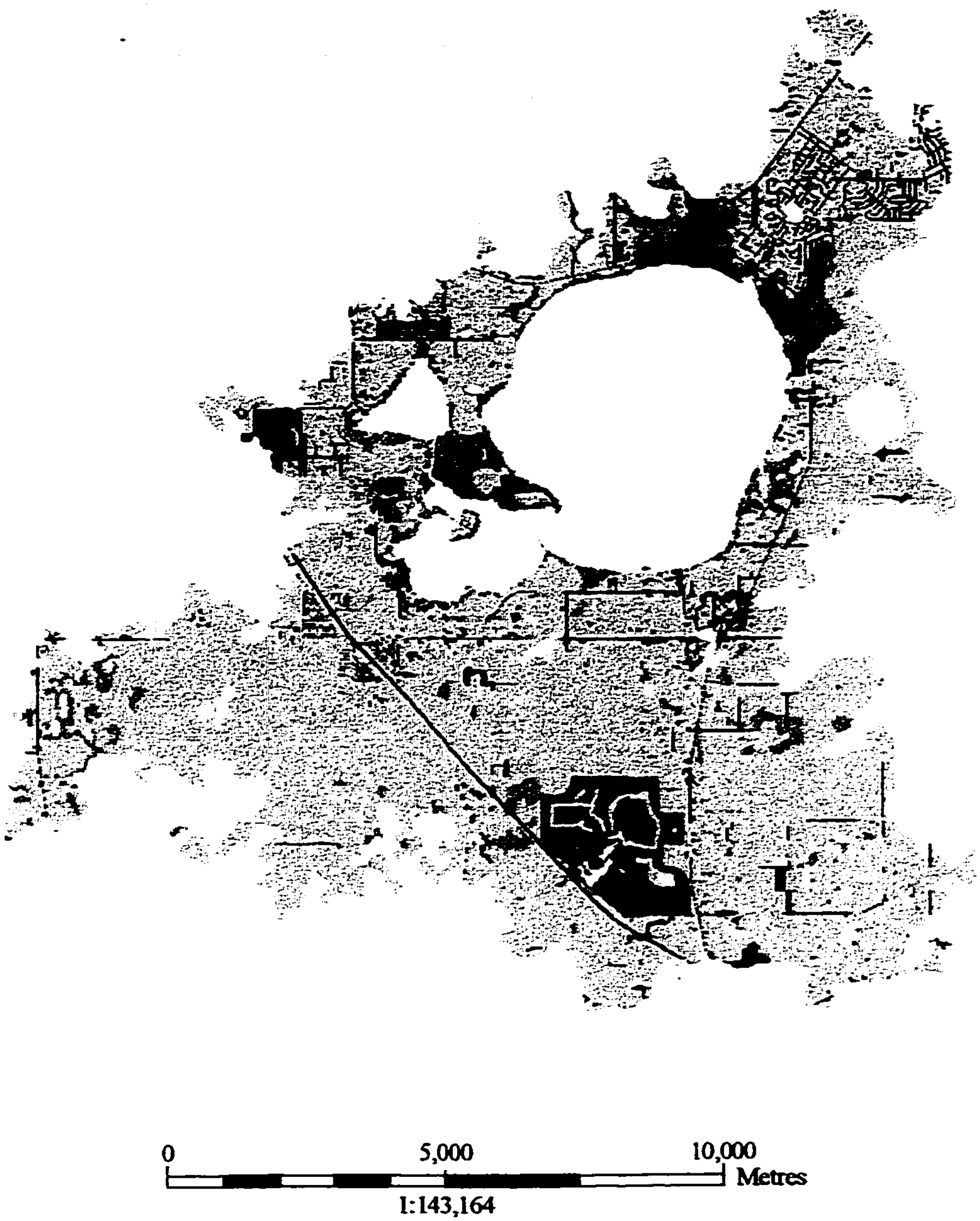


Figure 3.85. Placement of intervention based on points of emergy/mass greater than 2E12 sej/g, LakeWeir; purple areas indicate best siting

CHAPTER 4
SUMMARY AND RECOMMENDATIONS

Summary

This dissertation examines changing energy and material flows in watersheds and how they impact and shape the evolving productivity of the basin's focal point, in this case, lakes. Further, it evaluates emergent properties of concentrating material flows, the energy acting on them and the emergy embodied in them. Fox (1986), in discussing energy -driven systems states, "Energy flow is a necessary but not a sufficient condition for the living state of matter ... the living state is as much a consequence of special substances and their emergent properties as it is a consequence of energy flow."

This study specifically examines two watersheds in central Florida with very different characteristics, and focuses on water and phosphorus inputs to the lakes. Phosphorus is usually the material limiting productivity in freshwater (Wetzel 1983), and water moving downhill provides the kinetic energy necessary to bring phosphorus into a lake. Phosphorus, as both material and energy transducer in production of evolutionary building blocks, represents a special substance with emergent properties sufficient for evolution (Fox 1986).

One goal of this research was to present the system of constraint evident from quantifying the hierarchy between a watershed and its lake. The downhill movement of energy and mass into a lake is an obvious causal mechanism, or feed forward (Salthe

1985), but the extent of its control on the lake may not be dominant. The regulation of watershed activity by the lake, or feedback, is not as obvious, but is evident in use of the lake by humans for recreation, climate control and aesthetics and by migratory wildlife for food and habitat.

The research focused on the quantity and influence expected from diffuse non-point source material contributions converging on a lake, and showed that the emergy per mass of materials, both dispersed and concentrated in the watershed, is a dynamic property. Material, such as phosphorus, is applied in concentrated form to developed areas (agriculture, residential and urban), then diluted with stormwater, cycling it through the watershed. Concentration occurs when runoff from a much larger area is funneled to the lake edge, and all the energy used to move it accumulates (Odum, 1996).

However, mass quantities alone often disguise the real power of the material in relation to other materials in the system. Phosphorus, usually a limiting nutrient, is measured in *u*g, while water is best dimensioned with cubic meters and sediment with metric tons. Emergy best defines the real power in phosphorus and provides a higher ranking by including the previous energy used in moving the element into a concentration useable by primary producers (Odum, 1996).

This study proposed the use of dynamic system simulations and emergy as evaluative tools both for showing long term trends in watershed development and for providing early warnings for changes in lake productivity. Although not predictive, these simulations of a eutrophic and oligotrophic system showed comparative responsiveness to increased phosphorus loading.

One application arising from the research was a methodology for prioritizing remediation and conservation efforts, both within a watershed and between watersheds with lakes that are exhibiting increasing eutrophication. Because the runoff model is spatially specific and provides both patterns of high drainage and an expected loading from each area in the watershed, areas of proposed intervention can be tested for efficacy in reducing overall lake loading.

Specific advances of interest in watershed-lake relationships are discussed in this chapter.

1. Spatial patterns emerged that were both common to, or differentiated between, materials and watersheds.
2. A clear hierarchical relationship between systems within the watershed was established.
3. Simulated non-point source loading and observed lake productivity showed similar trends.
4. Dynamic properties of emergy per mass ratios emerged from time-series evaluation.
5. Simulations of in-lake loading impacts suggested differences between oligotrophic and eutrophic responses.
6. The use of watershed emergy and material ratios were representative of overall lake productivity.
7. Improvements in phosphorus loading were simulated using several decision strategies for placement of intervention ecosystems.

These findings are discussed individually in the following sections.

Spatial Patterns in Lake Watersheds

Two primary spatial patterns are evident in this study: patterns established over millenniums by geologic processes, and short-term development patterns created by humans. The former encompasses elevation and soil differences and establishes a baseline for watershed loading to the lake. These can provide information on the natural trophic state of the lake, or at least the long-term runoff loads the lake has organized around. The latter include increases in nutrient availability and impervious surfaces. These two factors combined increase the likelihood of cumulative loading to the lake in a persistent manner that is difficult to intercept, and can be expected to reinforce the level of connection between watershed and lake within a specific watershed.

Patterns from Geologic Processes

The Newnans Lake basin is very shallow with an average depth of about 1 meter. Water of this depth is completely available for evaporation (Chow et al. 1988). To retain a lake in a depression of this depth, stormwater inputs must therefore be greater than the volume. Newnans Lake is likely still a lake because its watershed has a high percentage of soils with low permeability, few areas without a confining layer and relatively few depressional areas within its overall boundary, allowing large amounts of runoff to move unimpeded through the landscape.

The spatial simulation shows that without development in the watershed, 37% of the watershed's rain reaches the lake. The total volume of runoff is 2.66E8 m3/yr. This corresponds to the 2.1E8 m3/yr runoff estimated with the Soil Conservation Service method for abstractions (Appendix C). This estimated runoff is 7 times higher than the calculated volume of the lake.

Lake Weir, on the other hand, exhibits a greater area of watershed in small depressional areas, particularly in the southeast quarter of the basin. Further, there is a greater percentage of highly permeable soil, with a larger percentage of the basin not occluded from the aquifer. We would expect the overall percentage of stormwater runoff to be lower than in Newnans, and in fact, the model shows a 7% difference in the amount of rain that becomes runoff.

The simulation of Lake Weir's watershed, without development, has an estimated runoff load of 30% of the total annual rainfall, or about 6.6E7 m3/yr. This is about 34% of the total lake volume.

Patterns from Human Development

Patterns of drainage intensity varied in complexity and magnitude between the two watersheds. The amount of watershed contributing to the lake (effective watershed) increased with urban or residential development near the lake. Each lake had a unique effective watershed, dependent on geology and soils, as originally hypothesized. Developments outside this area still contributed a substantial amount of runoff. However, the effective watershed in each instance contributed a greater amount than the outlying areas combined.

Both watersheds exhibited a tendency to concentrate development in two specific watershed areas - the sandier portions of the lake perimeter, and to a larger degree, the edges of the watershed where several watersheds adjoined. For the Gainesville area, this latter concentration was at the Newnans, Lake Alice and Paynes Prairie junction. For Lake Weir, there were three points of concentration: the Oklawaha River basin, the Withlacoochee River basin, and Lake Griffin.

Hierarchy of Lakes and Watersheds

Empower density establishes the hierarchy proposed in Chapter 1 (Figure 1.1 - 2), with urban and residential areas being of higher rank than the lakes. Concentration of materials and energy at the interface between watershed and lake place the lake much higher than the surrounding natural areas and somewhat higher in the hierarchy than agricultural areas. Although Newnans Lake is a higher emergy lake than Lake Weir, the same hierarchy is evident in both watersheds.

Empower density values in the Newnans Lake watershed are similar to those calculated in a recent study of Alachua County (Lambert, 1999). Both studies show scattered areas of high empower density throughout the watershed due to agricultural and residential land uses. Both indicate a large concentration of emergy in Gainesville and in the lake. However, this study has a lower estimate of the Gainesville empower density and a higher estimate of the lake's empower than Lambert's evaluation. Differences in Gainesville's values are related to Lambert's inclusion of human services specific to each hectare, whereas the current study evaluated only inflows crossing the watershed boundary and averaged them for Gainesville as a whole. Lake empower differences are due to the dynamic simulation input from runoff in this study.

Cumulative Watershed Loading and Lake Trophic Status

Phosphorus loading simulated by the spatial model, while generally showing the same trend as development in both watersheds, was not directly related to land use changes, either in quantity or location. This finding is reinforced by the earlier runoff study (Appendix C) showing a high correlation between chlorophyll and phosphorus loading, but no correlation with land use.

One key difference between Newnans Lake and Lake Weir arising from non-point source phosphorus estimates is that non-point sources are only about 1% of the total watershed exports from larger streams into Newnans Lake, but non-point inputs are essentially 100% of the exports for Lake Weir.

Although non-point phosphorus (TP) and stormwater loadings for Newnans Lake have increased over time, the overall increase is only 10% for TP and less than 2% for water between pre-development patterns and 1990 flows. The simulated TP loading and concomitant concentration values for the watershed appear to be stabilizing. Although only 4% of watershed area shifted from natural to developed between 1950 and 1990, this is an 86% increase in total developed area.

According to Vollenweider phosphorus loading models (Wetzel, 1983), input concentration values in post-development years would account for approximately 20ug/l of the observed lake chlorophyll concentrations. This level is considered within the eutrophic range (Wetzel, 1983), but is only about half of the long-term average (54 ug/l, Huber et al., 1982) between 1957 and 1980, and about 10% of 1993-1998 values (231 ug/l, Lakewatch, 1999).

For a lake with high levels of evaporation, the TP concentration of inflowing runoff might not be as important as the concentration remaining in the lake. In other words, using the ratio of non-point TP loading to the total lake volume as the concentration in Vollenweider loading equations accounts for close to 80 ug/l.

Lake Weir's simulation, on the other hand, while exhibiting a marked increase in overall runoff, shows a pronounced drop in TP loading between 1970 and 1990. This is directly due to conversion of citrus groves throughout the watershed to residential areas, resulting lower phosphorus deposition and increased impervious surfaces. The total watershed area in residential development in Weir's basin gained 8% during that period, while agricultural land use dropped by over 15 %of total watershed area.

According to Vollenweider TP loading models, input concentration values between 1950 and 1970 should have yielded chlorophyll concentrations of approximately 35ug/l. This is about six times the long-term average (6 ug/l, Huber et al., 1982) between 1956 and 1981. The 1990 simulated input concentration indicates a drop to 27 ug/L, or about twice 1991-1998 values (11 ug/L, Lakewatch, 1999).

Again, if phosphorus input is compared to total lake volume, rather than incoming concentration, a chlorophyll value closer to measured values results. A predicted value of less than 20ug/L is still higher than the observed 6 to 12 range from repeated water quality testing (Huber et al. 1982; Lakewatch 1999).

One very clear difference between the two watersheds emerges when simulated predevelopment material and emergy loads are compared to peak historical loading evaluated in this study – 1990 for Newnans and 1970 for Lake Weir. While Newnans TP loading is only 10% higher than estimated predevelopment loads, Weir's highest loading is more than two times higher than estimated baseline loading. A change of this magnitude might be expected to lead to a higher trophic status. Historical evidence suggests that Weir was originally oligotrophic (Kuntz, 1994), and current water quality data place it in the mesotrophic range (Lakewatch, 1999; Huber et al., 1982).

Emergy and Emergy per Mass Related to Lake Status

Emergy flows and the ratio of emergy flow to material inputs changed with time relative to changes in the lake. These changes were evaluated at three scales relevant to this study: total watershed inputs; watershed and atmospheric inputs to the lake; and at the individual material scales of water and TP.

The Watershed

Newnans Lake, with the larger watershed and high productivity, also had the highest emergy input to the watershed, both pre-development and post development. This is consistent with overall lake productivity and the level of concentrated development within the watershed.

Weir, having lost its agricultural base to a freeze, is now developing a concentration hierarchy similar to Newnans' watershed, with two main areas of high emergy convergence – the lake and a large residential development south of the lake. This may not impact productivity of the lake because, just as in Newnans, the second area of emergy concentration is outside the watershed area displaying highest export to the lake.

The Watershed-lake Interface

Water from runoff dominates the emergy flow to both lakes, and consequently, the emergy evaluation is not sensitive to changes in phosphorus input. Overall, emergy inflow to Newnans is not much different now than post-development. Weir, however, has doubled in emergy inputs. This suggests that Weir probably was originally at a lower trophic state than present, and that more influence to the lake is possible in this watershed. It further suggests that Newnans probably has always been eutrophic, but that non-point source inputs can still affect productivity.

Phosphorus

There are two key findings concerning phosphorus emergy in this study. Dilute phosphorus appears to have a lower emergy per mass limit of about 9E4 sej/g at a concentration of about 10 ppb. This is lower than the 9E9 sej/g ratio for oceanic upwelling phosphorus at a concentration of 50 ppb (Odum, 1996). Further, the average concentrated emergy per mass for both watersheds was very close to the ratio derived for the natural concentration of phosphate rock in Florida's wetlands - about 2E10 sej/g of phosphorus. However, this higher ratio had assistance from addition of phosphorus concentrated by industry.

Water

Use of actual soil capacity up to the first level of confinement for determining runoff is another difference between the current spatial model and most models, which use Soil Conservation Service (SCS) hydrological classifications (Adamus and Bergman , 1995; Heidtke and Auer, 1993). SCS classifications rank soils for ability to shed water, but they are neither a quantitative measure of capacity, nor an evaluation of sub-surface transport. Using the vertical distance to the confining layer may be acting as a transfer function for lateral subsurface flow, and the higher levels of water export predicted with this model may therefore be a measure of seepage. Quantity of seepage of this kind is an area of debate in Florida's sandy loamy watersheds (Deevey, 1992).

Sediments

Estimated sediment loading from Newnans watershed was higher than Lake Weir, with a higher estimated organic matter percent. The emergy use of sediments in

Newnans Lake is 1.4×10^{18}, and is 6.4×10^{16} in Lake Weir. However, sediment load is only a little more than 1% of Newnans Lake total emergy use, and a little less than 1% in Lake Weir.

Color from organic matter is an important component of function in Florida lakes (Crisman et al., 1999), and especially in Newnans Lake with high but variable observed color. This sediment simulation accounted only for average sediment loss based on soil type. This excludes an evaluation of the organic and humic acid contributions from surrounding cypress and hardwood wetlands.

Emdollars

Newnans Lake watershed contributes 73 million Em$/yr to the lake - about 8% of the total watershed real wealth. This equates to about 800 Em$ that each visitor receives when using Newnans Lake for recreation.

Lake Weir's watershed contributes 1.28 million Em$/yr to the lake - about 27% of the watershed total. This equates to about 5 Em$ that each visitor receives when using Lake Weir for recreational purposes. When Weir's watershed was dominated by citrus, the total Em$/yr for agricultural production was lower than the inputs to the lake — 1.23 million Em$ for citrus versus 1.28 million Em$ in the lake.

Use of Dynamic Simulations as Quality Indicators

Many schemes for assessing lake trophic state have been proposed (Carlson, 1977; Reckow, 1980; Huber et al., 1982). Most rely on long-term averages of several abiotic factors such as total nitrogen and phosphorus in the water column and algal biomass. Those using logarithm transformations to normalize data build in a resistance to fluctuations.

Simulations using the main trophic levels within the lake and normalized physical data available for each lake produced trophic state indices (TSI) comparable to those calculated for the same lakes using empirical data. Following addition of increased phosphorus, total biomass numbers (both autotrophs and heterotrophs) responded more quickly to the perturbation than TSI calculations. However, overall averages for both simulations reflected the change after an annual cycle.

Classification of Watersheds Using Material and Emergy Indices

Several numbers and ratios emerged as unique and discriminating values representative of water quality trends and watershed types. Newnans, with larger contributing area and hypereutrophic status, has 27 times more emergy use in its watershed than Weir. The average empower density for Newnans watershed is six times higher than Weir, and the emergy input to the lake is more than 10 times higher.

Similar differences were found in the resulting emergy per mass ratios for key elements in the lake's water column. Water ratios were 60 times higher in Newnans Lake than in Lake Weir and the TP ratio is 10 times higher. However, phytoplankton emergy per mass ratios were only different by a factor of three. Higher ratios for similar entities often mean that a less efficient process was used to create it. The high amount of watershed export used to create a much smaller volume in Newnans Lake may be an inefficient water storage process. The similar phytoplankton ratio may reflect the base amount of emergy inputs that algae have organized to use.

Observed recreational use for each lake was inversely proportional to emergy and water quality values. This is expected based on Americans' preference for clear recreational water. Fishing incidence was not separated from the total user incidence, and implications from accessibility differences between lakes were not considered.

Evidence for Watershed Intervention and Prioritization

Emergy values discussed in Chapter 1 are presented here in comparison to empirical water quality measures for each lake, both to provide a ranking for the overall watershed and the lakes and to assess the emergy required for organization within each watershed.

Intrawatershed Modification of Non-point Source Loading

Because of its spatial specificity, the water and phosphorus budget model can be used as a development planning tool. Several features make this spatial model different from its predecessors. It uses deposition and allows unique characteristics of each area to determine mass balance and export, as opposed to export coefficients averaged over several landscape and geology features (Adamus and Bergman , 1995; Heidtke and Auer, 1993). Further, it estimates total runoff that a given area will export to the lake. In other words, it does not estimate the amount leaving the cell, but rather the actual amount reaching the lake after additional infiltration occurs along the way. This allows identification of those areas contributing the greatest amount of runoff and directs attention to areas needing major remediation.

Two methods for siting intervention areas appeared effective in reducing overall simulated watershed phosphorus loads to lakes. Material convergence used drainage networks and the point of highest cumulative loads in the watershed to select areas for conversion to open ponds and high uptake wetlands. Emergy concentration was determined from cumulative emergy from phosphorus loads and the associated changing emergy per mass ratios.

Using the material export method to determine intervention siting in the watershed required less area than the emergy method. However, most of the remediation had to be in areas immediately adjacent to the lake. This required changes in zoning for lakefront property in order to be effective. Further, because this zone is subject to flooding during high water periods, the long-term benefit may be lost as material is transported to the lake. This interaction was not built into the model.

Cumulative emergy simulations identified areas exporting phosphorus at transformities considered inappropriate for each lake. When watershed areas with emergy per mass ratios for runoff phosphorus higher than the highest concentrated phosphorus deposited in the watershed were blocked, the resulting phosphorus load matched pre-development loads. The emergy method required that more watershed area be converted to intervention sites. However, most are small areas scattered throughout the watershed. This has the advantage of decreasing the burden on individual landowners, and organizes the watershed in a way closer to the distribution of smaller wetlands normally found in undisturbed watersheds.

Interwatershed Priorities

Decisions regarding allocation of funding for reclamation efforts among lakes can be assisted using the baseline parameters calculated in this study. A watershed either with baseline loading indicative of a highly productive lake or with watershed changes not resulting in large changes in loading may not be as responsive to in-lake or watershed remediation as one with lower baseline loading. Comparison of emergy values both pre and post-development suggests that Lake Weir would benefit more from remediation efforts.

Recommendations

Non-point Source Inputs

Regardless of the baseline level of lake productivity, non-point source phosphorus inputs will contribute to increasing eutrophication. Consequently, cessation of these inputs may eventually lead to a lower trophic state.

Phosphorus, unlike water, shows a much higher level of change with development, both in quantity and emergy transformity in both watersheds. Its influence would be expected to be substantial based on emergy values alone.

Lake Weir, without stream inputs, receives most of its water and nutrients as non-point input from the watershed. Consequently, the change in watershed loading has had a significant impact. Although Newnans receives 90% more phosphorus from its stream inputs than from the watershed, it is unlikely that the natural source of this input has changed significantly over time. Therefore, the lake has organized around this input, and changes in the smaller non-point source loads have likely contributed to the rising trophic state. This study does not determine conclusively whether in-lake resuspension or watershed loading is the dominant factor in shallow lake function.

Development Density

There is a different level of development in given areas of a watershed that will maintain desired trophic status of a lake, and can be viewed as the trophic carrying capacity for its individual watershed. Further, the lag time between changes in development and eventual changes in trophic state can be viewed as the turnover time for the entire lake.

The lake has organized around this level of inputs and will have a tendency to remain at that level until a certain level of change in its watershed is reached. However, the capacity cannot be given as a simple percentage of development, or at least cannot be determined with a study of only two lakes. Newnans, with 19.6% of the watershed developed, farmed or cleared in 1950 and 19.1% in 1990, has demonstrated an increase in eutrophication. Weir, with 80% cleared, farmed or developed by 1950 and 81% in 1990, experienced an anecdotal rise in eutrophication early in the century. However, between 1980 and now, the overall trophic state index of Lake Weir has dropped. Both of these water quality changes are in the opposite direction of development in the watershed, but they exhibit the same trend as simulated TP runoff. This would support the original hypothesis that watershed contributions to the lake are not solely dependent upon land use density, but rather are dependent on land use in a unique combination with soil and elevation.

Appropriate Scale for Stormwater Management

Water drainage to a lake is determined more by larger scale geologic patterns than by small developmental changes in a watershed. Consequently, stormwater should be managed at a watershed scale, not only at points of development.

This is supported by the low level of change in both overall quantity delivered to the lake and the transformity. Water effects changed less than 2% over the long term in both watersheds despite very different impervious surface development. This may not be true in highly urbanized watersheds, and the control that point-of entry may have on patchy phytoplankton populations is one area of spatial organization not addressed in this study.

Water management districts in Florida mandated on-site retention for stormwater in 1984 (Adamus and Bergman, 1995), and about 2% of Newnans' watershed was put into ponds between 1970 and 1990. However, as demonstrated in the model, stormwater runoff has continued to increase. This is due to the fact that the majority of the water increase is to the far northwest of the watershed and lies outside the effective watershed delineated in this study. The establishment of watershed retention mitigation banks would insure both fair representation from all developers and more effective intervention expenditures.

Use of Emergy as a Management Decision Tool

Comparison of pre-development to post-development emergy ratios of lake to watershed flows (or regional flows) suggests that priority for reclamation funds should be used for Lake Weir, if lower productivity in the lake is the primary cultural goal. If maximizing empower in the lake is a priority – maximizing protein or blue-green production for commercial purposes, for example – then current export of watershed emergy to the lake is a good strategy. However, holding rain and nutrients on land may maximize empower in the watershed leading to reduced trophic status in the lake and higher real wealth in a larger region.

Newnans phosphorus loading from the simulation of higher development is about 10% more than the baseline loading, while Lake Weir appears to be receiving 200% more phosphorus in this half of the century than prior to clearing and cultivation. Cessation of Weir's non-point source runoff, combined with higher depth, might be expected to lead to meaningful reductions in algal biomass and TP in the water column. Further, Newnans Lake emergy flow is about 8% of the total watershed emergy, while Lake Weir's emergy is almost 30% of its watershed flow.

Conclusion

This qualitative watershed time-series study lays the groundwork for reclamation science at a watershed scale, not in a restorative sense, but in creating new larger scale remediation patterns in response to development pressures. The synthesis of dynamic emergy created by geologic, natural and human patterns in the watershed is useful in demonstrating the strong connection between watersheds and Florida lakes, regardless of their depth.

Mapping phosphorus transformities results in a hierarchy of small and mid-sized areas of higher concentration that can be useful as retention areas on land, similar to the natural hierarchy of wetlands formed in many Florida watersheds. This is undoubtedly a modified network from a pre-development era, however it illustrates a way to incorporate the same ecological principles of spatial organization into watershed management.

This study raises some questions about adaptive system strategies at the watershed scale. If water and nutrients are retained on land at the points of emergy convergence, what will new total watershed productivity be? Is this higher than the productivity and emergy with current export to the lake? If increased fish protein (regardless of species) is a higher priority than clear water, would use of the fish at a watershed scale show that the current luxury loading of phosphorus to these systems is maximizing overall empower?

This study demonstrates that using only the annual loading of nutrients to a lake as a management criterion may overlook the effect of time lags in developing certain watershed areas. Annual loads may also minimize the effect of cumulative loads from increasing overland input, especially when channeled input is much larger.

Results support the concept of purchasing strategic areas for retroactive remediation, rather than putting all intervention efforts into on-site retention. Tracking the overland process by which runoff travels to the lake is an important management tool, and involves more than just the soil underlying the immediate contributing structure.

APPENDIX A
GIS INFORMATION

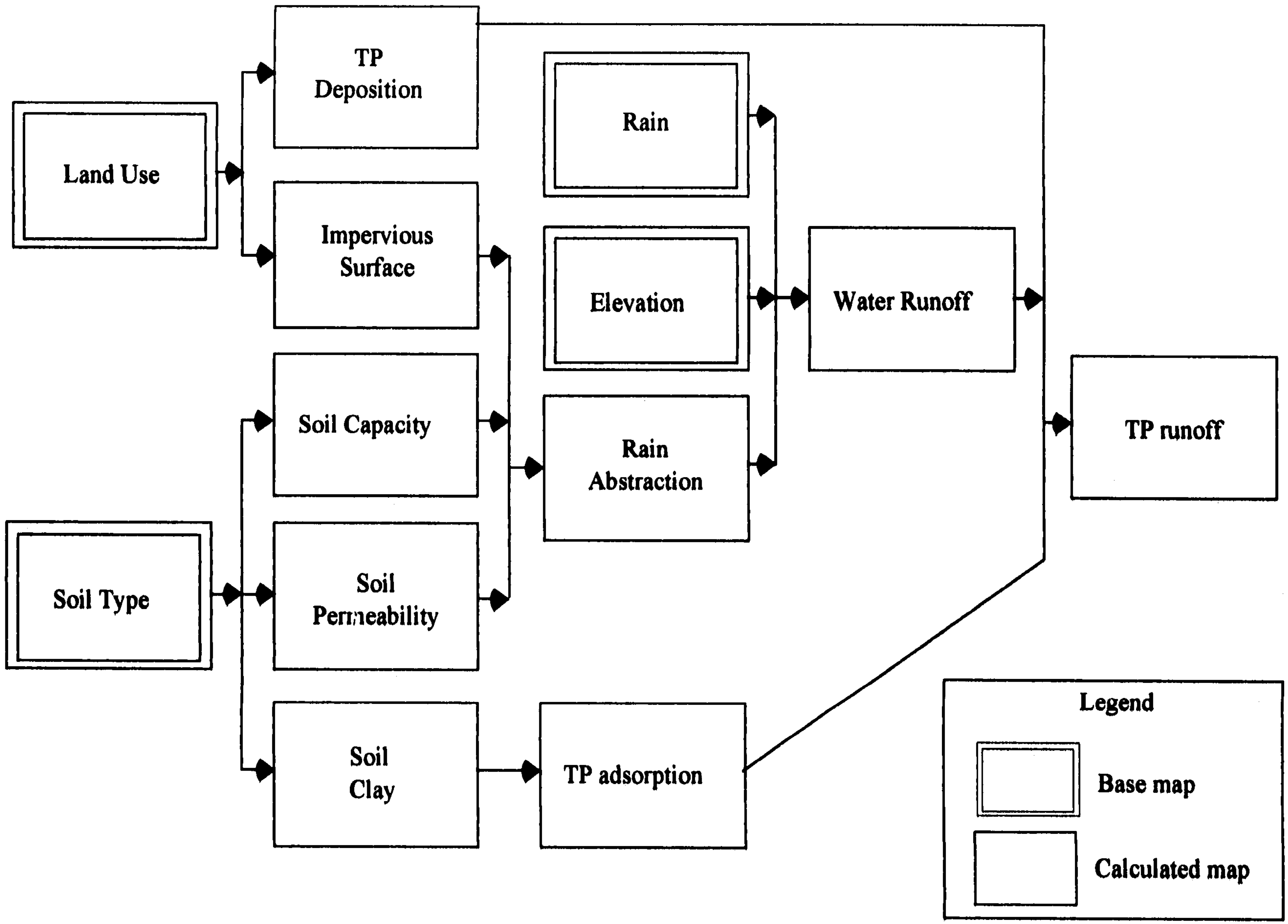


Figure A.1: A flow chart of the main steps in calculating the material balances around each cell.

APPENDIX B
SOIL DATA

Table B.1. Soil data, Newnans Lake.

Soil Name	Alachua Code	Hydrology	Depth to perm/capac change	Clay %	erosion K	organic %
Candler Fine Sand	2B, 2C, 47B	A	>82	<3	0.1	<1
Arredondo Fine Sand	3B, 3C, 4B	A	54	5 - 12	.1 - .24	<2
Ft. Meade f. sand, 0-5%	5B	A	>82	3 - 13	0.15	1-5
Apopka Sand	6B, 6C	A	61	0-.3	0.1	<2
Kanapaha sand, 0-5%	7B	D	44	2 -6	0.1	.5-4
Millhopper Sand	8B, 8C,9B, 45	A	64	2-8	0.1	.5-2
Riviera sand	11	D	32	1-6	0.1	.1-2
Pelham sand	13	D	27	1-8	0.1	1-2
Pomona sand	14, 25	D	43	1-6	0.1	1-2
Pompano Sand	15	D? (A)	>82	<5	0.1	1-5
Surrency sand	16	D	44	<10	0.1	1-15
Wauchula sand	17,18	D	28	<2	0.1	1-3
Monteocha loam sand	19	D	48	1-8	0.15	5-12
Tavares sand, 0-5%	20B	A	>82	0-4	0.1	.5-2
Newnan sand	21	C	59	<5	0.1	1-2
Floridana sand, depressional	22	D	30	3-10	0.1	6-15
Mulat sand	23	D	26	2-5	0.1	1-4
Samsula muck	26	D	35	0	0	>20
Urban	27					
Chipley sand	28	C?(A)	>82	1-5	0.1	2-5
Lochloosa f. sand	29B, 29C	C	35	2-12	0.1	1-4
Kendrick sand	30B, 30C	A	24	1-7	0.1	<2
Blichton sand	31A, B, C,44B	D	30	2-12	0.15	1-4
Bivans sand	32B,C,D	D	10	3-12	0.1	1-4
Norfolk loamy f. Sand	33B, C	B	9	2-8	0.2	.5-2
Placid sand, depressional	34	D?(A)	>82	<10	0.1	2-10
Gainesville sand	35B, C	A	>82	4-10	0.15	2-4
Arrents, 0-5%	36					

Table B.1 continued

Soil Name	Alachua Code	Hydrology	Depth to perm/capac change	Clay %	erosion K	organic %
Zolfo sand	37	C	60	1-5	0.1	.5-1
pits & dumps	38					
Bonneau f. sand, 2-5%	39B	A	29	2-8	0.15	.5-2
Pedro f. sand, 0-5%	41B	C	-	1-5	0.1	.5-2
Pedro-Jonesville, 0-5%	42B	B	29	1-5	0.1	.5-2
Jonesville-Cadillac-Bonneau, 0-5%	46B	A	29	2-8	0.1	.5-2
Myakka sand	48	D	24	<2	0.1	<2
Lochloosa f.sand, 0-2%	49A	C	44	2-12	0.1	1-4
Sparr f. sand	50	C	48	1-5	0.1	<3
Plummer f. sand	51	D	42	1-7	0.1	1-3
Ledwith muck	52	D	17	0	0	30-90
Shenks muck	53	D	21	0	0	>20
Emerelda f. sandy loam	54	D	18	6-12	0.15	3-10
Lake sand, 0-5%	55B,58B	A	>82	1-3	0.1	.5-1
Wauberg sand	56	D	24	1-12	0.15	1-4
Micanopy loamy f. sand, 2-5%	57B	C	12	0-12	0.15	1-5
Pottsburg sand	59	D	52	<5	0.1	<3
Udorthents, 0-2%	60	C	0	2-8	0.32	.5-2
Oleno clay, occ. flooded	61	D	0	46-85	0.37	1-3
Boardman loamy sand, 5-8%	62C	D	14	1-10	0.15	<1
Terra Ceia muck	63	D	>68	0	0	>60
Okkechobee muck	64	D	>80	0	0	>60
Martel sandy clay loam	65	D	16	15-35	0.32	1-6
Lynne sand	66	D	29	1-5	0.1	1-5
Wacahoota laomy sand, 5-8%	67C	D	32	1-10	0.15	2-4

Table B.2. Hydrologic capacity data.

Hydrologic Grouping	Permeability Range in/hr	Capacity Range in/in
A	6 - 20	.02-.17
B	6 - 20	
C	.2-20	
D	.02-20	.03-.4

Table B.3. Determination of impedance to water transport through spatial cells

Alachua Code	% infiltrate[1] 2 Yr Storm	% infiltrate[2] 100 Yr Storm	% capacity[3] 2 Yr Storm	% capacity[4] 100 Yr Storm	confining layer[5] Y/N	Impedance Factor[6] 2 Yr Storm	Impedance Factor[7] 100 Yr Storm
2B, 2C, 47B	100	100	67	48	N	0.67	0,48
3B, 3C, 4B	100	100	82	58	Y	0,82	0,58
5B	100	100	100	100	N	1,00	1,00
6B, 6C	100	100	61	43	Y	0,61	0,43
7B	67	47	44	31	Y	0,29	0,15
8B, 8C,9B, 45	100	100	97	69	Y	0,97	0,69
11	100	100	53	37	Y	0,53	0,37
13	100	100	36	25	Y	0,36	0,25
14, 25	100	100	19	13	Y	0,19	0,13
15	100	100	100	100	N	1,00	1,00
16	67	47	79	56	Y	0,53	0,26
17,18	67	47	25	18	Y	0,17	0,09
19	67	47	60	42	Y	0,40	0,20
20B	100	100	100	100	N	1,00	1,00
21	67	47	21	15	Y	0,14	0,07
22	100	100	73	52	Y	0,73	0,52
23	67	47	87	61	Y	0,58	0,29
26	100	100	100	100	Y	1,00	1,00
27	20	14			Y	0,20	0,14
28	100	100	100	100	N	1,00	1,00
29B, 29C	67	47	52	36	Y	0,35	0,17
30B, 30C	100	100	43	31	Y	0,43	0,31
31A, B, C,44B	100	100	40	28	Y	0,40	0,28
32B,C,D	20	14	50	35	Y	0,10	0,05
33B, C	67	47	18	13	Y	0,12	0,06
34	100	100	100	100	N	1,00	1,00
35B, C	100	100	100	100	N	1,00	1,00
36	20	14			Y	0,20	0,14

Table B.3 continued

Alachua Code	% infiltrate[1] 2 Yr Storm	% infiltrate[2] 100 Yr Storm	% capacity[3] 2 Yr Storm	% capacity[4] 100 Yr Storm	confining layer[5] Y/N	Impedance Factor[6] 2 Yr Storm	Impedance Factor[7] 100 Yr Storm
37	100	100	100	93	Y	1.00	0.93
38	100	100			Y	1.00	1.00
39B	67	47	39	27	Y	0.26	0.13
41B	100	100	36	25	Y	0.36	0.25
42B	100	100	36	25	Y	0.36	0.25
46B	100	100	39	27	Y	0.39	0.27
48	100	100	16	11	Y	0.16	0.11
49A	67	47	57	40	Y	0.38	0.19
50	100	100	88	62	Y	0.88	0.62
51	67	47	42	30	Y	0.28	0.14
52	20	14	75	53	Y	0.15	0.07
53	100	100	100	100	Y	1.00	1.00
54	100	100	63	45	Y	0.63	0.45
55B,58B	100	100	100	100	N	1.00	1.00
56	100	100	30	21	Y	0.30	0.21
57B	20	14	30	21	Y	0.06	0.03
59	100	100	52	37	Y	0.52	0.37
60	2	1	100	100	Y	0.02	0.01
61	2	1	100	100	Y	0.02	0.01
62C	20	14	23	16	Y	0.05	0.02
63	100	100	100	100	N	1.00	1.00
64	100	100	100	100	N	1.00	1.00
65	20	14	80	56	Y	0.16	0.08
66	100	100	28	20	Y	0.28	0.20
67C	100	100	60	43	Y	0.60	0.43

1. The percentage of the average rain intensity in the first hour of a two year event that infiltrates based only on permeability.
2. The percentage of the average rain intensity in the first hour of a 100 year event that infiltrates based only on permeability.

Table B.3 continued

3. The percentage of the average rain intensity in the first hour of a two year event that could be contained based only on capacity.
4. The percentage of the average rain intensity in the first hour of a 100 year event that could be contained based only on capacity.
5. A layer is considered confining if permeability drops below 0.2in/hr
6. Fraction in column one multiplied by fraction in column three.
7. Fraction in column two multiplied by fraction in column four.

APPENDIX C
VERIFICATION OF SPATIAL MODEL

A pilot study evaluating the relationship between non-point source phosphorus runoff and phytoplankton productivity and populations in lakes was conducted in 1995 as a project for a graduate GIS class in the Department of Environmental Engineering Sciences, University of Florida. The abstract for this project is presented below.

For further verification of the spatial simulation values, runoff for each watershed was estimated using the SCS Abstraction Method. Newnans Lake simulations are within 8% of SCS estimates (Table C.1). Lake Weir simulations result are approximately twice the SCS estimates (Table C.2).

Land Use Analysis of Potential Non-point Source Phosphate Runoff into Seven Eutrophic Florida Lakes Using a Geographical Information System

This project is a preliminary evaluation of the methods best suited for detailed GIS analysis of spatial factors affecting nutrient availability within a watershed, the probability of these nutrients reaching the lake and the correlation of predicted phosphate loading with measures of phytoplankton present within the lake. For the sake of initial simplification, the scope of this study has been limited to estimated phosphate runoff from aggregated categories of human land use. Seven eutrophic lakes receiving sewage input in central Florida were analyzed using MapII, a GIS software application for the Macintosh. Land use, soils, elevation and rainfall were the base maps for runoff estimation. Regressing the number of taxa versus combined amounts of developed areas resulted in a significant but negative relationship ($r^2 = 0.7439$). One month load using rainfall from the month immediately prior to collection of data showed a significant and positive correlation with chlorophyll concentrations ($r^2 = 0.946$). Annual loads regressed versus Huber et al. (1982) trophic state indices also resulted in a significant and positive correlation ($r^2 = 0.725$). Regression of land use alone did not show a correlation with either chlorophyll or trophic state indices. Point-source TP loadings did not correlate with trophic state indices, either.

Table C.1. Soil Conservation Service abstraction method calculations to determine expected runoff, Newnans Lake.

	Hydrologic Soil Group											
		A			B			C			D	
Land Use	%	CN	Product	%	CN	Product	%	CN	Product	%	CN	Product
Cultivated	0.12	72	8.62	0.00	81	0.00	0.22	88	19.55	0.03	91	2.57
Range	4.98	68	338.77	0.01	79	0.57	3.15	86	270.90	7.19	89	640.06
Forest	7.96	35	278.63	0.00	60	0.09	14.35	75	1076.31	42.94	80	3435.17
Commercial, Urban	1.38	89	122.86	0.00	92	0.00	0.29	94	27.44	0.33	95	31.12
Industrial	0.01	81	0.48	0.00	88	0.00	0.00	91	0.00	0.02	93	1.45
Residential	0.86	51	43.81	0.00	68	0.01	0.22	79	17.49	0.66	84	55.67
Pavement		95	0.00		95	0.00		95	0.00		95	0.00
Herb WL	0.06	30	1.93	0.00	58	0.00	0.15	71	10.45	0.48	78	37.80
Forest WL	0.47	25	11.84	0.00	55	0.00	1.31	70	91.91	12.80	77	985.51
	15.85		806.93	0.01		0.67	19.70		1514.06	64.45		5189.34

Summary Calculations		
Weighted CN =	75.11	
S=	3.31	in
Pe =	0.66	in
Tpe=	13.63	in
Runoff=	2.0E+08	m^3
Total Rain=	7.7E+08	
% Runoff	26.2%	

* All storm events are considered to be typical 2 year one hour events for the region. The total average rain for the year is divided by this number to determine the number of storm events, and is used to determine Tpe.

Table C.2. Soil Conservation Service abstraction method calculations to determine expected runoff, Lake Weir.

	Hydrologic Soil Group											
		A			B			C			D	
Land Use	%	CN	Product	%	CN	Product	%	CN	Product	%	CN	Product
Cultivated	19.50	72	1403.83	0.00	81	0.13	0.63	88	55.62	0.12	91	10.95
Range	55.39	68	3766.54	0.06	79	4.66	2.37	86	203.79	0.77	89	68.61
Forest	12.20	35	426.99	0.01	60	0.71	0.95	75	71.49	1.01	80	80.53
Commercial, Urban	0.01	89	1.09	0.00	92	0.00	0.00	94	0.00	0.00	95	0.00
Industrial	0.00	81	0.00	0.00	88	0.00	0.00	91	0.00	0.00	93	0.00
Residential	2.57	51	131.28	0.01	68	0.40	0.40	79	31.23	0.29	84	24.01
Pavement	1.17	95	110.76	0.00	95	0.00	0.07	95	6.83	0.05	95	4.64
Herb WL	0.34	30	10.07	0.00	58	0.00	0.13	71	9.22	0.93	78	72.37
Forest WL	0.12	25	3.05	0.00	55	0.00	0.05	70	3.23	0.86	77	66.34
			5853.60			5.91			381.42			327.45

Summary Calculations		
Weighted CN =	65.68	
S=	5.22	in
Pe =	0.32	in
Tpe=*	6.59	in
Runoff=	2.0E+07	m3
Total Rain=	1.6E+08	m3
% Runoff	12.68%	

* All storm events are considered to be typical 2 year one hour events for the region. The total average rain for the year is divided by this number to determine the number of storm events, and is used to determine Tpe.

APPENDIX D
EMPOWER DENSITY EVALUATIONS

Table D.1. Emergy evaluation of Bahia pasture, per ha per year.

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E13 sej/yr)	Em$ Value (1989 $/yr)
RENEWABLE RESOURCES						
1	Sun	J	5.93E+13	1	6	36
2	Rain	J	6.30E+10	1.80E+04	113	696
3	Et	J	5.43E+10	1.54E+04	84	513
NONRENEWABLE STORAGES						
4	Net Topsoil Loss	J	6.33E+07	7.38E+04	0	2
	Sum of free inputs (sun, rain omitted)				84	516
PURCHASED INPUTS						
Operational inputs						
5	Fuel	J	2.82E+06	6.60E+04	0	0
6	Electricity	J	2.22E+08	1.60E+05	4	22
7	Potash	g K	3.63E+04	1.10E+09	4	25
8	Lime	g	3.73E+05	1.00E+09	37	229
9	Pesticides	g	0.00E+00	1.50E+10	0	0
10	Phosphate	g P	7.38E+03	2.20E+10	16	100
11	Nitrogen	g N	1.55E+04	2.41E+10	37	229
12	Labor	J	6.79E+06	8.10E+04	0	0
13	Services	$	2.24E+01	1.63E+12	4	22
	Sum of purchased inputs				102	626
TRANSFORMITIES						
14	Total Yield, dry	g	3.63E+06	5.12E+08	186	1142
15		J	6.88E+10	2.71E+04		

Indices

Note	Name of Index	Expression	Quantity
16	Investment Ratio	(P + S)/(N + R)	1.2
17	Yield Ratio	Y/(P + S)	1.82
18	Emergy exchange ratio	Y/$ * (SEJ/$)	NA
19	Emdollar Contribution to State	(ha in production)*(Y/ha)/(SEJ/$)	5.98E+08
20	Nonrenewable/Renewable	(N + P)/R	1.2
21	Empower Density	sej/ha/yr	1.86E+15

Table D.1 - continued

Notes, Table D.1

1	**Sun, J**			
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
	Insolation:	6.90E+09	J/m2/yr	(Vishner 1954)
	Area:	1.00E+04	m2	
	Albedo:	0.14	Odum 1987)	
	Annual energy:	5.93E+13		
2	**Rain, J**			
	Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m3)(4.94J/g)(1 - runoff)		
	in/yr:	54		
	Area, m2:	10000		
	runoff coefficient:	7.00E-02	(AFSIRS estimate, Smajstrla, 1990)	
	Annual energy:	6.3E+10		
3	**Evapotranspiration, J**			
	Annual energy =	(J/acre)(2.47acre/ha)(area)		
	J/acre:	2.20E+10	(AFSIRS estimate, Smajstrla, 1990)	
	Area, ha:	1		
	Annual energy:	5.43E+10		
4	**Net Topsoil Loss, J**			
	Erosion rate =	7	g/m2/yr	[estim. from Pimentel et al., 1995]
	% organic in soil =	0.04		[Pimentel et al., 1995, p.1118]
	Energy cont./g organic	5.40	kcal/g	
	Net loss of topsoil = (farmed area)(erosion rate)			
	Organic matter in topsoil used up= (total mass of topsoil)(% organic)			
	Energy loss= (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)			
	Annual energy:	6.33E+07		
5	**Fuel, J per ha** (includes diesel, gasoline, lubricants)			
	(gallons fuel) * (1.51E5 J/gal)			
	Gallons:	1.87E+01	FAECM data (Fluck, 1992)	
	Annual energy:	2.82E+06		
6	**Electricity, J**			
	KWh*3.6E6 J/KWh			
	KWh:	6.15E+01	FAECM data (Fluck, 1992)	
	Annual energy:	2.22E+08		
7	**Potash, g K per ha**			
	(g fertilizer active ingredient)(78 gmol K/94 gmol K2O)			
	g:	4.38E+04	FAECM data (Fluck, 1992)	
	Annual consumption:	3.63E+04		
8	**Lime, g per ha**			
	Annual consumption, .	3.73E+05	FAECM data (Fluck, 1992)	
9	**Pesticides, g per ha** (includes pesticides, fungicides, herbicides)			

Table D.1 - continued

	Annual consumption,	0.00E+00	FAECM data (Fluck, 1992)
10	**Phosphate, g P per ha**		
	(g fertilizer active ingredient)(31 gmol P/132 gmol DAP)		
	g:	3.14E+04	FAECM data (Fluck, 1992)
	Annual consumption:	7.38E+03	
11	**Nitrogen, g N per ha**		
	(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)		
	g:	7.29E+04	FAECM data (Fluck, 1992)
	Annual consumption:	1.55E+04	
12	**Labor, J**		
	(pers-hours/ha/yr)*(3500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)		
	pers-hours:	3.71E+00	FAECM data (Fluck, 1992)
	Annual energy:	6.79E+06	
	Transformity:	8.10E+04	(uneducated labor,Odum and Odum 1983)
13	**Services, $ per ha**		
	$/yr:	2.24E+01	FAECM data (Fluck, 1992)
	Annual emergy	($ /yr)(sej/$)	
14	**Yield** - 3240 lb dry/acre		FAECM data (Fluck, 1992)
	Dry weight =	3.63E+06 g	
15	**Product in Joules**		
	18% protein, 3% fat, 79% carbohy (Pillsbury, 1993)		
	Energy content =	6.88E+10 J	
16	**Investment Ratio**		
	P = Items 5 + 6 + 7 + 8 + 9 + 10 + 11		
	S= Items 12 + 13		
	N= Item 4		
	R = Item 3		
17	**Yield Ratio**		
	Y = Items 3 + 4 + 5 + 6 + 7 + 8 + 9 + 10 + 11 + 12 + 13		
18	**Emergy exchange ratio** - NA		FAECM data (Fluck, 1992)
	$, total/ha =	NA	
19	**Emdollar Contribution to State**		
	ha in production:	5.23E+05	FAECM data (Fluck, 1992)
20	**Nonrenewable/Renewable,**		
	See Note 16		
21	**Empower Density** - sum of emergy per hectare per year		

Table D.2. Emergy Evaluation of Oranges, per ha per year.

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E13 sej/yr)	Em$ Value (1984 $/yr)
RENEWABLE RESOURCES						
1	Sun	J	5.93E+13	1	6	25
2	Rain	J	6.30E+10	1.80E+04	113	473
3	Et	J	6.51E+10	1.54E+04	100	418
NONRENEWABLE STORAGES						
4	Net Topsoil Loss	J	6.33E+08	7.38E+04	5	21
	Sum of free inputs (sun, rain omitted)				105	439
PURCHASED INPUTS						
Operational inputs						
5	Fuel	J	2.28E+07	6.60E+04	0	1
6	Electricity	J	4.68E+08	1.60E+05	7	31
7	Potash	g K	2.36E+05	1.10E+09	26	108
8	Lime	g	2.40E+05	1.00E+09	24	100
9	Pesticides	g	1.79E+04	1.50E+10	27	112
10	Phosphate	g P	1.12E+04	2.20E+10	25	103
11	Nitrogen	g N	3.01E+04	2.41E+10	73	302
12	Labor	J	3.79E+08	8.10E+04	3	13
13	Services	$	3.01E+02	2.40E+12	72	301
	Sum of purchased inputs				257	1071
TRANSFORMITIES						
14	Total Yield, dry	g	4.91E+06	7.37E+08	362	1510
15		J	8.65E+10	4.19E+04		

Indices

Note	Name of Index	Expression	Quantity
16	Investment Ratio	(P + S)/(N + R)	2
17	Yield Ratio	Y/(P + S)	1.41
18	Emergy exchange ratio	Y/$ * (SEJ/$)	0.3
19	Emdollar Contribution to State	(ha in production)*(Y/ha)/(SEJ/$)	3.39E+08
20	Nonrenewable/Renewable	(N + P)/R	2
21	Empower Density	sej/ha/yr	3.62E+15

Table D.2 - continued

Notes, Table D.2

1	**Sun, J**		
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)	
	Insolation:	6.90E+09 J/m2/yr	(Vishner 1954)
	Area:	1.00E+04 m2	
	Albedo:	0.14 Odum 1987)	
	Annual energy:	5.93E+13	
2	**Rain, J**		
	Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m3)(4.94J/g)(1 - runoff)	
	in/yr:	54	
	Area, m2:	10000	
	runoff coefficient:	7.00E-02 (AFSIRS estimate, Smajstrla, 1990)	
	Annual energy:	6.3E+10	
3	**Evapotranspiration, J**		
	Annual energy =	(J/acre)(2.47acre/ha)(area)	
	J/acre:	2.63E+10 (AFSIRS estimate, Smajstrla, 1990)	
	Area, ha:	1	
	Annual energy:	6.51E+10	
4	**Net Topsoil Loss, J**		
	Erosion rate =	70 g/m2/yr	[estim. from Pimentel et al., 1995]
	% organic in soil =	0.04	[Pimentel et al., 1995, p.1118]
	Energy cont./g organic	5.40 kcal/g	
	Net loss of topsoil = (farmed area)(erosion rate)		
	Organic matter in topsoil used up= (total mass of topsoil)(% organic)		
	Energy loss= (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)		
	Annual energy:	6.33E+08	
5	**Fuel, J per ha** (includes diesel, gasoline, lubricants)		
	(gallons fuel) * (1.51E5 J/gal)		
	Gallons:	1.51E+02 FAECM data (Fluck, 1992)	
	Annual energy:	2.28E+07	
6	**Electricity, J**		
	KWh*3.6E6 J/KWh		
	KWh:	1.30E+02 FAECM data (Fluck, 1992)	
	Annual energy:	4.68E+08	
7	**Potash, g K per ha**		
	(g fertilizer active ingredient)(78 gmol K/94 gmol K2O)		
	g:	2.84E+05 FAECM data (Fluck, 1992)	
	Annual consumption:	2.36E+05	
8	**Lime, g per ha**		
	Annual consumption, .	2.40E+05 FAECM data (Fluck, 1992)	
9	**Pesticides, g per ha** (includes pesticides, fungicides, herbicides)		

Table D.2 - continued

	Annual consumption, .	1.79E+04	FAECM data (Fluck, 1992)	
10	**Phosphate, g P per ha**			
	(g fertilizer active ingredient)(31 gmol P/132 gmol DAP)			
	g:	4.79E+04	FAECM data (Fluck, 1992)	
	Annual consumption:	1.12E+04		
11	**Nitrogen, g N per ha**			
	(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)			
	g:	1.42E+05	FAECM data (Fluck, 1992)	
	Annual consumption:	3.01E+04		
12	**Labor, J**			
	(pers-hours/ha/yr)*(3500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)			
	pers-hours:	2.07E+02	FAECM data (Fluck, 1992)	
	Annual energy:	3.79E+08		
	Transformity:	8.10E+04	(uneducated labor,Odum and Odum 1983)	
13	**Services, $ per ha**			
	$/yr:	3.01E+02	FAECM data (Fluck, 1992)	
	Annual emergy	($ /yr)(sej/$)		
14	**Yield** - 4378.5 lb dry/acre	FAECM data (Fluck, 1992)		
	Dry weight =	4.91E+06	g/ha	
15	**Product in Joules**			
	8.6% protein, 91.4% carbohydrate (Paul and Southgate, 1978)			
	Energy content =	8.65E+10	J	
16	**Investment Ratio**			
	P = Items 5 + 6 + 7 + 8 + 9 + 10 + 11			
	S= Items 12 + 13			
	N= Item 4			
	R = Item 3			
17	**Yield Ratio**			
	Y = Items 3 + 4 + 5 + 6 + 7 + 8 + 9 + 10 + 11 + 12 + 13			
18	**Emergy exchange ra**	1984	$1750/acre	FAECM data (Fluck, 1992)
			$, total/ha =	4.32E+03
		1994	$0.22/lb fresh	(est. from FL Statistical Abstract 1994)
			$, total/ha =	3.67E+03
19	**Emdollar Contribution to State**			
	1984 ha in production:	2.25E+05	FAECM data (Fluck, 1992)	
	1994 ha in production:	2.07E+05	FL Statistical Abstract 1994	
20	**Nonrenewable/Renewable,**			
	See Note 16			
21	**Empower Density** - sum of emergy per hectare per year			

Table D.3. Emergy evaluation of pecans, per ha per year.

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E13 sej/yr)	Em$ Value (1989 $/yr)
RENEWABLE RESOURCES						
1	Sun	J	5.93E+13	1	6	36
2	Rain	J	6.30E+10	1.80E+04	113	696
3	Et	J	6.50E+10	1.54E+04	100	614
NONRENEWABLE STORAGES						
4	Net Topsoil Loss	J	6.33E+08	7.38E+04	5	21
	Sum of free inputs (sun, rain omitted)				105	635
PURCHASED INPUTS						
Operational inputs						
5	Fuel	J	1.51E+07	6.60E+04	0	1
6	Electricity	J	2.96E+08	1.60E+05	5	29
7	Potash	g K	7.45E+04	1.10E+09	8	50
8	Lime	g	3.73E+05	1.00E+09	37	229
9	Pesticides	g	7.20E+03	1.50E+10	11	66
10	Phosphate	g P	2.11E+04	2.20E+10	46	284
11	Nitrogen	g N	4.88E+04	2.41E+10	118	721
12	Labor	J	6.34E+07	8.10E+04	1	3
13	Services	$	2.11E+03	1.63E+12	344	2111
	Sum of purchased inputs				570	3495
TRANSFORMITIES						
14	Total Yield, dry	g	NA		674	4130
15		J	NA			

Indices

Note	Name of Index	Expression	Quantity
16	Investment Ratio	(P + S)/(N + R)	5
17	Yield Ratio	Y/(P + S)	1.18
18	Emergy exchange ratio	Y/$ * (SEJ/$)	NA
19	Emdollar Contribution to State	(ha in production)*(Y/ha)/(SEJ/$)	2.01E+07
20	Nonrenewable/Renewable	(N + P)/R	2
21	Empower Density	sej/ha/yr	6.74E+15

Table D.3 - continued

Notes, Table D.3

1	**Sun, J**		
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)	
	Insolation:	6.90E+09 J/m2/yr	(Vishner 1954)
	Area:	1.00E+04 m2	
	Albedo:	0.14 Odum 1987)	
	Annual energy:	5.93E+13	
2	**Rain, J**		
	Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m3)(4.94J/g)(1 - runoff)	
	in/yr:	54	
	Area, m2:	10000	
	runoff coefficient:	7.00E-02 (AFSIRS estimate, Smajstrla, 1990)	
	Annual energy:	6.3E+10	
3	**Evapotranspiration, J**		
	Annual energy =	(J/acre)(2.47acre/ha)(area)	
	J/acre:	2.63E+10 (AFSIRS estimate, Smajstrla, 1990)	
	Area, ha:	1	
	Annual energy:	6.50E+10	
4	**Net Topsoil Loss, J**		
	Erosion rate =	70 g/m2/yr	[estim. from Pimentel et al., 1995]
	% organic in soil =	0.04	[Pimentel et al., 1995, p.1118]
	Energy cont./g organic	5.40 kcal/g	
	Net loss of topsoil = (farmed area)(erosion rate)		
	Organic matter in topsoil used up= (total mass of topsoil)(% organic)		
	Energy loss= (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)		
	Annual energy:	6.33E+08	
5	**Fuel, J per ha** (includes diesel, gasoline, lubricants)		
	(gallons fuel) * (1.51E5 J/gal)		
	Gallons:	9.97E+01 FAECM data (Fluck, 1992)	
	Annual energy:	1.51E+07	
6	**Electricity, J**		
	KWh*3.6E6 J/KWh		
	KWh:	8.21E+01 FAECM data (Fluck, 1992)	
	Annual energy:	2.96E+08	
7	**Potash, g K per ha**		
	(g fertilizer active ingredient)(78 gmol K/94 gmol K2O)		
	g:	8.97E+04 FAECM data (Fluck, 1992)	
	Annual consumption:	7.45E+04	
8	**Lime, g per ha**		
	Annual consumption,.	3.73E+05 FAECM data (Fluck, 1992)	
9	**Pesticides, g per ha** (includes pesticides, fungicides, herbicides)		

Table D.3 - continued

	Annual consumption, .	7.20E+03	FAECM data (Fluck, 1992)
10	**Phosphate, g P per ha**		
	(g fertilizer active ingredient)(31 gmol P/132 gmol DAP)		
	g:	8.97E+04	FAECM data (Fluck, 1992)
	Annual consumption:	2.11E+04	
11	**Nitrogen, g N per ha**		
	(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)		
	g:	2.30E+05	FAECM data (Fluck, 1992)
	Annual consumption:	4.88E+04	
12	**Labor, J**		
	(pers-hours/ha/yr)*(3500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)		
	pers-hours:	3.46E+01	FAECM data (Fluck, 1992)
	Annual energy:	6.34E+07	
	Transformity:	8.10E+04	(uneducated labor,Odum and Odum 1983)
13	**Services, $ per ha**		
	$/yr:	2.11E+03	FAECM data (Fluck, 1992)
	Annual emergy	($ /yr)(sej/$)	
14	**Yield -**		
	Dry weight =	g	
15	**Product in Joules**		
	Energy content =	J	
16	**Investment Ratio**		
	P = Items 5 + 6 + 7 + 8 + 9 + 10 + 11		
	S= Items 12 + 13		
	N= Item 4		
	R = Item 3		
17	**Yield Ratio**		
	Y = Items 3 + 4 + 5 + 6 + 7 + 8 + 9 + 10 + 11 + 12 + 13		
18	**Emergy exchange ratio -**		FAECM data (Fluck, 1992)
	$, total/ha =		
19	**Emdollar Contribution to State**		
	ha in production:	4.85E+03	FAECM data (Fluck, 1992)
20	**Nonrenewable/Renewable,**		
	See Note 16		
21	**Empower Density** - sum of emergy per hectare per year		

Table D.4. Emergy evaluation of soybeans, per ha per year.

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E13 sej/yr)	Em$ Value (1989 $/yr)
RENEWABLE RESOURCES						
1	Sun	J	5.93E+13	1	6	36
2	Rain	J	6.30E+10	1.80E+04	113	696
3	Et	J	6.15E+10	1.54E+04	95	581
NONRENEWABLE STORAGES						
4	Net Topsoil Loss	J	1.81E+07	7.38E+04	0	1
	Sum of free inputs (sun, rain omitted)				95	581
PURCHASED INPUTS						
Operational inputs						
5	Fuel	J	7.01E+06	6.60E+04	0	0
6	Electricity	J	2.97E+08	1.60E+05	5	29
7	Potash	g K	3.73E+04	1.10E+09	4	25
8	Lime	g	3.72E+05	1.00E+09	37	228
9	Pesticides	g	7.07E+02	1.50E+10	1	7
10	Phosphate	g P	1.05E+04	2.20E+10	23	142
11	Nitrogen	g N	2.38E+03	2.41E+10	6	35
12	Labor	J	1.03E+07	8.10E+04	0	1
13	Services	$	1.48E+02	1.63E+12	24	148
	Sum of purchased inputs				100	615
TRANSFORMITIES						
14	Total Yield, dry	g	4.04E+05	4.83E+09	195	1197
15		J	9.86E+09	1.98E+05		

Indices

Note	Name of Index	Expression	Quantity
16	Investment Ratio	(P + S)/(N + R)	1
17	Yield Ratio	Y/(P + S)	1.95
18	Emergy exchange ratio	Y/$ * (SEJ/$)	4.1
19	Emdollar Contribution to State	(ha in production)*(Y/ha)/(SEJ/$)	3.87E+07
20	Nonrenewable/Renewable	(N + P)/R	1
21	Empower Density	sej/ha/yr	1.95E+15

Table D.4 - continued

Notes, Table D.4

1	**Sun, J**			
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
	Insolation:	6.90E+09	J/m2/yr	(Vishner 1954)
	Area:	1.00E+04	m2	
	Albedo:	0.14	Odum 1987)	
	Annual energy:	5.93E+13		
2	**Rain, J**			
	Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m3)(4.94J/g)(1 - runoff)		
	in/yr:	54		
	Area, m2:	10000		
	runoff coefficient:	7.00E-02	(AFSIRS estimate, Smajstrla, 1990)	
	Annual energy:	6.3E+10		
3	**Evapotranspiration, J**			
	Annual energy =	(J/acre)(2.47acre/ha)(area)		
	J/acre:	2.49E+10	(AFSIRS estimate, Smajstrla, 1990)	
	Area, ha:	1		
	Annual energy:	6.15E+10		
4	**Net Topsoil Loss, J**			
	Erosion rate =	2	g/m2/yr	[estim. from Pimentel et al., 1995]
	% organic in soil =	0.04		[Pimentel et al., 1995, p.1118]
	Energy cont./g organic	5.40	kcal/g	
	Net loss of topsoil = (farmed area)(erosion rate)			
	Organic matter in topsoil used up= (total mass of topsoil)(% organic)			
	Energy loss= (loss of organic matter)(5.4 kcal/g)(4186 J/kcal)			
	Annual energy:	1.81E+07		
5	**Fuel, J per ha** (includes diesel, gasoline, lubricants)			
	(gallons fuel) * (1.51E5 J/gal)			
	Gallons:	4.65E+01	FAECM data (Fluck, 1992)	
	Annual energy:	7.01E+06		
6	**Electricity, J**			
	KWh*3.6E6 J/KWh			
	KWh:	8.25E+01	FAECM data (Fluck, 1992)	
	Annual energy:	2.97E+08		
7	**Potash, g K per ha**			
	(g fertilizer active ingredient)(78 gmol K/94 gmol K2O)			
	g:	4.49E+04	FAECM data (Fluck, 1992)	
	Annual consumption:	3.73E+04		
8	**Lime, g per ha**			
	Annual consumption, .	3.72E+05	FAECM data (Fluck, 1992)	
9	**Pesticides, g per ha** (includes pesticides, fungicides, herbicides)			
	Annual consumption, .	7.07E+02	FAECM data (Fluck, 1992)	

Table D.4 - continued

10 **Phosphate, g P per ha**
(g fertilizer active ingredient)(31 gmol P/132 gmol DAP)
g: 4.49E+04 FAECM data (Fluck, 1992)
Annual consumption: 1.05E+04
11 **Nitrogen, g N per ha**
(g fertilizer active ingredient)(28 gmol N/132 gmol DAP)
g: 1.12E+04 FAECM data (Fluck, 1992)
Annual consumption: 2.38E+03
12 **Labor, J**
(pers-hours/ha/yr)*(3500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)
pers-hours: 5.61E+00 FAECM data (Fluck, 1992)
Annual energy: 1.03E+07
Transformity: 8.10E+04 (uneducated labor,Odum and Odum 1983)
13 **Services, $ per ha**
$/yr: 1.48E+02 FAECM data (Fluck, 1992)
Annual emergy ($ /yr)(sej/$)
14 **Yield** - 20 BU/acre FAECM data (Fluck, 1992), 60 lb/bu (USFDA, 19)
70% water (Stetens Livsmedelsverk, 1988)
Dry weight = 4.04E+05 g
15 **Product in Joules**
40% protein, 21% fat, 39% carbol (Stetens Livsmedelsverk, 1988)
Energy content = 9.86E+09 J
16 **Investment Ratio**
P = Items 5 + 6 + 7 + 8 + 9 + 10 + 11
S= Items 12 + 13
N= Item 4
R = Item 3
17 **Yield Ratio**
Y = Items 3 + 4 + 5 + 6 + 7 + 8 + 9 + 10 + 11 + 12 + 13
18 **Emergy exchange ratio** - $117/acreFAECM data (Fluck, 1992)
$, total/ha = 2.89E+02
19 **Emdollar Contribution to State**
ha in production: 32375 FAECM data (Fluck, 1992)
20 **Nonrenewable/Renewable,**
See Note 16
21 **Empower Density** - sum of emergy per hectare per year

Table D.5. Emergy evaluation of Alachua Co. rural residence, ~0.5ha avg.

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E13 sej/yr)	Em$ Value (1990 $/yr)
RENEWABLE RESOURCES						
1	Sun	J	2.97E+13	1	3	20
2	Rain	J	2.61E+10	1.80E+04	47	313
	Sum of free inputs (sun omitted)				47	313
PURCHASED INPUTS						
Operational inputs						
3	Gas	J	2.27E+08	6.60E+04	2	10
4	Electricity	J	6.18E+10	1.60E+05	990	6597
5	Goods & Services	$	8.07E+03	1.55E+12	1251	8338
	Sum of purchased inputs				2242	14945
	Sum of all inputs				2289	15258
EMPOWER DENSITY					4.58E+16 sej/ha/yr	

Notes, Table D.5

1 **Sun, J**

Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
Insolation:	6.90E+09	J/m2/yr	(Vishner 1954)
Area:	5.00E+03	m2	
Albedo:	0.14	Odum 1987)	
Annual energy:	2.97E+13		

2 **Rain, J**

Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m3)(4.94J/g)(1 - runoff)	
in/yr:	52	(SJRWMD, 1995)
Area, m2:	5.00E+03	(FL Statistical Abstract, 1995)
runoff coefficient:	2.00E-01	(SJRWMD, 1995)
Annual energy:	2.61E+10	

3 Gas, J

Alachua Co consumption*3.1 per/residence

Consumption 486 gal/pers/yr (FL Statistical Abstract, 1995)

4 **Electricity, J**

KWh/pers*3.1 pers*3.6E6 J/KWh

KWh/pers:	5.54E+03	(FL Statistical Abstract, 1995)
Annual energy:	6.18E+10	

5 Goods & Services (50% of income)

Average annual income per residence: 16138

Table D.6. Emergy evaluation of Gainesville, incorporated area per year.

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E17 sej/yr)	Em$ Value (E4) (1990 $/yr)
RENEWABLE RESOURCES						
1	Sun	J	1.44E+17	1.00E+00	1	10
2	Rain	J	7.93E+13	1.80E+04	14	95
	Sum of free inputs (sun omitted)				14	95
PURCHASED INPUTS						
Operational inputs						
3	Coal	J	6.44E+15	4.00E+04	2575	17168
4	Gas	J	6.40E+12	6.60E+04	4	28
5	Electricity	J	0.00E+00	0.00E+00	0	0
6	Goods & Services	$	1.41E+09	1.55E+12	21857	145714
	Sum of purchased inputs				24437	162910
	Sum of all inputs				24451	163006
EMPOWER DENSITY					1.01E+18 sej/ha/yr	

Notes, Table D.6

1 **Sun, J**

Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
Insolation:	6.90E+09	J/m2/yr	(Vishner 1954)
Area:	2.43E+07	m2	
Albedo:	0.14	Odum 1987)	
Annual energy:	1.44E+17		

2 **Rain, J**

Annual energy =	(in/yr)(Area)(0.0254 m/in)(1E6g/m3)(4.94J/g)(1 - runoff)	
in/yr:	52	
Area, m2:	2.43E+07	(FL Statistical Abstract, 1995)
runoff coefficient:	5.00E-01	(SJRWMD, 1995)
Annual energy:	7.93E+13	

3 Coal, J

(Total coal purchased for electricity in FL/electricity produced)*GRU production

Coal:	6.52E+14	(FL Statistical Abstract, 1995)
Electricity:	1.40E+08	(FL Statistical Abstract, 1995)
GRU production	1.31E+06	(FL Statistical Abstract, 1995)

4 Gas, J

(Alachua Co consumption/Alachua Co population)*Gainesville population

Consumption	486 gal/pers/yr	(FL Statistical Abstract, 1995)

Table D.6 - continued

	Population, county	181,596	(FL Statistical Abstract, 1995)
	Population, G'ville	85075	(FL Statistical Abstract, 1995)
5	Electricity, J		
	Produced within city limits, not considered an imput		
6	Goods & Services		
	(Gross sales in Alachua Co/Alachua population)* Gainesville population		
	Gross sales:	3.01E+09 $/yr	

APPENDIX E
WATERSHED-LAKE INTERFACE EMERGY EVALUATIONS

Table E.1. Emergy analysis of Newnan's Lake watershed/lake interface, 1990.

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E15sej/yr)	1970 EM$ (E4 US$)
Atmospheric inputs						
A	Insolation	J	1.78E+17	1	178	2
B	Wind shear	J	2.61E+14	1.50E+03	391	5
C	Rain, chemical potential	J	1.96E+14	1.82E+04	3574	45
D	Transpiration emergents	J	1.03E+12	1.54E+04	16	<1
E	TP in Rain	g	7.14E+06	2.00E+06	<1	<1
		Total atmospheric (sun omitted)			3981	50
Watershed inputs						
F	Stream, geopotential	J	1.38E+13	1.85E+03	26	<1
G	Stream, chemical potential	J	1.60E+03	1.82E+04	<1	<1
H	Sediment	J	3.16E+12	7.30E+04	231	3
I	Runoff, non-point	J	1.30E+15	6.31E+04	82118	103
J	TP in streams	g	3.70E+09	6.85E+09	25318	32
K	TP in runoff	g	4.28E+07	6.85E+09	293	4
				Total watershed	107987	135
		Total emergy/lake/yr			111968	140
		Total emergy/ha/yr			37	
Transformities						
1	Phytoplankton			6.77E+12 sej/g		
2	TP in water column			2.98E+13 sej/g		
3	Water			6.33E+05 sej/J		

Notes:

TP = total phosphorus

A Annual energy = (Avg. Total Annual Insolation J/yr)(Area)(1-albedo)

Insolation:	6.90E+09	J/m2/yr	(Vishner, 1954)
Area:	3.01E+07	m2	
Albedo:	0.14		(Odum, 1987)
Annual energy:	1.78E+17 J/yr		

B Wind mixing energy =

(density, kg/m3)(drag coefficient)(geostrophic wind velocity3,m3/s3)(area)

u = wind velocity (m/s) = 3.58 m/s

Table E.1 continued

	geostrophic wind velocity =	5.97 m/s	
	Energy = 1.3 kg/m3 * 1E-3 *212.77 m3/s3 * 3.14 E7 s/y * 3.01E7 m2		
	Energy/yr =	2.61E+14 J/yr	
C	Rain, chemical potential = (rain,m)(lake area,m2)(1E6 g/m3)*G		
	Rain, m	1.32E+00 m	
	Lake area, m2	3.01E+07 m2	
	G, free energy, J/g	4.94E+00 J/g	
	Energy/yr =	1.96E+14 J/yr	
D	Transpiration from emergent and floating macrophytes		
		14.2 ha cover	(Huber et al., 1982)
		7.30E+10 J/ha, estimated transpiration	(Odum, 1996)
E	Phosphorous in rain =	area * rainfall * concentration	
	Area =	3.01E+07 m2	
	Rainfall =	1.4224 m/yr	(~52 in, NOAA, 1995)
	Concentration =	0.167 g/m3	(Brezonik, 1969)
	Annual amount =	7.14E+06 g/yr	
F	Stream, geopotential, J/yr = (flow volume)(density)(dh)(gravity)		
	Hatchett Creek		
	flow,cfs =	18 cfs	(SJRWMD, 1997)
	dh, m =	76 m	(Brandt-Williams, 1999)
	Energy/yr = 18cfs*0.028317m3/ft3*3.1536E7sec/yr*1E6g/m3*7 1.20E+13		
	Little Hatchett Creek		
	flow, cfs =	4 cfs	(SJRWMD, 1997)
	dh, m =	53 m	(Brandt-Williams, 1999)
	Energy/yr =	1.86E+12 J	
G	Stream, chemical potential = (volume flow)(density)(G)		
	G = (8.33J/mole/deg)(300°K)/18 g/mole)*ln[(1E6 - S) / 965000] J/g		
	S, ppm =	5.9	(calculated from turbidity, SJRWMD, 1997)
	Flow,cfs =	18 cfs	
	Energy/yr =	1.60E+03 J/yr	
H	Sediment = (Sediment kg/yr)*(1E3 g/kg)*(avg. % organic)*(5.4 Cal/g OM)*(4186 J/Cal)		
	Energy = (2.8E7 kg/yr)*(1E3 g/kg)*(0.5% Organic)*(5.4 Cal/g)*(4186 J/Cal)		
		= 3.16E+12 J/yr	
I	Runoff, nonpoint = (volume/yr)(G) = (Volume,m3)(4.82 J/g)(1 E6 g/m3)		
	Volume=	2.70E+08 m3/yr	
	Energy/yr =	1.30E+15 J/yr	
	Transformity =	6.31E+04 sej/J	
	Transformity calculated from spatial simulation of total emergy at lake perimeter divided by total volume of water converted to Joules		

Table E.1 continued

J	Total phosphorus in streams			
	= (volume,cfs)(P,mg/l)(0.02831,m3/ft3)(3.1536E7,sec/yr)(1E-3 g/mg)(1E6 L/m3)			
	Volume ,cfs =	1.80E+01	cfs	(SJRWMD, 1997)
	Average concentration, mg/l	0.23	mg/l	(SJRWMD, 1997)
	Average TP mass =	3.70E+09	g/yr	
	Transformity =	1.82E+04	sej/g	(Appendix D)
K	Phosphorous in runoff from spatial model			
	Annual amount =	4.28E+07	g/yr	
	Transformity =	6.85E+09	sej/g	
	Transformity calculated from spatial simulation of total emergy at lake perimeter divided by total mass of phosphorus			

Transformities calculated from this analysis

1	Phytoplankton, g			
	= (avg. chlorophyll a concentration, g/m3)(lake volume, m3)(2g phytoplankton/g Chl a)			
	Avg Chl a =	0.231	g/m3	(Huber et al., 1982)
		1.65E+07	g	
2	TP in water column, g	= (avg. TP in water column, mg/L)(lake volume, m3)		
	Average concentration	0.113	mg/l	(Huber et al., 1982)
	Total g	3.76E+06		
3	Water, J = (lake volume, m3)(1E6 g/m3)(4.94 J/g)			
	Volume	3.58E+07	m3	(SJRWMD, 1997)
	Energy stored	1.77E+14	J	

Table E.2: Emergy analysis of Lake Weir watershed/lake interface, 1990

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E15sej/yr)
Renewable					
	Atmospheric inputs				
A	Insolation	J	1.58E+17	1	158
B	Wind shear	J	2.32E+14	1.50E+03	347
C	Rain, chemical potential	J	1.74E+14	1.82E+04	3171
D	Transpiration emergents	J	1.03E+12	1.54E+04	16
E	P in Rain	g	6.34E+06	2.00E+06	0
		Total atmospheric (sun omitted)			3534
	Watershed inputs				
F	Runoff, non-point	J	3.23E+14	1.86E+04	6000
G	P in runoff	g	3.40E+07	1.27E+10	432
			Total watershed		6432
		Total emergy/lake/yr			9965
		Total emergy/ha/yr			4
Transformities					
1	Phytoplankton, g		4.29E+09	2.32E+09	
2	TP in water column, J		6.99E+09	1.42E+09	
3	Water, J		9.46E+14	1.05E+04	

Notes:

A **Annual energy = (Avg. Total Annual Insolation J/yr)(Area)(1-albedo)**

Insolation:	6.90E+09	J/m2/yr	(Vishner 1954)
Area:	2.67E+07	m2	
Albedo:	0.14	Odum 1987)	
Annual energy:	1.58E+17	J/yr	

B **Wind mixing energy =**

(density, kg/m3)(drag coefficient)(geostrophic wind velocity3,m3/s3)(area)

u = wind velocity (m/s) = 3.58

geostrophic wind velocity = 5.97

Energy = 1.3 kg/m3 * 1E-3 *212.77 m3/s3 * 3.14 E7 s/y * 2.67E7 m2

Energy/yr = 2.32E+14 J/yr

C **Rain, chemical potential = (rain,m)(lake area,m2)(1e6g/m3)*G**

Rain, m 1.32E+00

Lake area, m2 2.67E+07

Table E.2 continued

	G, free energy, J/g	4.94E+00		
	Energy/yr =	1.74E+14		
D	**Transpiration from emergent and floating macrophytes**			
		14.2	ha cover	(Huber, et al. 1982)
		7.3E10	J/ha estimated transpiration/ha	(Odum 1996)
E	**Phosphorous in rain =**	area * rainfall * concentration		
	Area =	2.67E+07	m2	
	Rainfall =	1.4224	m/yr (~56 in, NOOA, 1995)	
	Concentration =	0.167	g/m3 (Brezonik, 1969)	
	Annual amount =	6.34E+06	g/yr	
F	**Runoff, nonpoint = (volume/yr)(G) =**		(Volume,m3)(4.82 J/g)(1 E6 g/m3)	
	Volume=	6.71E+07	m3/yr	
	Energy/yr =	3.23E+14		
G	**Phosphorous in runoff from spatial model**			
	Annual amount =	3.40E+07	g/yr	
	Transformity =	1.27E+10	(Brandt-Williams, 1999)	

Transformities

1	**Phytoplankton, g**	~2*Chl a		
2	**TP in water column, J**			
	Average concentration	0.011	mg/l	(Huber,et al. 1982)
	Total g	2.01E+07		
	Energy stored	6.99E+09		
3	**Water, J**			
	Volume	1.91E+08	m3	
	Energy stored	9.46E+14		

APPENDIX F
TRANSFORMITIES AND EMERGY PER MASS RATIOS

Emergy per mass ratios for all phosphorus compounds used in this study are presented in this appendix. Figures F.1 and F.2 are graphs of emergy per mass ratios relative to concentrations of phosphorus in a water solution. These represent dilution processes. Two kinds of phosphorus solutions were evaluated. To compare the lowest emergy forms of the two components, the emergy per gram of total solution for rock phosphorus dissolved in rainwater was calculated at increasing concentration of phosphorous in solution (Figure F.1 and Table F.1). For comparison with runoff from industrial or commercial land uses, the emergy for reagent phosphorus was diluted in ground water and used to determine the ratio (Figure F.2 and Table F.2).

Conversely, the emergy per gram of phosphorus in both natural and industrial concentrating processes was also evaluated (Figure F.3 and Table F.3). The ocean was considered the natural emergy sink for phosphorus and was given an emergy/gram ratio of one (1). Values from other evaluations for phosphorus were converted to parts per billion and compared to the emergy per gram calculated in each study.

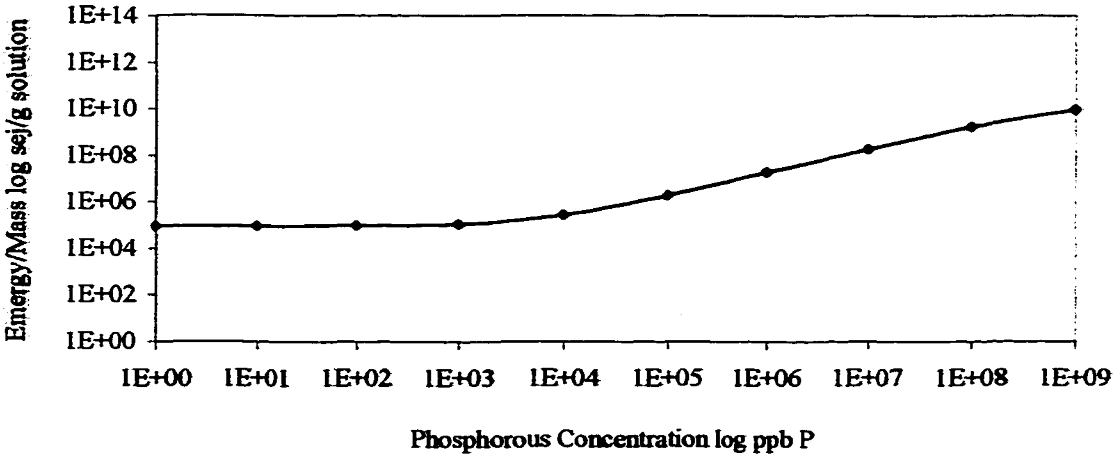


Figure F.1. Phosphorus emergy per gram relative to concentrations of mined rock dissolved in rain water.

Table F.1. Phosphorus emergy per gram relative to concentrations of mined rock dissolved in rain water as shown in Figure F.1.

ppb P	Emergy/gram solution1	g P/l H2O	Total grams	Emergy P2	Emergy H2O3
1	9.00E+04	0.000001	1000.000001	1.78E+04	9.00E+07
10	9.02E+04	0.00001	1000.00001	1.78E+05	9.00E+07
100	9.18E+04	0.0001	1000.0001	1.78E+06	9.00E+07
1000	1.08E+05	0.001	1000.001	1.78E+07	9.00E+07
10000	2.68E+05	0.01	1000.01	1.78E+08	9.00E+07
100000	1.87E+06	0.1	1000.1	1.78E+09	9.00E+07
1000000	1.79E+07	1	1001	1.78E+10	9.00E+07
10000000	1.76E+08	10	1010	1.78E+11	9.00E+07
100000000	1.62E+09	100	1100	1.78E+12	9.00E+07
1000000000	8.90E+09	1000	2000	1.78E+13	9.00E+07

1. Emergy per gram of P solution is the sum of emergy per gram in the water and the phosphorous divided by the total grams of solution

2. Emergy/gram of phosphorous is the total grams of P in solution multiplied by the transformity of phosphorous in mined rock

3. Emergy in H_2O in solution is the transformity of rain water multiplied by 1 liter

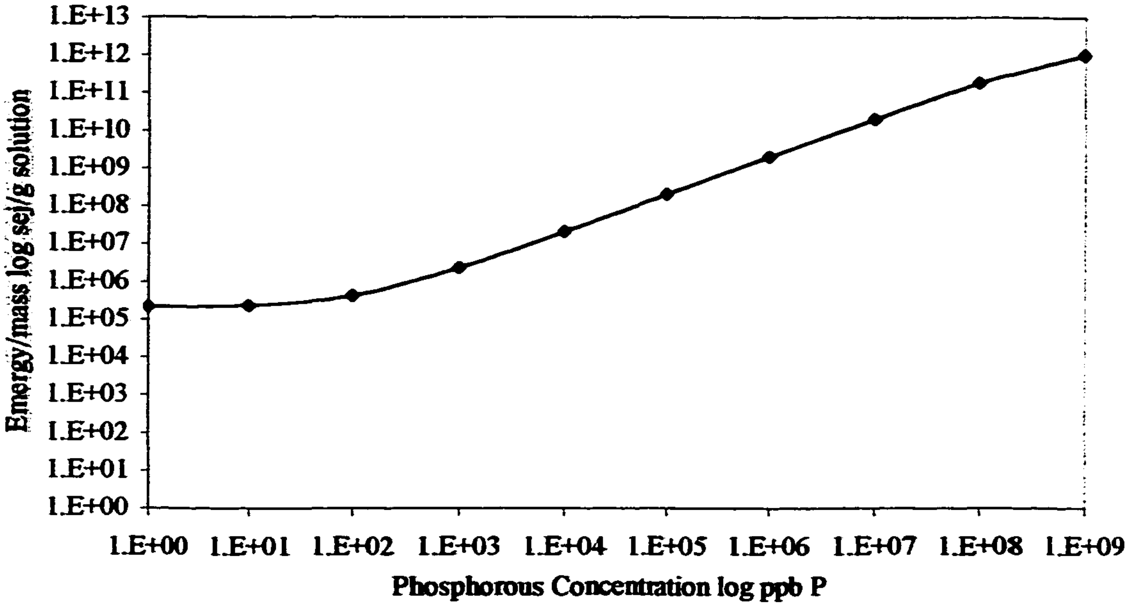


Figure F.2. Phosphorus emergy per gram relative to emergy/mass of industrial reagent in ground water

Table F.2. Phosphorus emergy per gram relative to emergy/mass of industrial reagent in ground water as shown in Figure F.2

ppb P	Emergy/gram solution[1]	g P/l H2O	Total grams	Emergy P[2]	Emergy H2O[3]
1	2.07E+05	0.000001	1000.000001	2.06E+06	2.05E+08
10	2.26E+05	0.00001	1000.00001	2.06E+07	2.05E+08
100	4.11E+05	0.0001	1000.0001	2.06E+08	2.05E+08
1000	2.26E+06	0.001	1000.001	2.06E+09	2.05E+08
10000	2.08E+07	0.01	1000.01	2.06E+10	2.05E+08
100000	2.06E+08	0.1	1000.1	2.06E+11	2.05E+08
1000000	2.05E+09	1	1001	2.06E+12	2.05E+08
10000000	2.04E+10	10	1010	2.06E+13	2.05E+08
100000000	1.87E+11	100	1100	2.06E+14	2.05E+08
1000000000	1.03E+12	1000	2000	2.06E+15	2.05E+08

1. Emergy per gram of P solution is the sum of emergy per gram in the water and the phosphorous divided by the total grams of solution

2. Emergy/gram of phosphorous is the total grams of P in solution multiplied by the transformity of phosphorous in 100% P_4 commercial grade reagent (see Appendix F)

3. Emergy in H_2O in solution is the transformity of groundwater multiplied by 1 liter

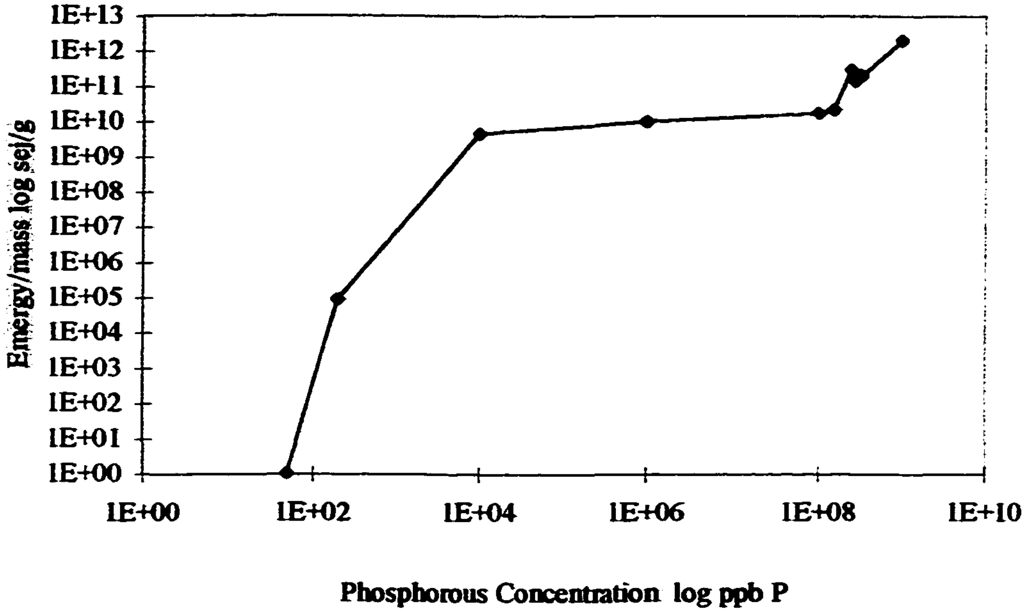


Figure F.3. Phosphorus emergy per gram relative to emergy/mass of natural and industrial concentration processes

Table F.3. Phosphorus emergy per gram relative to emergy/mass of natural and industrial concentration processes as shown in Figure F.3

Item	P concentration, ppb	sej/gram	Source
Ocean	5.00E+01	1	a
Rain, Florida	2.00E+02	9.02E+04	a, b
Newnans Lake, hypereutrophic	1.00E+04	4.50E+09	c
Coweeta vegetation	1.00E+06	1.00E+10	d
10% wetland concentration process	1.00E+08	1.78E+10	a
Industrial P2O5	1.50E+08	2.18E+10	c
Diammonium phosphate fertilizer	2.40E+08	3.02E+11	c
85% H3PO4	2.70E+08	1.45E+11	c
100% H3PO4	3.20E+08	2.05E+11	c
100% P4	1.00E+09	2.06E+12	c

a. Odum 1996

b. Brezonik 1969

c. Brandt-Williams 1999 (this study)

d. Tilley 1999

Table F.4. Emergy evaluation of 100% P_4, per 1000g production.

Note	Item	Unit	Data (units)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E12 sej)	Em$ Value (1996 $)
NONRENEWABLE STORAGES						
1	Water	J	3.74E+04	4.80E+04	0	0
	Sum of free inputs (sun, rain omitted)				0	0
PURCHASED INPUTS						
Operational inputs						
2	Electricity	J	1.25E+07	1.60E+05	20	17
3	Silica	g	1.50E+03	9.70E+08	15	12
4	CaO	g	1.60E+02	1.00E+09	2	1
5	Coke	g	1.12E+03	2.05E+09	23	19
6	Phosphate	gP	1.12E+04	1.78E+10	1997	1664
	Sum of purchased inputs				2056	1714
TRANSFORMITIES						
7	Total Yield	g P	1.00E+03	2.06E+12	2056	1714

Notes

1 **Water, J**

gal H20 * 3785.43 cm3/gal * density H2O

Gal H2O:	2.00E+00	(estimated from Shreve 1945)
Density, ambient:	1.00E+00 g/cm3	
Gibbs Energy:	4.94 J/g	
Total Energy:	3.74E+04 J	
Transformity:	4.80E+04 sej/J	(Odum, 1995)

2 **Electricity, J**

KWh*3.6E6 J/KWh

KWh:	3.47E+00	(estimated from Shreve 1945)
Energy:	1.25E+07	
Transformity:	1.60E+05 sej/J	(coal plant; Odum 1996)

3 **Silica, g**

Feedstock g:	1.50E+03 (Sittig 1978)	
Emergy/gram	9.70E+08 sej/g	(Odum 1996)

assume equivalent to pelagic and abyssal sediment transformity

4 **CaO, g**

Feedstock g:	1.60E+02	(Sittig 1978)
Emergy per gram	1.00E+09	(limestone ; Odum 1996)

5 **Coke, g**

Feedstock g:	1.12E+03	(Sittig 1978)

Table F.4 - continued

	Emergy per gram	2.05E+09 sej/g	
6	**Phosphate, g P**		
	Feedstock g:	1.12E+04	(Sittig 1978)
	Emergy per gram	3.90E+09 sej/g	(rock; Odum 1996)
7	**Yield**		
	g P4	1000	

Table F.5. Emergy evaluation of 100% H_3PO_4 (32 % P), per 908 kg H3PO4.

Note	Item	Unit	Data (units)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E13 sej)	Em$ Value (1996 $)
NONRENEWABLE STORAGES						
1	Air	J	3.76E+10	2.12E+03	80	664
2	Water	J	3.74E+07	4.80E+04	2	15
	Sum of free inputs (sun, rain omitted)				82	679
PURCHASED INPUTS						
Operational inputs						
3	Electricity	J	1.25E+10	1.60E+05	199	1661
4	Labor	J	1.31E+06	2.46E+07	3	27
5	Silica	g	6.80E+05	9.70E+08	66	550
6	Coke	g	3.40E+06	2.05E+09	697	5808
7	Phosphate	gP	2.72E+06	1.78E+10	4842	40347
	Sum of purchased inputs				5807	48392
TRANSFORMITIES						
8	Total Yield	gP	2.87E+05	2.05E+11	5889	49072

Notes

1 **Air, J**

Drying ft3: 450,000 (Shreve, 1945)

Furnace temperature: 1500 °K

Assume furnace pressure 1 atm

Superheated air: enthalpy: 1046.6 kJ/kg (Vasserman and Rabinovich, 1970)

entropy: 8.22 kJ/kg*T (Vasserman and Rabinovich, 1970)

volume: 3829 dm3/kg (Vasserman and Rabinovich, 1970)

F = H - t S = -1.13E4 kJ/kg

J/ ft3 = (F kJ/kg) * (1 kg/3829 dm3) * (28.32 dm3/ 1 ft3)= 83577 J/ft3

J= 3.76E+10

Transformity: 2.12 E3 (Odum, 1996)

assumes O2 as byproduct of gross photosynthesis

2 **Water, J**

gal H20 * 3785.43 cm3/gal * density H2O

Gal H2O: 2.00E+03

Density, ambient: 1.00E+00 g/cm3

Gibbs Energy: 4.94 J/g

Total Energy: 3.74E+07 J

Transformity: 4.80E+04 sej/J (Odum, 1995)

Table F.5 - continued

3	**Electricity, J**		
	KWh*3.6E6 J/KWh		
	KWh:	3.46E+03	(Shreve, 1945)
	Energy:	1.25E+10	
	Transformity:	1.60E+05 sej/J	(average coal plant; Odum, 1996)
4	**Labor, J**		
	(pers-hours)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)		
	pers-hours:	1.00E+00	(Shreve, 1945)
	Energy:	1.31E+06	
	Transformity:	2.46E+07 sej/J	(high school graduate; Odum 1996)
5	**Coke, g**		
	Feedstock lb:	748	(Shreve, 1945)
	g:	3.40E+05	
	Emergy/gram:	2.05E+09 sej/g	(Brandt-Williams, 1999)
6	**Silica, g**		
	Feedstock lb:	1270 (Shreve, 1945)	
	g:	5.77E+05	
	Emergy/gram:	9.70E+08 sej/g	(Odum, 1996)
		assume equivalent to pelagic and abyssal sediment transformity	
7	**Phosphate, g P**		
	Feedstock lb:	3970	(Shreve, 1945)
	g:	1.80E+06	
	Transmassity:	3.90E+09 sej/g	(rock; Odum, 1996)
8	**Yield**		
	kg H_3PO_4	908	
	Ratio P to H_3PO_4: 31gmol P/ 98 gmol H_3PO_4		
	g P:	2.87E+05	

Table F.6. Emergy evaluation of 85% H_3PO_4 (27% P), per 908 kg.

Note	Item	Units	Data (units)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E13 sej)	Em$ Value (1996 $)
PURCHASED INPUTS						
Operational inputs						
1	Electricity	J	1.25E+10	1.60E+05	199	1661
2	Labor	J	1.31E+06	2.46E+07	3	27
3	Silica	g	5.77E+05	9.70E+08	56	466
4	Coke	g	3.40E+06	2.05E+09	697	5808
5	Phosphate	g P	1.80E+06	1.78E+10	3204	26700
	Sum of purchased inputs				4159	34662
TRANSFORMITIES						
6	Total Yield	g P	2.87E+05	1.45E+11	4159	34662

Notes

1 **Electricity, J**

KWh*3.6E6 J/KWh

KWh:	3.46E+03	(Shreve, 1945)
Energy:	1.25E+10	
Transformity:	1.60E+05 sej/J	(average coal plant; Odum, 1996)

2 **Labor, J**

(pers-hours)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)

pers-hours:	1.00E+00	(Shreve, 1945)
Energy:	1.31E+06	
Transformity:	2.46E+07 sej/J	(high school graduate; Odum, 1996)

3 **Coke, g**

Feedstock lb:	748	(Shreve, 1945)
g:	3.40E+05	
Emergy/gram:	2.05E+09 sej/g	

4 **Silica, g** assume equivalent to pelagic and abyssal sediment transformity

Feedstock lb:	1270	(Shreve, 1945)
g:	5.77E+05	
Emergy/gram:	9.70E+08 sej/g	(Odum, 1996)

5 **Phosphate, g P**

Feedstock lb:	3970	(Shreve, 1945)
g:	1.80E+06	
Emergy/gram:	3.90E+09 sej/g	(rock; Odum, 1996)

6 **Yield**

kg H3PO4	908	(Shreve, 1945)

Ratio P to H3PO4: 31gmol P/ 98 gmol H3PO4

g P:	2.87E+05

Table F.7. Emergy evaluation of 35% P2O5 (15 % P), per 908 kg.

Note	Item	Unit	Data (units)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E12 sej)	Em$ Value (1996 $)
NONRENEWABLE STORAGES						
	Water	J	1.40E+08	4.80E+04	7	6
	Sum of free inputs (sun, rain omitted)				7	6
PURCHASED INPUTS						
Operational inputs						
2	Electricity	J	1.89E+08	1.60E+05	30	25
3	Labor	J	1.05E+06	2.46E+07	26	22
4	H2SO4 (94%)	g	8.85E+05	9.12E+07	81	67
5	Phosphate	g P	1.07E+06	3.90E+09	4173	3478
	Sum of purchased inputs				4310	3591
TRANSFORMITIES						
6	Total Yield	g P	3.96E+05	2.18E+10	8633	7194

Notes

1 **Water, J**

gal H20 * 3785.43 cm3/gal * density H2O

Gal H2O:	7.50E+03	(Shreve, 1945)	
Density, ambient:	1.00E+00	g/cm3	
Gibbs Energy:	4.94	J/g	
Total Energy:	1.40E+08	J	
Transformity:	4.80E+04	sej/J	(Odum, 1995)

2 **Electricity, J**

KWh*3.6E6 J/KWh

KWh:	5.25E+01	(Shreve, 1945)
Energy:	1.89E+08	
Transformity:	1.60E+05 sej/J	(average coal plant; Odum, 1996)

3 **Labor, J**

(pers-hours)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)

pers-hours:	8.00E-01	(Shreve, 1945)
Energy:	1.05E+06	
Transformity:	2.46E+07 sej/J	(high school graduate; Odum, 1996)

4 **H2SO4, g**

Feedstock lb:	1950	(Shreve, 1945)
g:	8.85E+05	
Emergy/gram:	9.12E+07 sej/g	(Pritchard, 1996)

5 **Phosphate, g P**

Table F.7- continued

	Feedstock lb:	2350	(Shreve, 1945)
	g:	1.07E+06	
	Emergy/gram:	3.90E+09 sej/g	(rock; Odum, 1996)
6	**Yield**		
	kg P2O5	908	
	Ratio P to P2O5: 62gmol P/ 142 gmol P2O5		
	g P:	3.96E+05	

Table F.8. Emergy evaluation of coke, per 635600g.

Note	Item	Unit	Data (units)	Unit Solar EMERGY (sej/unit)	Solar EMERGY (E12 sej)	Em$ Value (1996 $)
NONRENEWABLE STORAGES						
1	Water	J	3.74E+07	4.80E+04	2	1
	Sum of free inputs (sun, rain omitted)				2	1
PURCHASED INPUTS						
Operational inputs						
2	Electricity	J	3.24E+07	1.60E+05	5	4
3	Labor	J	1.57E+07	2.46E+07	386	322
4	Sulfuric Acid	g	1.14E+04	9.12E+07	1	1
5	Bituminous Coal	g	9.08E+05	1.00E+09	908	757
6	Lime	g	9.08E+02	1.00E+09	1	1
	Sum of purchased inputs				1301	1084
TRANSFORMITIES						
7	Total Yield	g	6.36E+05	2.05E+09	1303	1086

Notes

1 **Water, J**

gal H20 * 3785.43 cm3/gal * density H2O

Gal H2O:	2.00E+03	(Shreve 1945)
Density, ambient:	1.00E+00 g/cm3	
Gibbs Energy:	4.94 J/g	
Total Energy:	3.74E+07 J	
Transformity:	4.80E+04 sej/J	(Odum, 1995)

2 **Electricity, J**

(pers-hours/ha/yr)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)

KWh:	9.00E+00	(Shreve 1945)
Total Energy:	3.24E+07	
Transformity:	1.60E+05	(average coal plant; Odum 1996)

3 **Labor, J**

(pers-hours)*(2500 kcal/day)*(4186J/Cal) / (8 pers- hrs/day)

pers-hours:	1.20E+01	(Shreve 1945)
Total Energy:	1.57E+07	
Transformity:	2.46E+07 sej/J	(high school graduate; Odum 1996)

4 **Sulfuric Acid, g**

Feedstock:	1.14E+04	(Shreve 1945)
Emergy/mass:	9.12E+07 sej/g	(L. Pritchard, 1996)

Table F.8 - continued

5	**Bituminous Coal, g**		
	Feedstock:	9.08E+05	(Shreve 1945)
	Emergy/mass:	1.00E+09 sej/g	(Odum, 1996)
6	**Lime, g**		
	Feedstock:	9.08E+02 g	(Shreve 1945)
	Emergy/mass:	1.00E+09 sej/g	(Odum 1996)

Table F.9. Emergy evaluation of Diammonium (Superphosphate) Fertilizer

Note	Item	Units	Units/ Production	Transformity (sej/unit)	Solar Emergy (E16 sej)
PURCHASED INPUTS					
Construction inputs					
1	Capital, '84	$	3.69E+05	2.20E+12	81
	'81	$	2.51E+06	2.70E+12	678
	'79	$	2.84E+05	3.50E+12	99
	'75	$	1.56E+06	6.00E+12	936
Operational inputs					
2	Fuel	J	2.74E+14	4.80E+04	1,315
3	Electricity	J	1.08E+15	1.60E+05	17,280
4	Labor	J	2.43E+12	2.46E+07	5,978
5	NH_3	g N	2.78E+11	4.60E+09	127,880
6	P_2O_5 (35%)	g	1.14E+12	9.37E+09	1,068,180
	Sum of purchased inputs				1,222,427
Transformity with Services					
7	Total Yield	g	2.41E+12	5.07E+09	1,222,427
		g P	5.53E+11	2.21E+10	
		g N	5.05E+11	2.42E+10	
Transformity without Services					
	Total Yield	g	2.41E+12	5.06E+09	1,220,633
		g P	5.53E+11	2.21E+10	
		g N	5.05E+11	2.42E+10	

NOTES: Production of 2.4 E9 kg of Diammonium Phosphate

1 Capital = (plant capital costs)/(life expectancy)/(% of capacity dedicated to DAP)

2 Fuel - 2.6 E 6 therms natural gas

(2.6 E6 therms)(1.05 E8 J/therm) = 2.74 E14 J

3 Electricity - 3.01 E8 KWh

(3.01 E8 kwh)(3.6 E6 J/kwh) = 1.08 E15 J

4 Labor - 1.86 E6 pers-hrs

(1.86 E6pers-hrs)(2500kcal/day)(4186 J/Kcal)(/(8 pers-hrs/day) = 2.43 E12 J

Transformity - high school graduate (Odum 1996)

Table F.9 continued

5 Ammonia - 3.37 E11 g
(3.37 E11 g)(14g N/17g NH_3) = 2.78 E11 gN
6 P_2O_5 35% - 1.14 E12 g
7 Yield - 2.4 E9 kg $(NH_4)_2(HPO_4)$
Ratio P: 31gmol P/ 132 gmol DAP
Ratio N: 28gmol N/ 132 gmol DAP

APPENDIX G
IN-LAKE SIMULATION CALIBRATIONS

This appendix contains calibration calculations for each simulation. A QBASIC program for one simulation is included.

Table G.1. Coefficient calibration, eutrophic conditions.

Sed =		0.1
Org =		5
P =		30
M =		1000
Pl =		60
Z =		5
F =		50
I =		3.24E+00
Ro =		4.86E-01
R1=		3.09E+00
R2 =		3.02E+00
R3=		1.00E+00
ko=	2756 /(Ro*P*M)=	1.89E-01
k1=	150 /(R1*Sed)=	4.85E+02
k2=	74 /(R2*Org)=	4.91E+00
k3=	2016 /(R3*P*Pl)=	1.12E+00
k4=	4 /Ro*P*M=	2.74E-04
k5=	0.02 /F*M=	4.00E-07
k6=	0.18 /Z*M=	3.60E-05
k7=	1.8 /M=	1.80E-03
k8=	2 /M=	2.00E-03
k9=	15 /R3*P*Pl=	8.33E-03
k10=	3 /Pl*F=	1.00E-03
k11=	1 /Pl*Z=	3.33E-03
k12=	6 /Pl=	1.00E-01
k13=	5 /Pl=	8.33E-02
k14=	0.2 /Z*F=	8.00E-04
k15=	0.13 /Z=	2.60E-03
k16=	0.05 /F=	9.20E-04
k20=	0.08 /P*Pl=	4.67E-05
k21=	1.3 /P*M=	4.33E-05
k22=	0.01 /P=	4.67E-04
k24=	0.04 /z*Org=	1.60E-03
k26=	0.04 /Org=	8.00E-03
k27=	0 /F*M=	4.00E-08
k28=	0 /F*Pl=	1.33E-06

k29=	0.04 /F*Z=	1.60E-04

Table G.1 continued

k30=	0.3 /Z*M=	6.00E-05
k31=	0.03 /Pl*Z=	1.00E-04
k32=	0 /org*Z=	1.20E-04
fr=	0.8 /(k7M+k12Pl+k15Z+k16F)=	1.02E-01
frorg=	0.06 /(k7M+k12Pl+k15Z+k16F)=	7.63E-03

Table G.2. QBASIC in-lake simulation program

```
REM Macintosh
REM Lake: Generic
REM graph subroutine
   GOSUB 700

REM  COEFFICIENTS
      k0 = .000195             'albedo
      k1 = 1.1103              'light:sediment inhibition
      k2 = .022239             'light:organic inhibition
      k3 = .004929             'light use by phyto
      k4 = 4.1152E-07          'macrophyte production
      k5 = 1.9048E-07          'macrophyte predation by fish
      k6 = .000058             'macrophyte predation by zooplankton
      k7 = 2.52667E-03         'macrophyte feces and mortality
      k8 = .003                'macrophyte basal functions
      k9 = 3.1328E-05          'phytoplankton production
      k10 = .001               'phytoplankton predation by fish
      k11 = .0033              'phytoplankton predation by zooplankton
      k12 = .1                 'phytoplankton mortality
      k13 =.0833               'phytoplankton basal functions
      k14 = .0008              'zooplankton predation by fish
      k15 = .00286             'zooplankton feces and mortality
      k16 = .0054              'fish feces and mortality and predation by fish
      k20 =.0003316            'phosphate uptake by phyto
      k21 = 9.9467E-07         'phosphate uptake by macro
      k22 = .0000333           'phosphate sedimentation
      k23 = .02                'sediment settling
      k24 = .0274956           'organic consumption by zooplankton
      k26 = .0028              'organic sedimentation
      k27 = 8E-08              'fish utilization of macrophytes
      k28=.0000233             'fish utilization of phytoplankton
      k29=.0008                'fish utilization of zoo
      k30=.00002               'zooplankton utilization of macrophytes
      k31=.000133              'zooplankton utilization of phytoplankton
      k32=.012                 'zooplankton utilization of POM
      kr3 = .0015835


REM initial conditions
      pl = 60                  'phytoplankton
      m = 900                  'macrophytes
      p = 20                   'phosphate
      sed = .1                 'sediment
      org = 5                  'organics
      h2o = 2000               'lake volume
      z = 5                    'zooplankton
      f = 50                   'fish
      sc = .00001              'sediment in runoff
      oc = .00001              'organics in runoff
      pc= .0002                'phosphate in runoff
      al = 400                 'lake surface area
      aw = 4000                'watershed area
      rc = .0003               'runoff coefficient
```

Table G.2 continued

```
   fr= .01018155#            'fraction of phosphate in decomposition
      frorg = .08007962#        'fraction of organic in decomposition



t0 = 0
tend = 3650
dt = .1
FOR t = t0 TO tend STEP dt

REM  PLOTTING subroutine

REM scaling coefficients
ts = t*630/3650
ms = m*430/(1*1000)
pls = pl*430/(5*100)
fs = f* 430/(10*100)
zs = z*430/(5*100)
ps = p*430/(2*50)

PSET (ts, 430- ms)
PSET (ts, 344 - pls)
PSET (ts, 258 - fs)
PSET (ts, 172 - zs)
PSET (ts, 86 - ps)



REM  rate EQUATIONS
     rain = .00035*dt + .00035 *dt* SIN(t*.017)   'cumulative = 54 in
     i = 3800*dt + 800*dt*SIN(t*.017)
     rainlk = rain*al
     runin = rc*rain*aw
     p0 = pc*runin*1000/h2o
     s0 = sc*runin*1000/h2o
     o0 = oc*runin*1000/h2o
     pr = rainlk*.167/h2o

     r0 = i/(1+k0*p*m)
     r1=i/(1+k1*sed)
     r2 = r1/(1+k2*org)
     r3 = r2/(1+k3*p*pl)

REM mass differentials
     dm = k4*r0*p*m -k5*f*m - k6*z*m - k7*m - k8*m
     dpl = k9*r3*p*pl-k10*pl*f - k11*pl*z -k12*pl - k13*pl
     dz = k32 *org*z + k30*z*m + k31 * pl*z - k14*z*f - k15*z
     df = k27*f*m + k28*f*pl + k29*f*z - k16*f
     phin = p0 +fr*(k7*m + k12*pl + k15 * z + k16*f)
     phout = k20*p*pl + k21 *p*m + k22*p
     dp = phin - phout
     'dsed = s0*runin - k23*sed
     orgin = o0 + frorg*(k7 *m + k12*pl + k15*z + k16*f)
```

Table G.2 continued

```
      dorg = orgin - k24*z*org - k26*org

REM accumulations
      m = m + dm*dt
      pl = pl + dpl*dt
      z = z + dz*dt
      f = f + df * dt
      p = p + dp*dt
      'sed = sed + dsed*dt
      org = org + dorg*dt

NEXT t

700
LINE (0,0)-(330,430),,B
LINE (0,86)-(330,86)
LINE (0,172)-(330,172)
LINE (0,258)-(330,258)
LINE (0,344)-(330,344)
LINE (0,430)-(330,430)
RETURN
```

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BIOGRAPHICAL SKETCH

Sherry Brandt-Williams was born and raised in Miami, Florida during the time when some of the Dade pine stands and Everglade sloughs still existed in southern Dade County. She attended high school in Lake County, Florida, and there began a lifelong infatuation with Florida's lakes. After a long hiatus as an art major at Eckerd College, amateur naturalist, applied piano and music theory instructor, stained glass artisan and manager of a polymer furniture fabrication operation, she received a Bachelor of Science in Chemical Engineering from the University of Florida.

She worked as a research engineer for five years in the paper division of Procter & Gamble in Cincinnati, Ohio, receiving a patent for a product invention. With a revived interest in protecting natural resources, Sherry returned to Florida and designed and built a home in a hydric hammock in Central Florida as a working example of universal design for the handicapped on a minimally disturbed site. At the same time she home-schooled her son until he was 10, using the environment as the classroom. She then returned to graduate school in Environmental Engineering Sciences at the University of Florida, studying ecological engineering and aquatic systems ecology and receiving a National Science Foundation Minority Engineering Doctorate Initiative Fellowship.

After receiving her Ph.D., Sherry took a position as project coordinator for an ecological landscape characterization study with FDEP-Rookery Bay NERR.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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