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8

Landscape Development Intensity and Pollutant Emergy/Empower Density Indices as Indicators of Ecosystem Health

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CONTENTS

8.1 Introduction

In this chapter, an index of Landscape Development Intensity (LDI) is presented as a tool to evaluate ecosystem health. The LDI was recently proposed by Brown and Vivas (2005) following earlier work of Brown (1980) and an evaluation of the relationship of development intensity to water quality in the St. Marks River watershed in Florida (Brown et al. 1998; Parker 1998). The LDI is an index based on nonrenewable areal empower density of land uses. The LDI has been used as a human disturbance gradient in developing wetland bio-indicators of ecosystem health (Lane and Brown 2006; Reiss 2006) and in developing a Stream Condition Index (Fore et al. 2007). Recently the LDI was tested as an indicator of human disturbance against a large wetland data set in Ohio (Mack 2006).

Here we propose a new method for calculating the LDI of a landscape unit based on a $\log_{10}$ scale of the ratio of the nonrenewable areal empower density of the landscape unit to an areal empower density of the environmental baseline of the landscape unit. The environmental baseline is the average renewable areal empower density. In addition, we propose a spatial averaged LDI for point source pollutants, especially those associated with pollutants such as nutrients, metals, and other toxins. In general, metals, nutrients, and toxins have high Unit Emergy Values (UEVs) and as a result, when excess concentrations occur, they are capable of instigating significant changes in ecosystem processes, which often result in declines in ecosystem health.

8.2 Emergy, Time, and Area

Emergy is defined as the amount of energy of one type (usually solar) that is directly or indirectly required to provide a given flow or storage of energy or matter. The units of emergy are emjoules (abbreviated eJ) to distinguish them from energy joules (abbreviated J). We propose that the Greek letter epsilon (ε) be used for emergy in equations. Solar emergy is expressed in solar emergy joules (seJ, or solar emjoules). Emergy per unit time is *empower,* in units of emjoules per time. Solar empower is solar emjoules per time (e.g., seJ/time). We propose that the Greek letter omega (ω) be used for empower in equations.

When the emergy required to make something is expressed as a ratio to the available energy of the product, the resulting ratio is called a *transformity.* The solar emergy required to produce a unit flow or storage of available energy is called *solar transformity* and is expressed in solar emergy joules per joule of output flow (seJ/J). The transformity of solar radiation is assumed equal to one (1.0 seJ/J). We propose that the Greek letter tau (τ) be used for transformity in equations.

Specific emergy is the unit emergy value of matter defined as the emergy per mass, usually expressed as solar emergy per gram (seJ/g). Solids may be evaluated best with data on emergy per unit mass for its concentration. Because energy is required to concentrate materials, the unit emergy value of any substance increases with concentration. Elements and compounds not abundant in nature therefore have higher emergy/mass ratios when found in concentrated form since more work was required to concentrate them, both spatially and chemically. We propose that the Greek letter sigma (σ) be used for specific emergy in equations.

8.2.1 Area Empower Intensity

The following paragraphs provide background on our choice of the terminology for emergy per unit time per unit area, *areal empower intensity.* In the past we have proposed the terms areal empower density to describe emergy per unit time per unit area; however, in light of our need to define a new concept of emergy per unit time per unit volume, we suggest differentiating between *intensity* and *density* following the lead of physics.

In physics, especially related to sound, *intensity* is a measure of the time-averaged energy flux, or in other words, the amount of energy that is transported past a given area of a medium per unit of time. Intensity is the energy per time per area (energy*time^{-1}*area^{-1}), and since the energy per time ratio is equivalent to the quantity *power,* intensity is simply the power per area. Emergy intensity, then, is the emergy per time per area, and since emergy per time is *empower,* emergy intensity is empower per area. It should be noted that *energy intensity* as used in economics is defined as the measure of the energy efficiency of a nation's economy. It is calculated as units of energy per unit of gross domestic product (GDP). We suggest that the term *areal empower intensity* be used to describe emergy per unit time per unit area and that we use the Greek letters alpha, omega, iota (αωι) to denote it in equations.

8.2.2 Environmental Emergy Density

In physics, *density* is defined as the ratio of the mass of any substance to the volume occupied by it (usually expressed in kg/m^3). *Energy density* is usually defined as the amount of energy stored per unit volume, or per unit mass, depending on the context (usually expressed in J/g or J/L). When considering concentrations of pollutants in environmental systems, it is often appropriate to express them as concentrations (i.e., mg/L, µg/L, ppm, ppb). Since pollutants can be expressed as emergy using their specific emergy (seJ/g) then concentrations of pollutants in the environment, especially in aqueous environments, can be expressed as emergy density (i.e., seJ/m^3 or seJ/L). We propose that the terminology *emergy density* be used to describe emergy per unit volume (seJ/volume) in environmental systems and that the Greek letters epsilon delta (εδ) be used to denote it in equations.

8.2.3 Environmental Empower Density

In engineering, the term *power density* refers to power per unit volume. It is often used to describe the amount of power delivered by an energy source, divided by some measure of the size or mass of the source. In the environment, when pollutants are released over time their emergy per unit time per unit volume can be calculated from the pollutant's specific emergy and the quantities released. We have used the term *empower density* and, more recently, *areal empower density* to describe emergy per unit time per unit area. However, in keeping with engineering and physics definitions of density, we suggest the term *empower density* be used to describe emergy per unit time per unit volume ($seJ*time^{-1}*volume^{-1}$) and that the Greek letters phi delta ($\phi\delta$) be used to denote it in equations.

8.3 Landscape Development Intensity

In a previous paper, Brown and Vivas (2005) suggested that the ecological health of landscapes and the ecosystems within them is strongly related to levels of human activity that can affect adjacent ecological communities through direct, secondary, and cumulative impacts. In that paper, land use data were used in a development intensity measure derived from energy use per unit area and calculated as an index of Landscape Development Intensity (LDI), relating the index to direct measures of water quality in watersheds and the biological condition of hydrologically isolated wetlands measured through a field-based rapid assessment method.

8.3.1 Area Weighted LDI Calculation

As the method matured in its use, several limitations were realized that resulted in redefining LDI based on a background areal empower intensity. In previous publications (Brown and Vivas 2005; Lane and Brown 2006; Reiss 2006), LDI was calculated using a simple area weighted relationship between nonrenewable areal empower intensity of land uses as follows:

$$LDI_{Total} = \sum \%LU_i * LDI_i \tag{8.1}$$

where

LDI_{total} = LDI ranking for landscape unit

$\%LU_i$ = percent of the total area of influence in land use *i*

LDI_I = landscape development intensity coefficient for land use *i*

The area weighted LDI calculation served as a human disturbance gradient for development of indices of wetland condition for marshes, cypress domes, and riparian forested wetlands in Florida (Figure 8.1). Using community condition indices for three separate communities, significant

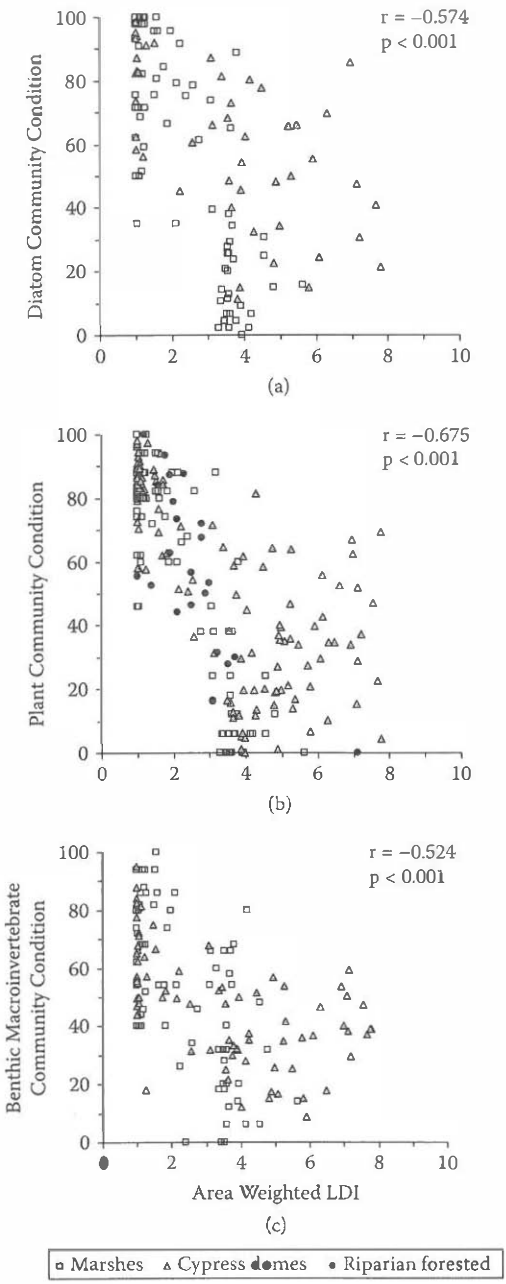

FIGURE 8.1
Area weighted LDI calculation as a human disturbance gradient with indices of wetland condition for (a) diatoms, (b) plants, and (c) benthic macroinvertebrate communities for marshes, cypress domes, and riparian forested wetlands in Florida. Values represent Pearson r correlation coefficients.

($p < 0.001$) correlations were found for the area weighted LDI with diatom community condition (Pearson r = –0.574), plant community condition (Pearson r = –0.675), and the benthic macroinvertebrate community condition (Pearson r = –0.524) using Minitab, version 15.1.

LDIs for larger areas calculated in this manner involved the averaging of logs (since individual land use LDIs are natural logs of their areal empower intensity). This method of calculating average LDIs for landscape areas composed of several land use types inserted significant bias in favor of the land uses with lower areal empower intensity. Further, it was apparent that impact of human disturbance intensity should in some way be related to the background renewable areal empower intensity of the landscape. That is to say, the effect of the nonrenewable emergy intensity is proportionally smaller if the background renewable emergy intensity is greater. This led to redefining the LDI in relation to the renewable background areal empower intensity. Finally, a limitation resulted from defining strict classes of land use types and limiting the calculation of LDIs to known land uses and their areal empower intensity. By redefining the LDI based on the nonrenewable empower intensity of land uses rather than a predetermined LDI for each land use, more flexibility in application of the method may result.

8.3.2 Renewable Background Areal Empower Intensity LDI Calculation

The calculation of a landscape, basin, or watershed LDI requires a land use/land cover map of the landscape unit of interest, aerial empower density multipliers for land use types (Table 8.1 is an example for Florida land uses), and the ability to calculate areas of land use within the landscape unit. The step-by-step procedure is as follows.

First, areas of each land use type within the landscape unit are summed and expressed as percent of total area. Second, percent of land use types are multiplied by the nonrenewable areal empower intensity of each type and summed. Then the following equations are applied:

$$\text{LDI} = 10 * \log (\alpha\varpi\iota_{\text{Total}}/\alpha\varpi\iota_{\text{Ref}}) \qquad (8.2)$$

where

LDI = Landscape Development Intensity index for a given landscape unit

$\alpha\varpi\iota_{\text{Total}}$ = Total areal empower intensity (sum of renewable background areal empower intensity and nonrenewable areal empower density of land uses)

$\alpha\varpi\iota_{\text{Ref}}$ = Renewable areal empower intensity of the background environment (Florida = 1.97 E15 seJ*ha^{-1}*yr^{-1}; Vivas 2007).

The total areal empower intensity ($\alpha\varpi\iota_{\text{Total}}$) is calculated as follows:

$$\alpha\varpi\iota_{\text{total}} = \alpha\varpi\iota_{\text{Ref}} + \sum(\%LU_i * \alpha\varpi\iota_i) \qquad (8.3)$$

where

$\%LU_i$ = Percent of the total area in land use *i*

$\alpha\varpi\iota_i$ = The nonrenewable empower intensity for land use *i*

Table 8.1 lists common land use types found in the Florida landscape. The second column lists typical nonrenewable areal empower intensities for land uses. The third column lists LDIs for 1 ha of the various land use types calculated using Equations (8.1) and (8.2) and the Florida renewable areal empower intensity of the background environment (1.97 E15 $seJ^{*}ha^{-1*}yr^{-1}$).

This method facilitates the calculation of LDIs for any area, using the areal empower intensity of land uses. The LDI scale begins with zero (i.e., equal to average renewable empower of the landscape unit), and there is

TABLE 8.1

Landscape Development Intensity (LDI) Coefficients for Typical Land Uses

Notes	Land Use	Nonrenewable Areal Empower Intensity (E15 $seJ^{-1*}ha^{-1*}yr^{-1}$)	LDI_{FI}[a]
1	Natural land/open water	0.0	0.00
2	Pine plantation	0.5	1.00
3	Low intensity open space/recreational	0.5	1.02
4	Unimproved pastureland (with livestock)	0.5	1.04
5	Improved pasture (no livestock)	2.0	3.07
6	Low intensity pasture (with livestock)	3.4	4.34
7	High intensity pasture (with livestock)	5.9	6.03
8	Medium intensity open space/recreational	6.1	6.10
9	Citrus	7.8	6.94
10	General agriculture	15.1	9.38
11	Row crops	20.3	10.53
12	High intensity agriculture (dairy farm)	50.4	14.25
13	Recreational/open space (high intensity)	123.0	18.02
14	Single-family residential (low density)	197.5	20.05
15	Transportation—2-lane highway	308.0	21.97
16	Single-family residential (med. density)	658.3	25.25
17	Single-family residential (high density)	921.7	26.71
18	Transportation—4-lane highway, low intensity	2533.7	31.10
19	Multifamily residential (low density)	4213.3	33.30
20	Institutional	4042.2	33.12
21	Transportation—4-lane highway, high intensity	5020.0	34.06
22	Low intensity commercial (comm. strip)	5173.4	34.19
23	Industrial	5210.6	34.23
24	High intensity commercial (mall)	8372.4	36.28
25	Multifamily residential (high rise)	12771.7	38.12

(continued)

TABLE 8.1 (continued)

Landscape Development Intensity (LDI) Coefficients for Typical Land Uses

Notes	Land Use	Nonrenewable Areal Empower Intensity (E15 $seJ^{-1}*ha^{-1}*yr^{-1}$)	LDI_{FI}[a]
26	Central business district (avg. 2 stories)	16150.3	39.14
27	Central business district (avg. 4 stories)	29401.3	41.74

[a] $LDI = 10 * \log[(\alpha\varpi\iota_i + \alpha\varpi\iota_{ref}) / \alpha\varpi\iota_{ref}]$

where

$\alpha\varpi\iota_i$ = nonrenewable areal empower density of Land Use *i*

$\alpha\varpi\iota_{ref}$ = areal empower density of background environment;
Florida = 1.97E+15 $seJ^{-1}*ha^{-1}*yr^{-1}$

Notes:

1. Nonrenewable empower density for natural systems = 0.
2. Doherty (1995).
3. Average of empower densities of 2 and 4.
4. Based on 0.09 cows/ha/yr (27 acres/animal) (Kalmbacher and Ezenwa 2006). Empower density to support 0.09 cows: 0.53 E15 sej/ha/yr (Brandt-Williams 2002).
5. Brandt-Williams (2002).
6. Based on 0.57 steer/ha/yr (1.76 ha/animal) (Arthington et al. 2007). Empower density to support 0.57 steer: 3.38 E15 sej/ha/yr = Improved Pasture (5) + 1.61 E15 sej/ha/yr
7. Based on 2 steer/ha/yr (Brandt-Williams 2002). Empower density to support two steer: 5.93 E15 sej/ha/yr
8. Assume three times intensity of improved pasture. In an urban landscape applies generally to grassy lawns (Falk 1976).
9. Brandt-Williams (2002).
10. Average of all crops (Brandt-Williams 2002).
11. Average of empower densities for 6 row crops (Brandt-Williams 2002).
12. Brandt-Williams (2002).
13. Based on the emergy evaluation for a golf course (Behrend 2000).
14. Parker (1998) and Brown (1980). Assumes 1.5 units per hectare.
15. Parker (1998).
16. Parker (1998) and Brown (1980). Assumes 5 units per hectare.
17. Based on Brown (1980). Assumes 7 units per hectare.
18. Brown and Vivas (2005).
19. Parker (1998) and Brown (1980). Assumes 32 units per hectare.
20. Brown (1980).
21. Vivas and Brown (2007).
22. Vivas and Brown (2007).
23. Parker (1998) and Brown (1980).
24. Vivas and Brown (2007).
25. Parker (1998) and Brown (1980). Assumes 97 units per hectare.
26. Brown (1980).
27. Brown (1980).

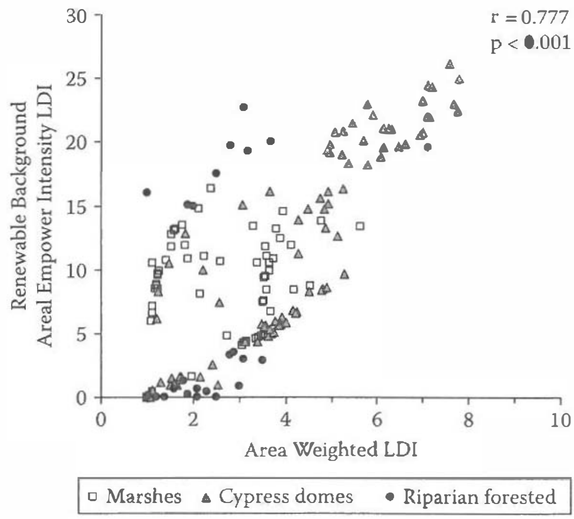

FIGURE 8.2
Correlation of renewable background areal empower intensity LDI calculation with the previous area weighted LDI calculation for marshes, cypress domes, and riparian forested wetlands in Florida. Values represent Pearson r correlation coefficients.

no upper limit. The LDI is calculated for the entire area of interest, without averaging logs, but instead calculating the weighted average nonrenewable areal empower intensity. Figure 8.2 shows the significant correlation between the renewable background areal empower intensity LDI calculation with the area weighted LDI calculation (Pearson r = 0.777, $p < 0.001$). While calculating an LDI based on land use/land cover appears to capture a great deal of the human disturbance gradient, a modifier that accounts for point source pollutants directly discharged into the ecosystem of interest is proposed below.

8.4 Pollutant Emergy and Empower Density

While the LDI can be used to estimate the impacts of general development intensity on ecological systems, it is well known that toxics and other pollutants have deleterious effects far from their initial source of introduction into the environment. Often they are released as dispersed materials in air and water and later become concentrated in aquatic systems or terrestrial food chains. Under these circumstances, the LDI calculated for land uses may not capture the production or subsequent concentration of the pollutant. If pollutants of known concentration are present in the environment, a Pollutant Density Index (PDI) can be calculated that relates the intensity of pollutants to the average intensity of the reference environment. Where pollutants are discharged into the aquatic environments, their flux in the environment can be deleterious to productive processes. Using the flux of the pollutant and the productivity of the background environment (measured as empower of the environment), an index of Pollutant Empower Density (PED) can be calculated.

8.4.1 Pollutant Density Index

The actions of chemical stressors including metals, toxins, and nutrients may be explained by their emergy and empower density relative to background environments. Table 8.2 lists the Unit Emergy Values (UEVs) for several metals and other pollutants. As UEVs increase, their potential effect within ecosystems increases. Effects can be both positive and negative. The ultimate impact of a pollutant or toxin is not only related to its UEV, but, more important, to its concentration, measured as emergy density in the ecosystem. Genoni et al. (2003) measured concentrations of 25 different elements in trophic compartments and in the physical environment of the Steina River in Germany. They calculated transformities of each element based on global emergy supporting the river ecosystem, which cycles the elements and their Gibbs energy. They suggested that the tendency to bioaccumulate was related to transformity of the elements and the transformity of accumulating compartments (i.e., metals and heavy elements accumulated in high transformity compartments).

The PDI is calculated in much the same manner as the LDI, however, using the standing stock of pollutant (concentration * volume) in the environment

$$\text{PDI} = 10 * \log (\varepsilon\delta_{\text{Total}} / \varepsilon\delta_{\text{Ref}}) \tag{8.4}$$

where

PDI = Pollutant Density Index for a given environmental volume

$\varepsilon\delta_{\text{Total}}$ = Total emergy density of the volume (sum of reference emergy density and pollutant emergy density [$\varepsilon\delta_i$])

$\varepsilon\delta_{\text{Ref}}$ = Emergy density of the background environment (freshwater = 1.45 E8 seJ/L; Odum et al. 2000)

The total emergy density ($\varepsilon\delta_{\text{Total}}$) is calculated as follows:

$$\varepsilon\delta_{\text{Total}} = \varepsilon\delta_{\text{Ref}} + \sum \varepsilon\delta_i \tag{8.5}$$

where

$\varepsilon\delta_i$ = Emergy density of pollutant i

Where emergy density of a stressor is significantly higher than the average of the ecosystem components it is released into, one might expect significant changes in ecosystem function. For instance, because of the very high

TABLE 8.2

Unit Emergy Values (UEVs) of Selected Metals, Nutrients, and Pesticides

Item	Specific Emergy (seJ/g)	Source
Elements		
Silicon	5.07E+08	See Appendix 8.1
Aluminum	1.74E+09	"
Iron	2.78E+09	"
Calcium	3.84E+09	"
Sodium	5.10E+09	"
Potassium	5.44E+09	"
Magnesium	6.75E+09	"
Titanium	2.26E+10	"
Hydrogen	1.00E+11	"
Phosphorus	1.08E+11	"
Carbon	1.49E+11	"
Manganese	1.56E+11	"
Sulfur	2.70E+11	"
Barium	2.81E+11	"
Chlorine	3.12E+11	"
Chromium	4.01E+11	"
Fluorine	4.84E+11	"
Zirconium	5.61E+11	"
Nickel	7.39E+11	"
Copper	2.06E+12	"
Nitrogen	7.02E+12	"
Lead	1.40E+13	"
Arsenic	6.68E+13	"
Uranium	7.80E+13	"
Cadmium	9.36E+14	"
Silver	1.75E+15	"
Mercury	2.09E+15	"
Gold	4.53E+16	"
Pesticides		
Herbicides	1.7E+10	From Pimentel (1980)
Insecticides	2.7E+10	From Pimentel (1980)

specific emergy of most metals (Table 8.2), their concentrations need only be in the parts per billion range to still have emergy densities greater than most natural ecosystems. Table 8.3 lists several metals and other pollutants and their EPA water quality criteria. Most of the metals have acute and chronic concentrations in the parts per billion range, while the criteria for nutrients are recommendations only. The sixth and seventh columns list the emergy

TABLE 8.3

US EPA Water Quality Criteria, Resulting Emergy Density, and Calculated PDI

Parameter	Units	Acute[a]	Chronic[a]	EPA Recommended[b]	Emergy Density[c] (seJ/L)	PDI[d]
Aluminum	μg/L	750	87		1.31E+06	0.09
Chromium	μg/L	16	11		6.42E+06	0.42
Copper	μg/L	13	9		2.68E+07	1.64
Lead	μg/L	65	2.5		9.10E+08	19.55
Arsenic	μg/L	340	150		2.27E+10	50.27
Cadmium	μg/L	2	0.25		1.87E+09	26.01
Mercury	μg/L	1.4	0.77		2.93E+09	30.21
Pesticide (Chlordane)	μg/L	2.4	0.0043		6.48E+04	0.00
Phosphorus (total)	μg/L			10	1.50E+05	0.01
Nitrogen (total)	mg/L			0.52	8.32E+06	0.54

[a] From the US EPA National Recommended Water Quality Criteria from May 2005. http://www.epa.gov/waterscience/criteria/wqcriteria.html

[b] EPA document EPA-822-B-00-013 from December 2000. http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/lakes/

[c] Calculated as the product of UEV in Table 8.2 and acute quantity of constituent.

[d] PDI = 10 * log ($\varepsilon\delta_{Total}/\varepsilon\delta_{Ref}$) where $\varepsilon\delta_{Ref}$ = 1.45 E8 seJ/L for freshwater (Odum et al. 2000).

density (seJ/L) for the acute concentrations and the PDI, assuming the pollutant is in a freshwater environment.

For instance, using the specific emergy of materials in Table 8.2 and the average concentrations of pollutants in landfill leachate in Table 8.4 the emergy density of the pollutants in the leachate totals 1.56 E10 seJ*L^{-1} and the PDI when calculated using the emergy density of freshwater (1.45E8 seJ*L^{-1}; Odum et al. 2000) is 33.6. When compared with the LDI indices in Table 8.1 it is apparent that the emergy density of leachate is extremely high. This emergy density of all the constituents is about two orders of magnitude greater than the emergy density of freshwater.

8.4.2 Pollutant Empower Density

Where pollutants are discharged into aquatic environments, their flux in the environment can be deleterious to productive processes. Concentrations at any one point can be calculated, but more important is the flux of the pollutant measured as the empower per unit volume (seJ*$time^{-1}$*$volume^{-1}$) as compared to the empower of the background environment. An example is the point discharge of pollutants into a stream. The stream ecosystem has characteristic productivity measured by its total empower (without the pollutant

TABLE 8.4
Concentrations, Emergy Density, and PDI of Some Landfill Leachate Constituents

Constituent	Units	Range[a]	Median Value[a]	Emergy Density[b] (seJ/L)	PDI[c]
Arsenic	mg/L	0.0002–1.6	0.8	5.34E+10	45.69
Barium	mg/L	0.08–5	2.5	7.03E+08	8.13
Cadmium	mg/L	0.0007–0.15	0.03	2.81E+10	39.35
Copper	mg/L	0.004–9	4.5	9.27E+09	28.65
Lead	mg/L	0.005–1.6	0.8	8.32E+09	27.64
Mercury	mg/L	0.0002–0.05	0.025	5.23E+10	45.47
Nickel	mg/L	0.02–2.227	1.12	8.28E+08	9.07
Phosphorus	mg/l	5–10	7.5	8.10E+08	8.95
			Total	1.54E+11	56.18

[a] Englehardt et al. (2006).
[b] Calculated as the product of UEV in Table 8.2 and quantity of constituent.
[c] PDI = 10 * log ($\varepsilon\delta_{Total}/\varepsilon\delta_{Ref}$) where $\varepsilon\delta_{Ref}$ = 1.45 E8 seJ/L (Odum et al. 2000).

discharge). The index of PED is calculated using the flux of the pollutant and the productivity of the background environment (measured as the empower of the environment) as follows:

$$\text{PED} = 10 * \log\left(\phi\delta_{\text{Total}}/\phi\delta_{\text{Ref}}\right) \tag{8.6}$$

where

PED = Pollutant Empower Density index for a given landscape unit
$\phi\delta_{Total}$ = Total empower density (sum of background empower density and pollutant empower density)
$\phi\delta_{Ref}$ = Empower density of the background environment

The total empower density ($\phi\delta_{Total}$) is calculated as follows:

$$\phi\delta_{\text{total}} = \phi\delta_{\text{Ref}} + \sum \phi\delta_i \tag{8.7}$$

where

$\phi\delta_i$ = Empower density of pollutant *i*

Table 8.5 lists typical empower densities of aquatic ecosystems as examples of the background productivity (reference environment) to be used in Equation (8.6).

TABLE 8.5
Empower Density of Aquatic Ecosystems

Ecosystem	Empower Intensity ($seJ^*m^{2*}yr^{-1}$)	Empower Density ($seJ^*m^{3*}yr^{-1}$)	Source
Freshwater systems			
Subtropical spring	3.80E+11	1.90E+11	Collins and Odum 2000
Subtropical lake	9.40E+11	4.09E+11	Brown and Bardi 2001
Subtropical herb. wetland	3.69E+11	5.59E+11	Bardi and Brown 2000
Subtropical eutrophic lake	3.30E+12	2.75E+12	Brown and Bardi 2001
Saltwater systems			
Louisiana estuarine sys.	9.60E+09	9.60E+09	Odum and Collins 2002
Oyster reef	7.57E+09	1.51E+10	Odum and Collins 2002
Coral reef	2.60E+11	1.73E+11	McClanahan 1990

8.5 Summary

In this chapter we have:

1. Proposed nomenclature to clearly define concepts of emergy intensity, empower intensity, areal empower intensity, emergy density, and empower density
2. Outlined an approach to calculating a human disturbance gradient using the Landscape Development Intensity (LDI) index
3. Outlined an approach to calculating pollutant emergy and empower density indices that can be used when known discharges of pollutants impact aquatic systems

The indices outlined in this chapter are our attempt to relate impacts for two general sources to potential alteration in ecosystem structure and function, which might collectively be termed ecosystem health. While the LDI has had several rounds of development and evaluation using a reference wetland database in Ohio (Mack 2006), data collected for herbaceous and forested wetlands of Florida (Reiss and Brown 2007), and riverine ecosystems in Arkansas (Vivas and Brown 2007), the PDI and PED indices are new concepts that require thorough vetting. Much research is needed to further develop these concepts and gather empirical evidence required to fully examine the theory.

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Appendix 8.1

Specific Emergy of Selected Elements

Element	% of Crust by Weight[a]	Weight (g)[b]	Specific Emergy[c] (seJ/g)
Total crust	100	2.82E+25	1.40E+08
Silicon	27.690	7.81E+24	5.07E+08
Aluminum	8.070	2.28E+24	1.74E+09
Iron	5.050	1.42E+24	2.78E+09
Calcium	3.650	1.03E+24	3.84E+09
Sodium	2.750	7.76E+23	5.10E+09
Potassium	2.580	7.28E+23	5.44E+09
Magnesium	2.080	5.87E+23	6.75E+09
Titanium	0.620	1.75E+23	2.26E+10
Hydrogen	0.140	3.95E+22	1.00E+11
Phosphorus	0.130	3.67E+22	1.08E+11
Carbon	0.094	2.65E+22	1.49E+11
Manganese	0.090	2.54E+22	1.56E+11
Sulfur	0.052	1.47E+22	2.70E+11
Barium	0.050	1.41E+22	2.81E+11
Chlorine	0.045	1.27E+22	3.12E+11
Chromium	0.035	9.87E+21	4.01E+11
Fluorine	0.029	8.18E+21	4.84E+11
Zirconium	0.025	7.05E+21	5.61E+11
Nickel	0.019	5.36E+21	7.39E+11
Copper	0.0068	1.92E+21	2.06E+12
Nitrogen	0.0020	5.64E+20	7.02E+12
Lead	0.0010	2.82E+20	1.40E+13
Uranium	0.00018	5.08E+19	7.80E+13
Silver	0.000008	2.26E+18	1.75E+15
Mercury	0.0000067	1.89E+18	2.09E+15
Gold	0.00000031	8.74E+16	4.53E+16

[a] Clarke and Washington (1924).

[b] Calculated as the percent of earth's crust by weight times the weight of the earth's crust. Weight of continental and oceanic crust = 2.82 E25 g.

[c] Annual emergy driving the geobiosphere = 1.58 E25 seJ/yr (Odum et al. 1998). Crust turnover time 2.5 E8 years. Total emergy driving geologic processes = turnover time * annual emergy flow. Emergy total = 1.58 E25 seJ/yr * 2.5 E8 yrs = 3.96 E33 seJ.