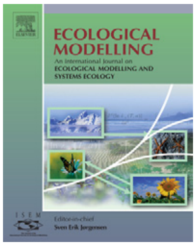
ECOLOGICAL MODELLING 205 (2007) 255–264

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ecolmodel



Stream order, hierarchy, and energy convergence of land use

Shu-Li Huang[a,*], William W. Budd[b], Shih-Liang Chan[c], Ying-Chen Lin[d]

[a] Graduate Institute of Urban Planning, National Taipei University, Taipei 10433, Taiwan
[b] School of Earth and Environmental Science, Washington State University, Pullman, WA 99164-4430, United States
[c] Department of Real Estate and Built Environment, National Taipei University, Taipei 10433, Taiwan
[d] Graduate Institute of Urban Planning, National Taipei University, Taipei 10433, Taiwan

ARTICLE INFO

Article history:
Received 28 August 2006
Received in revised form
10 February 2007
Accepted 20 February 2007
Published on line 30 March 2007

Keywords:
Energy convergence
Hierarchy
Land use
Stream network
Transformity
Tansui River

ABSTRACT

The streams in a watershed are organized as a network. From an ecological energetic point of view, this hierarchical organization is a result of the convergence of energy. This paper investigates the convergence of river energy and its relation to the energetic hierarchy of land use in the Tansui River Basin. Stream order is used to rank and measure stream position in the hierarchy of tributaries. Stream transformity is used to measure the energetic hierarchy of streams and the relative position of any particular stream in a scale of increasing energy quality. The spatial analysis capability of GIS is used to calculate the spatial distribution of accumulated rainfall emergy, the geopotential energy of runoff, and transformities of surface runoff and streams. The results indicate that stream order corresponds to transformity. The series of transformities increase with successive convergence of streams and this explains the hierarchical organization of the Tansui River. The spatial pattern of land-use transformity is also compared with runoff and stream transformities in the Tansui River Basin. As a result, the hierarchy of land use in Tansui River Basin is correlated to the hierarchy of streams and runoff and supports the hypothetical influence of stream energetic convergence on the spatial pattern of land use.

1. Introduction

Although the major function of a stream is to convey runoff and transport sediment, much of the landscape is sculpted and organized by stream systems (Odum and Odum, 2001). One reason for the hierarchical organization of streams in the landscape is allow streams to seek the path of least resistance from their origin to their end as described by Leopold and Langbein (1962). Another reason for the hierarchy of stream networks is the convergence of energy (Odum, 1987). Streams not only structure basins but also send high-quality waters and valuable substances downstream to enhance the fertility of valleys and coastal zones (Odum and Odum, 2001). Romitelli (1997) evaluated work done by water energies for six Brazilian watersheds. That analysis indicated that river water accumulates energy through the river network, and in the lower reaches of the watershed, the physical energy of the stream water spreads sediments and nutrients out onto the flood plains impacting lowland productivity.

The relationships between watershed dynamics and urban development have frequently been addressed. Most of this literature has emphasized the effects of urbanization on stream flows and networks (Kibler, 1982). For example, urbanization increases the imperviousness of land surfaces diverting more surface runoff to storm sewers resulting in significant changes in stream flow characteristics. But assessments of the underlying energetic driving force of streams and the spatial relations between stream networks and the hierarchy of land use has

---

[*] *Corresponding author*. Tel.: +886 2 2500 9713; fax: +886 2 2505 4954.
E-mail address: shuli@mail.ntpu.edu.tw (S.-L. Huang).

0304-3800/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2007.02.023

received far less attention. It has been hypothesized that the spatial configuration of human activities depends largely on energy production and consumption conditions (Huang, 1998). This paper focuses on the spatial energetic hierarchy of a stream system and examines the relations between stream hierarchy and land use hierarchy. Our objective is to demonstrate that ecological energetics can be useful in describing the spatial relationships between stream hierarchies and land use hierarchies. In addition, we are interested in exploring the hypothetical influence of stream energetic convergence on the spatial patterns of land use. Our analysis uses the Tansui River Basin to investigate the convergence of river energy and its relationship to the energetic hierarchy of land uses. A spatial analysis for the investigation of stream hierarchy is used to reveal the spatial pattern of land use follows the energetic hierarchy of the stream system. Emergy theory (Odum, 1988, 1996) is used to study the energetic hierarchy of a stream network. GIS is applied to perform a spatial analysis of stream ordering and calculations of the transformities of each stream segment.

We begin by expanding some concepts emerging from ecological energetics. In Section 2, the characteristics of a stream system is described from the viewpoint of the energy hierarchy. This section is followed by the introduction of emergy theories and transformity. The calculation of stream transformity using GIS is also described. In the next section, this method is applied to measure the transformity of stream flows within Tansui River Basin in order to identify the spatial distribution of the hierarchical position of stream flows. The relationships between stream hierarchy and stream characteristics are also analyzed. The overall purpose of this work is to extend the energetic analysis of streams to reveal the interrelationships between the stream and land use hierarchies.

2. Energy, hierarchy and streams

There are a number of factors that collectively are responsible for variations in the stream hierarchy. These factors include precipitation, geology, topography, and land cover. Precipitation falling on the watershed is the major source of water inflows. After surface runoff is collected in channels, it converges spatially and provides valuable life-support services for downstream consumers. Consequently a watershed is more than a collection of streams and their adjacent land areas. A watershed should be regarded as a natural system in which humans and other organisms interact with the land and water resources.

The interaction of water and land in a large-scale hydrological system creates a specific drainage pattern. The patterns that stream form in the landscape (e.g. dendritic, radial, or trellis) is often determined by local geologic structure. This stream network is hierarchically organized to minimize the total energy expenditure promoting better energy efficiency and system stability (Leopold, 1974). Horton (1945) applied morphometric analysis to a variety of stream attributes and proposed a number of laws of drainage composition. One of the first attributes to be quantified was the hierarchy of stream segments according to an ordering classification system. Stream ordering in itself may not be very useful. However, stream order can be used as a correlate to other stream parameters such as the number of streams, gradient, drainage area and discharge (Leopold et al., 1964). As shown in Fig. 1, the geopotential energy of rain falling at higher elevations is used up in transformation steps as small streams combine to generate larger ones. Rains also bring to land the chemical potential energy of freshwater. The geopotential energy of surface runoff and stream flow is converted into kinetic energy, friction, and work on geological and biological systems (Odum, 1996). In the development of emergy and energy hierarchy theory, Odum (1996) used the river to demonstrate the self-organization of watersheds. Using the geopotential energy from upstream areas higher transformity streams are developed that can disperse waters in floodplains and lower deltas, thus maximizing the biological productivity and other contributions of the downstream areas. The results of emergy analysis of the Mississippi River indicate that the geopotential energy of rain is used by streams as they combine and become streams of higher order (Odum, 1987). Romitelli (1997) studied the organization of watersheds by evaluating work done by water energies on the landscape and explored the hypothesis that self-organizing watersheds couple the geopotential and chemical potential energy use to maximize biological and geological production.

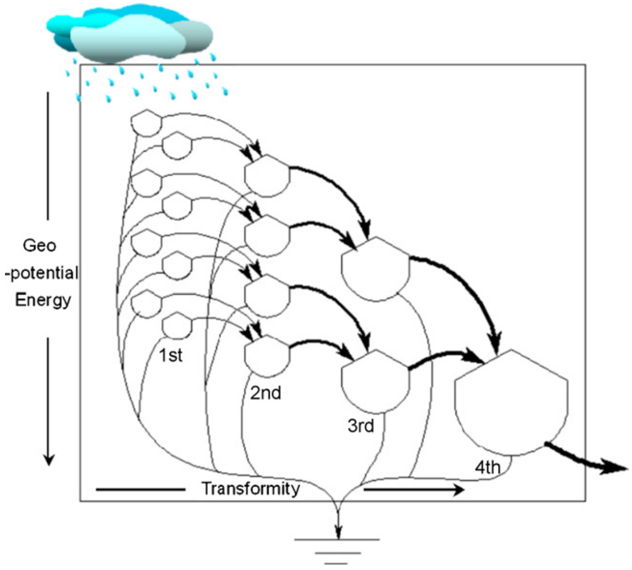


Fig. 1 – Energetic hierarchy of stream flow.

In an attempt to define a biophysical value theory applicable with equal facility to both ecological and economic systems, Odum noted that all forms of energy do not accomplish an equivalent amount of work (Odum, 1983). Emergy and transformity were introduced by Odum (1988, 1996) in order to take into account the varied qualities of energy inherent in the hierarchy of system components and to allow their comparison on a common basis. Emergy is "*the energy of one type required in transformation to generate a flow or a storage*". The solar emergy of a flow or storage is the solar equivalent energy required to generate that flow, or storage. Its units are solar emergy joule (sej). Extending the food chain concept to thermodynamics, Odum defined transformity as "*the emergy of one type required* *to make a unit of energy of another type*" (Odum, 1988, 1996). The solar transformity is expressed as the solar emergy per unit of energy (sej/J). Transformity measures relative position in a scale of increasing quality of energy. Like the efficiency ratio, transformity is defined by a simple input–output ratio, but transformity involves both direct and indirect energy flows. Therefore, transformity can also be defined as the ratio of emergy input to energy output. During the process of energy transformation, the total quantity of energy decreases, but transformity increases, meaning that the transformed energy increases its ability to reinforce other units of the system.

Hierarchy theory allows the decomposition of a complex system into an interconnecting network. The hierarchy approach to ecosystems portrays a phenomenon as a series of hierarchical relationships. Ecosystem components can be arranged in a series according to the number of transformation steps from one item to another. At each transformation, most of the available energy is degraded and dispersed as a necessary process of the second law of thermodynamics in order to generate a smaller amount of energy at the next hierarchical level. Since energy flows are converging at each step to make fewer flows of energy at the next, it is an energy hierarchy. In this hierarchical system, many units of smaller size and territory converge to a fewer number of large size and territory (Odum, 1988). Transformity is a measure of the hierarchy of energy and is applicable to all quantities of energy, material, or information (Odum, 1996). With the concept of transformity, we have a scale of energy quality that indicates position within the energy hierarchy.

Using emergy as a common numerator to evaluate the work of nature provides a rigorous theoretical basis for ecosystem studies. The flows of energy not only generate hierarchies in all systems but also develop hierarchical spatial patterns (Odum and Odum, 2001). As a result, the transformities and emergy concentration increases at the places where the energy from natural processes of wind, water, and earth converge and produce high-quality resources for human societies (Odum and Odum, 2001). Thus urban centers have high concentrations of energy and resource use, high empower density and transformity. In an effort to investigate the energy hierarchy of an urban landscape system, Huang et al. (2001) used the Taipei metropolitan region to study the effect of energy flows on the hierarchies and spatial organization of urban zonation. The results indicate that the empower density and transformity increase from rural areas to the urban center.

3. Methodology

Emergy was introduced by H.T. Odum to take into account the different quality of driving forces supporting a process and to allow for comparisons to be made using a common metric. After the energy content of a flow has been estimated, it can be multiplied by its solar transformity to obtain its solar emergy:

$$\text{Solar emergy (sej)} = \text{energy (J)} \times \text{solar transformity (sej/J)} \quad (1)$$

Odum (1996) noted that "energy flows of the universe are organized in an energy transformation hierarchy. The position in the energy hierarchy is measured with transformities". Leopold (1994) also defined stream order as "a measure of the position of a stream in the hierarchy". The main task in our research, therefore, is to calculate the distribution of surface water transformities and to use these transformities to make a comparison between different stream orders for the discussion of the spatial hierarchy of streams within a watershed.

Solar transformities of surface runoff or stream flow at each location can be calculated as the quotient of the input emergy of geopotential in rainfall from its drainage areas and the geopotential energy of surface runoff or stream flows:

$$\text{Transformity of runoff} = \frac{\text{Total geopotential rain emergy}}{\text{Geopotential energy of runoff}} \quad (2)$$

$$\text{Total geopotential rain emergy} = (R)\,(A)\,(\text{EL})\,(D)\,(g)\,(\text{TR}_{\text{rain-g}}) \quad (3)$$

$$\text{Geopotential energy of runoff} = (\text{SR})\,(D)\,(\text{EL})\,(g) \quad (4)$$

$$\text{Runoff} = (R)\,(C)\,(A) \quad (5)$$

where A is the drainage area (m^2), C the runoff coefficient, D the density of water ($10^3\,\text{kg/m}^3$), EL the elevation (m), g the gravity ($9.8\,\text{m/s}^2$), R the rainfall (m), SR the surface runoff (m^3), $\text{TR}_{\text{rain-g}}$ is the transformity of physical energy of rain (10,488 sej/J) (Odum, 1996).

The quantities of rainfall and runoff used for the calculation of transformities at each location are calculated as the accumulated value from its drainage area.

The Tansui River Basin (Fig. 2) is situated in the northern region of Taiwan encompassing 2726 km^2. The river flows approximately 158.7 km from its headwaters in Hsin-Chu County, passing through Tao-Yuan County, Taipei County, and Taipei City, before draining into the Taiwan Strait. The major tributaries to the Tansui River include Ta-Han Creek, Hsin-Tien Creek, and Keelung River. These tributaries intersect and become the main branch of the Tansui River in the low lying geomorphic basin areas. Land use in Tansui River Basin is approximately 82% forested (mostly on the steep slope area on the south), 9.5% agricultural, and 8.5% urban. Major cities and towns are located in the low lying geomorphic basin area on the northern portion. Data from various statistical and geo-

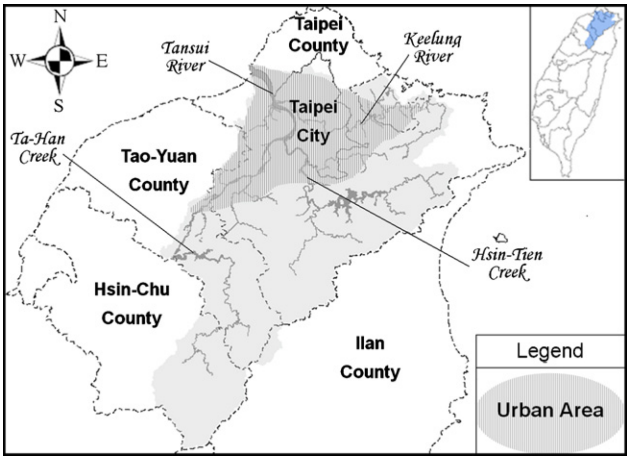


Fig. 2 – Regional context of Tansui River Basin.

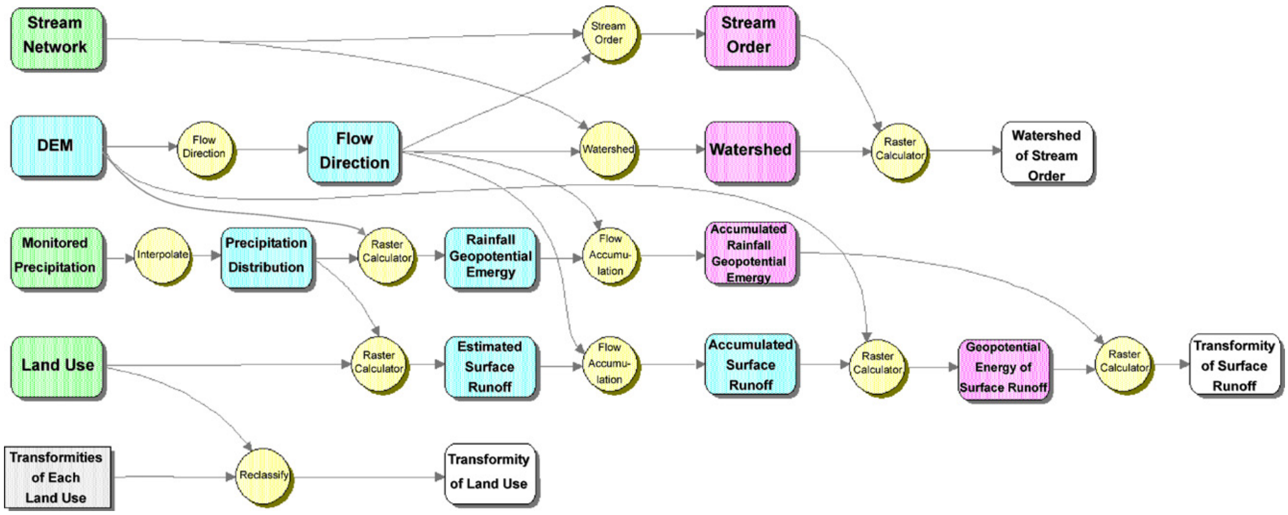


Fig. 3 – Procedure of spatial analysis for calculating transformity of runoff and stream using GIS.

graphical information sources concerning Tansui River Basin's natural processes (e.g. precipitation, topography, stream network, land use, etc.) were collected to understand the Tansui River's stream system and to calculate the spatial distribution of emergy and transformity of streams. Land use transformities measured by Huang et al. (2001) in the Taipei Metropolitan Region were used to represent the spatial hierarchy of land use in the Tansui River Basin.

To calculate the spatial distribution of transformities of surface water and to compare stream hierarchy with land use hierarchy a spatial analysis using Geographic Information Systems (GIS) was made. A flowchart of the steps in the spatial analyses for the calculation of the spatial distribution of Tansui River Basin's stream transformity is shown in Fig. 3. These steps can be summarized as follows:

- Digital elevation map and stream network were used to delineate watershed boundaries.
- Monitored precipitation data were interpolated to generate a precipitation distribution map.
- Precipitation distribution and land use maps were then used to estimate surface runoff. These data were then used to derive the accumulated surface runoff on each grid and the subsequent stream flows in the channel.
- Digital elevation map and precipitation distribution map were used to calculate the emergy of geopotential in rainfall.
- Total geopotential rainfall emergy contributed to each location was estimated by summing all the rainfall emergy on each drainage area.
- Transformity of surface runoff and stream flows were then calculated by dividing the total geopotential rainfall emergy contributed to each specific location with the geopotential energy of water.
- The spatial distribution of land use transformities was then estimated using land use map and previous research on the transformities of each land use.
- Comparisons between stream hierarchy and hierarchy of land use were then made.

4. Results—transformity of Tansui River

The characteristics of the Tansui River can be conceptualized as properties emerging from geomorphic, climatic, and land cover variables. The highest elevation in the Tansui River Basin is approximately 3500 m (Fig. 4A). The eastern mountainous region has the highest annual precipitation in the basin (Fig. 4B). The streams of the Tansui River Basin drain from south, east and west toward the low-lying geomorphic basin in the north. Using Strahler's stream ordering system, the stream network of Tansui River is classified from first to seventh order streams (Fig. 4C). A land use map (Fig. 4D) of the Tansui River Basin shows that the upstream watershed is dominated by forested areas while urban land uses are concentrated in the low-lying geomorphic basin areas where Ta-Han Creek and Hsin-Tien Creeks intersect and become the main branch of the Tansui River.

Using land use to estimate runoff coefficient, surface runoff can be calculated. In order to measure the stream transformities of the Tansui River Basin rainfall and stream flows were converted into emergy and energy units. The flow accumulation function of GIS spatial analysis was used to calculate the accumulated geopotential rainfall emergy and the geopotential energy of runoff. Stream flow and stream flow energy change from the headwaters to mouth of the Tansui River was examined. Headwater streams are typically small with greater velocity and a steeper gradient. As these streams flow downhill, they merge with other streams becoming a bigger slower moving body of water with less gradient. Although the down stream channels have higher stream runoff then upstream channels, the geopotential energy at each stream junction declines (see Fig. 5). The transformities of surface runoff and stream flows can be derived by dividing the accumulated geopotential rainfall emergy with geopotential energy of surface runoff (Fig. 5). As shown by Fig. 6, transformities of surface runoff increase along their pathways toward the downstream areas. Transformity is highest at the places where waters and their content converge most and the emergy of the whole Tan-

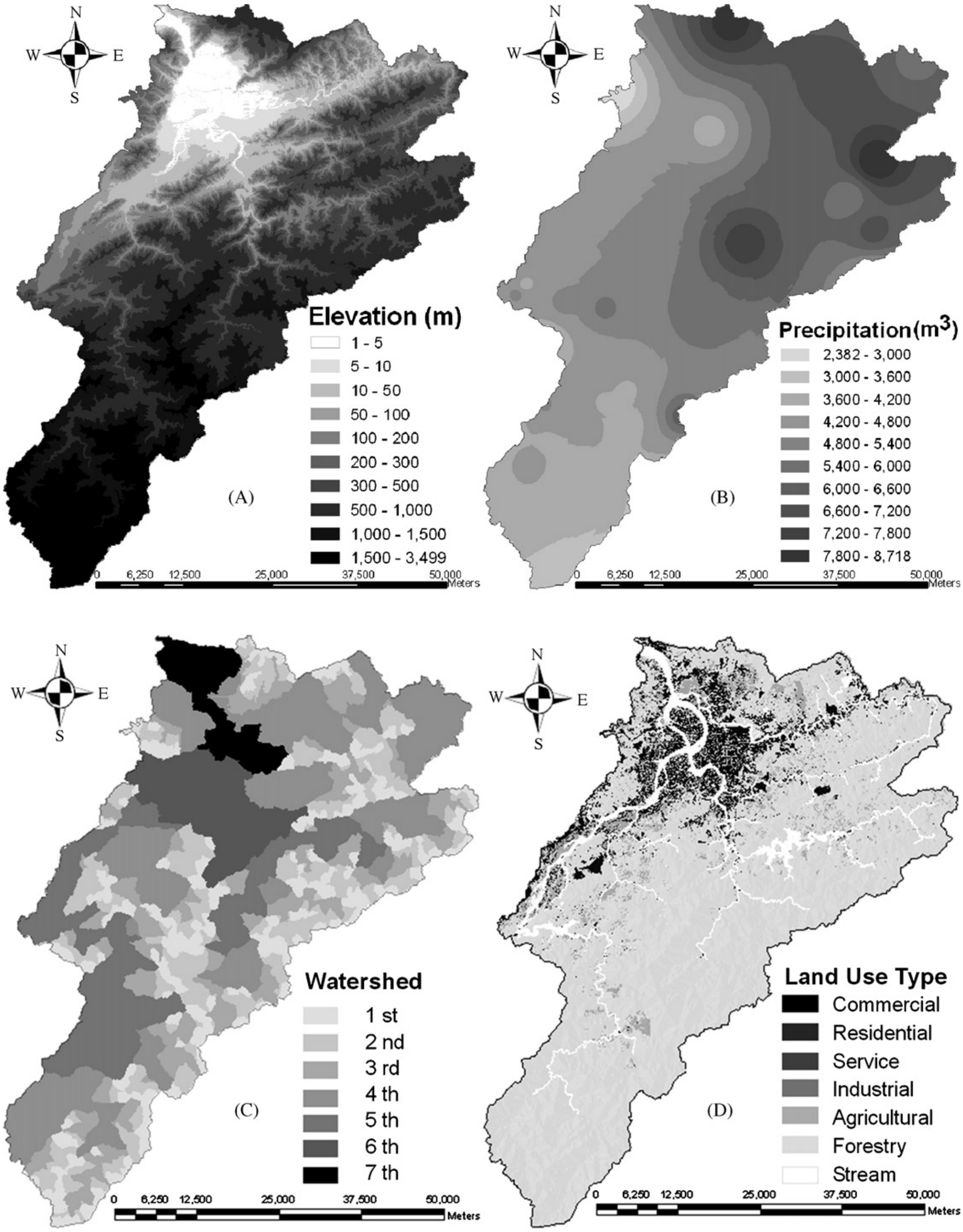


Fig. 4 – Tansui River Basin: (A) elevation; (B) precipitation; (C) stream order watershed; (D) land use.

sui River Basin is available. The average transformities and geopotential energy for each stream order are shown in Fig. 7. Due to the low stream flows in headwater streams and the relatively lower altitude of sixth and seventh order streams, the fifth order streams have the highest geopotential energy in the entire Tansui River Basin. The transformities calculated for each stream order of the Tansui River have a range of values. The average value provides an approximate transformity for a given stream order and can be used to determine its hierarchical position in the system. Fig. 7 shows the distribution of transformities of each stream order of the Tansui River. The average transformities of 1st order to 4th order streams increase with geopotential energy in stream flows. But, due to the sudden drop of geopotential energy beyond 5th order stream flows, there appears an inverse relationship of transformity to geopotential energy in stream flows of 5th order to 7th order streams of the Tansui River. As the rainfall from the uplands accumulates as runoff and flows into stream channels transformity increases. A breakdown of stream transformities for each sub-basin (Table 1) reveals that for the sub-basin of

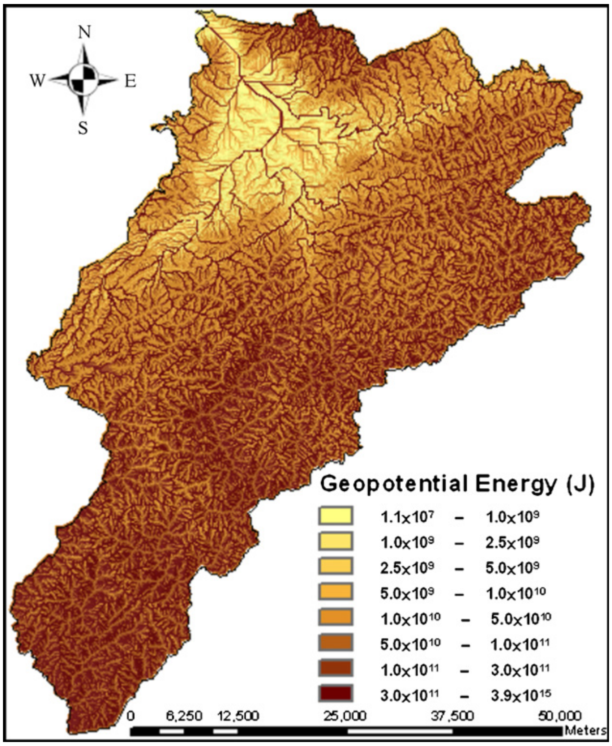


Fig. 5 – Geopotential energy of surface water of the Tansui River Basin.

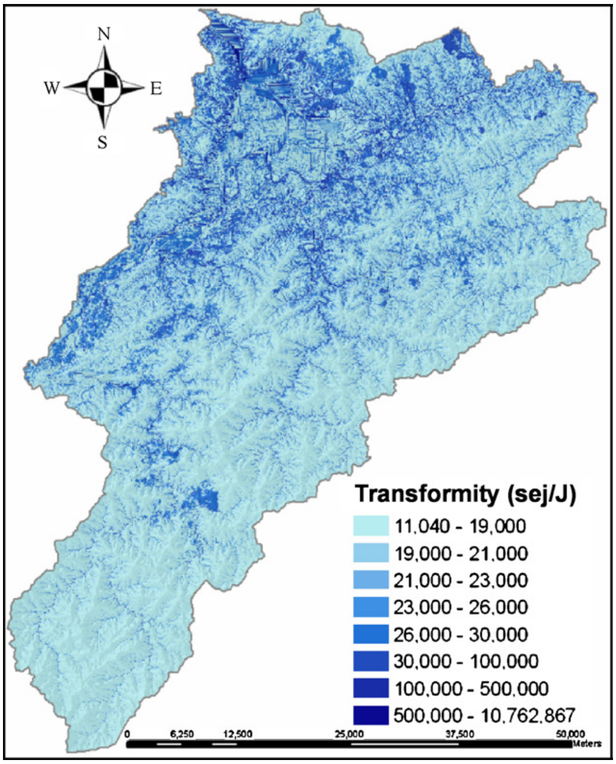


Fig. 6 – Transformity of surface runoff of the Tansui River Basin.

Ta-Han Creek, the stream transformity of each order stream increases transformity with stream hierarchy. The 5th order streams of Hsin-Tien Creek are located on high altitude areas, which have high geopotential river energy and results in the low value of stream transformity. The 3rd order streams of Keelung River are located on areas with highest precipitation in the basin; the high geopotential rain emergy in these areas result in stream transformity higher than 4th order streams.

Because the annual precipitation of the 5th order stream watersheds of Ta-Han creek is the lowest in Tansui River Basin, the accumulated rainfall emergy is not high. This results in relatively low stream transformity as compared to the 4th stream order watersheds of Keelung River and the main branch of Tansui River. The average transformity of the 5th order stream of the entire Tansui River Basin also does not appear to follow this increasing rule of transformity with stream hierarchy. This phenomenon is likely the result of the 5th stream

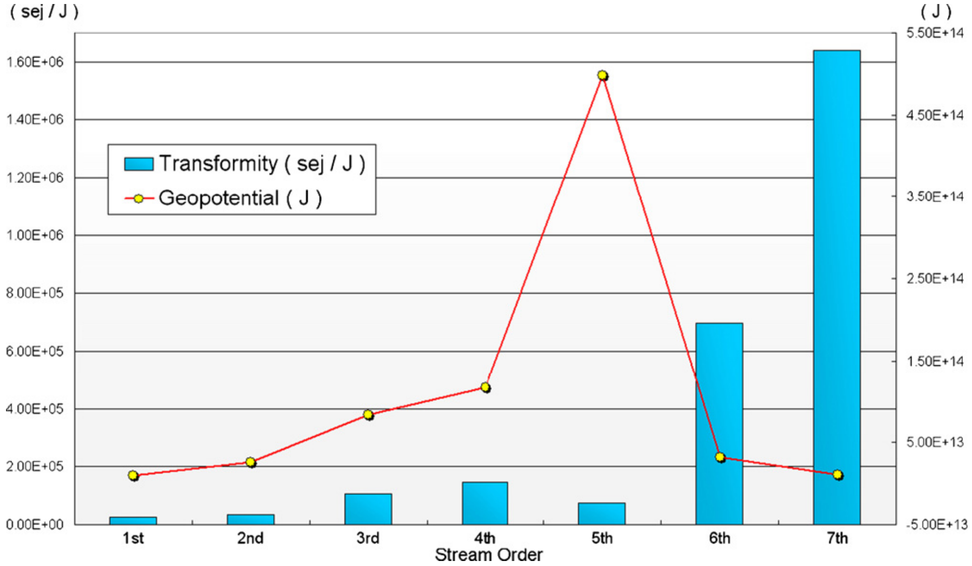


Fig. 7 – Geopotential energy and stream transformity of different stream order of the Tansui River Basin.

Table 1 – Transformities of different stream orders for each sub-basin in the Tansui River

Watershed	Stream order						
	1st	2nd	3rd	4th	5th	6th	7th
Ta-Han Creek Sub-Basin	2.22	2.84	3.08	4.40	8.54	114.27	–
Hisn-Tien Creek Sub-Basin	2.40	2.74	3.30	7.45	5.27	49.42	–
Keelung River Sub-Basin	2.90	5.05	46.07	27.22	–	–	–
Tansui River Main Branch	8.95	1.19	24.97	28.54	–	–	164.05
Entire Tansui River Basin	2.62	3.43	10.71	14.70	7.53	69.83	164.05

Unit: 10^4 sej/J.

order watersheds in Tansui River Basin being located either at higher elevations or in low precipitation areas (see Fig. 4B and C).

5. Discussion—spatial hierarchical pattern of stream order and land use

In the Tansui River Basin, the longitudinal changes of stream characteristics can be observed by disaggregating the river into a hierarchy of stream orders. As the water moves across these landscapes sediment erodes and is carried downstream. In this chain of stream flow transformations, geopotential energy decreased through successive transformations, but the source emergy is transmitted and the solar transformities of runoff and stream flow increase as the order of stream hierarchy increases. The series of increasing transformities with the successive convergence of streams explains the energetic hierarchy of the Tansui River. The transformity of streams represents the position of flows in the entire river basin's energy hierarchy. By spreading out the nutrients, sediments, and water in flood plains, the spatial convergence pattern of the river network brings in highly concentrated stream flows of high emergy into the low lying basin areas providing the resource base for agricultural productivity.

Beyond structural changes of stream channels in the Tansui River Basin, there are observable changes in land cover and land use along the streams from the headwaters to the mouth (see Fig. 4D). The abrupt changes in land use are associated with a decrease in stream gradient and geopotential energy along a stream's course. However, it should also be noted that land use change is also associated with the increase of surface water transformity. Different types and amounts of energy flow tend to be associated with different intensities of urbanization in the Taipei area (Huang and Chen, 2005). But, for the case of the Tansui River Basin, to what extend does the hierarchy of land use correlate with the hierarchy of streams?

In an attempt to study the energetic hierarchy of the urban landscape system, Huang et al. (2001) calculated the spatial distribution of emergy flows of Taipei metropolitan region, using GIS, and indicated that empower density increases from rural to urban center (Fig. 8). In their assessment, transformity of land use was also calculated by summing all emergy flows during past two hundred years and then divided by the current potential energy. Based on the calculation by Huang et al. (2001), the land use transformity of the Tansui River Basin (see Fig. 9) increases from upstream watersheds in the southwest toward the low lying basin in the northeast where the urban areas are located. Using the emergy concept, the hierarchy of energy flows can also explain land use hierarchies and their arrangement in the landscape. In examining the spatial pattern of land use hierarchy and the hierarchy of surface runoff and streams, there appears to be a correspondence between the transformity of surface runoff and empower density (Fig. 8) and the transformity of land uses (Fig. 9). Major human settlements with higher empower density and transformity, a measure of land use hierarchy, tend to originate along streams with higher orders and transformity while upstream watersheds with lower stream orders are mostly dominated by natural areas with lower empower density and land use transformity. Table 2 summarizes the average transformities of surface runoff and land use for watersheds of

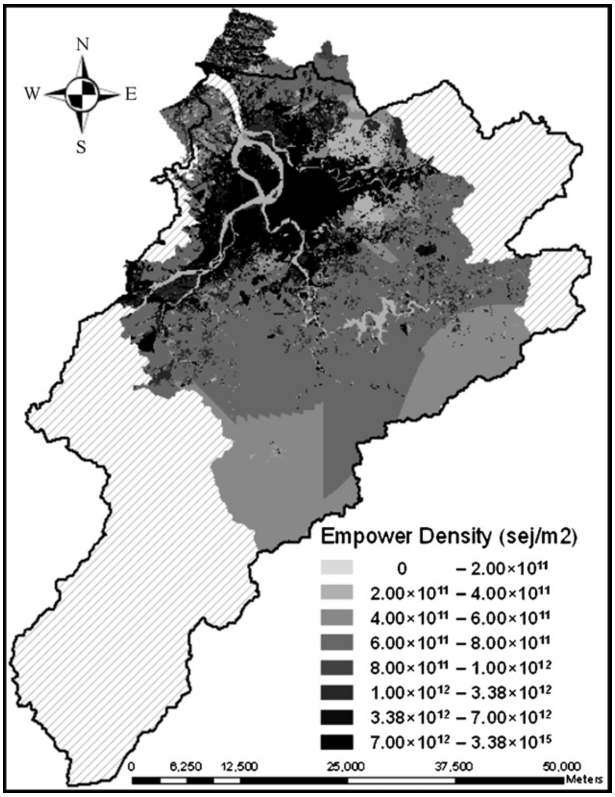


Fig. 8 – Empower density of Taipei metropolitan area.

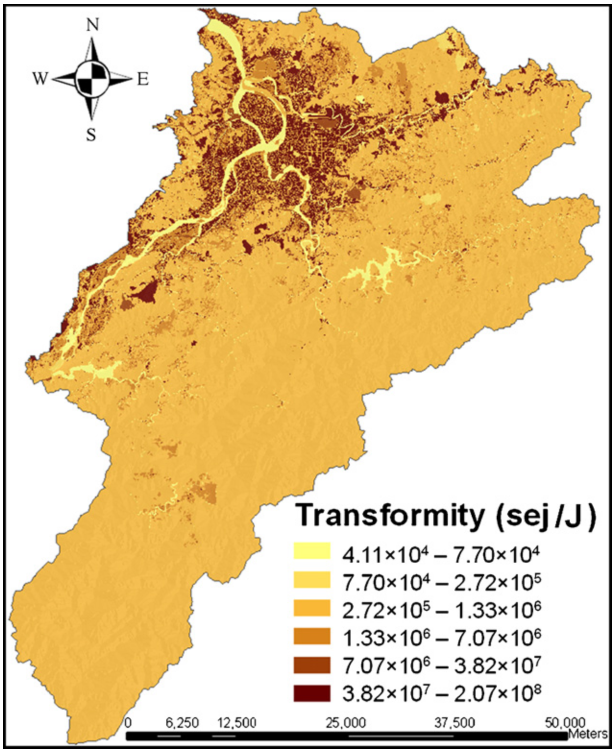


Fig. 9 – Land use transformity of the Tansui River Basin.

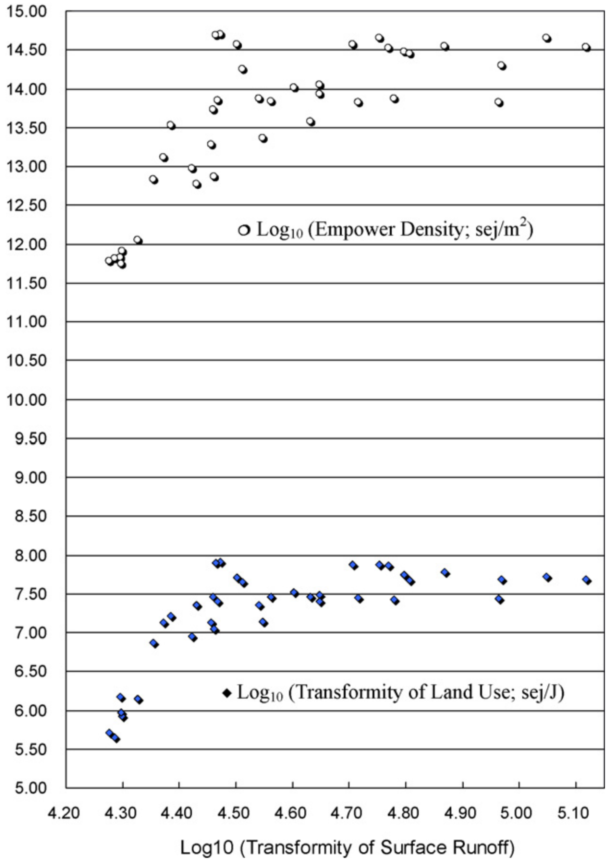


Fig. 10 – Correlation between average empower densities, land use transformities and surface runoff transformities of 47 administrative districts in the Tansui River Basin.

different stream orders in Tansui River Basin. Although the average runoff transformity of 5th order stream watersheds does not follow the rule of increasing stream transformity with stream order, the value of land use transformities does correspond with runoff transformities. Watersheds with higher runoff transformity (e.g. 6th and 7th order stream watersheds) also have higher land use transformities. The percentage of urban land use in these two watersheds, 22.19% and 36.84%, respectively, is relatively higher than the other watersheds with lower stream order. When we examined the 47 administrative units in Tansui River Basin (Fig. 10) the correlation between empower density, land use transformity and runoff transformity is even more pronounced.

Although there maybe different approaches to scale, scale as hierarchy or scale as magnitude, the study of the scale as hierarchies of streams and land uses is related to scale of magnitude. The transformities of land uses are related to the total magnitude of different energy inputs to each land use category. The size of settlements, stream flow, and transformity in Tansui River Basin provide an interesting model to examine the relationships between hierarchy and magnitude. As shown in Fig. 11, the size of settlements in Tansui River Basin is also correlated to the stream flow and transformity of the stream nearby. Small settlements are located in the upstream watersheds with lower stream orders and transformities. Conversely, larger settlements like Taipei city are located along the main branch of Tansui River with high stream flows and transformities.

Table 2 – Average transformities of land use and surface runoff for watersheds of different stream order

Watershed	1st	2nd	3rd	4th	5th	6th	7th
Surface runoff transformity (10^4 sej/J)	1.96	2.04	2.46	2.79	2.26	4.81	8.89
Land use transformity (10^6 sej/J)	3.25	3.21	4.87	13.42	4.48	26.15	44.72
Major land use	F: 93.08% A: 3.50% U: 2.94% S: 0.47%	F: 91.30% A: 4.90% U: 2.65% S: 1.14%	F: 80.71% A: 7.01% U: 8.44% S: 3.84%	F: 78.61% A: 7.89% U: 10.31% S: 3.19%	F: 79.42% A: 10.22% U: 3.25% S: 7.10%	F: 60.36% A: 9.28% U: 22.19% S: 8.17%	F: 41.69% A: 9.32% U: 36.84% S: 12.15%

F: forest; A: agricultural; U: urban; S: stream.

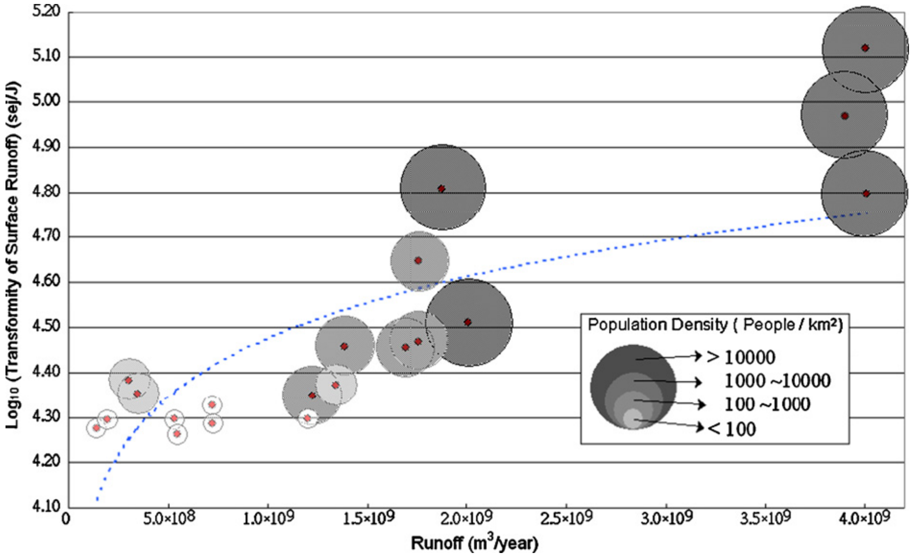


Fig. 11 – Correlation of settlement size, stream runoff and transformity in the Tansui River Basin.

6. Conclusion

The study of ecosystem energetics shows that materials can be concentrated if there is abundant energy to drive the accumulation process (Odum, 1996). From viewpoint of energetic hierarchy, a river system proves to be especially suitable system for the investigation of natural processes across spatial scales. The energy transformation series of a river system is laid out spatially and its hierarchical branches can be easily recognized. Streams within a watershed are organized as a network and the stream order classification provides a valuable framework for investigating the hierarchical organization of river networks. Viewing the stream network as a successive transfer of energy from rainfall to stream flow provides a workable conceptual linkage between fluvial processes and ecosystem processes. Transformity measures the position of any energy flow or storage in the universal energy hierarchy. The transformity of a stream is therefore a measure of the position of a stream in the hierarchy of tributaries. Our results indicate that stream order not only correlates with gradient, drainage area, and discharge, but also corresponds to transformity, a measure of energy hierarchy. Observations of abrupt changes in land uses associated with changes in the transformity of surface water and streams supports the concept that hierarchy of land use and the hierarchy of streams are correlated.

Odum and Odum (2001) noted that before the era of fossil fuels, human settlements were organized around the hydrological cycle and adapted to the zones with higher stream transformity. However in recent times hydrological processes are frequently modified (e.g. water diversion to dams and construction of levees, etc.) to fit a fuel-based urban economy without regard to losses of public value. The contribution of river emergy should also be taken into consideration when planning at the scale of the landscape. As suggested by Odum and Odum (2001) maps of empower density and transformity can be used as a reference for planning future developments. The imported emergy of renewable sources and goods and services from an economic system must match with the renewable flows from indigenous sources. The spatial distribution of the intensities and concentration of natural energies, for example, the river emergy and transformity as discussed in this paper, can be used in spatial planning to determine where in space activities may be most compatible.

The Tansui River case study has provided, from an emergy point of view, a framework for examining the relationship between land use hierarchy and stream hierarchy. Future application of the emergy concept to the study of the relationships between river and city needs to examine a number of other areas. Through what mechanisms and to what extent does emergy contributed from the river drive land use change? How does urban sprawl correspond to the transformity of surface runoff and streams? How can stream transformity be used for spatial planning? And what is the ideal matching ratio between emergy from the economic system and emergy contributed from the river system?

REFERENCES

Horton, R.E., 1945. Erosional developments of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bull. 56, 275–370.

Huang, S.L., 1998. Ecological energetics, hierarchy, and urban form: a system modeling approach to evolution of urban zonation. Environ. Plan. B: Plan. Des. 25, 391–410.

Huang, S.L., Chen, C.W., 2005. Theory of urban energetics and mechanisms of urban development. Ecol. Model. 189, 49–71.

Huang, S.L., Lai, H.Y., Lee, C.L., 2001. Energy hierarchy and urban landscape system. Landscape Urban Plan. 53, 145–161.

Kibler, D.F. (Ed.), 1982. Urban Stormwater Hydrology. American Geophysical Union, Washington, DC.

Leopold, L.B., 1974. Water—A Primer. W.H. Freeman and Co., San Francisco.

Leopold, L.B., 1994. A View of the River. Harvard University Press, Cambridge, MA.

Leopold, L.B., Langbein, W., 1962. The Concept of Entropy in Landscape Evolution, Geological Survey Professional Paper 500-A. U.S. Government Printing Office, Washington, DC.
Leopold, L.B., Wolman, M.G., Miller, J.P., 1964. Fluvial Processes in Geomorphology. W.H. Freeman and Co., San Francisco.
Odum, H.T., 1983. Systems Ecology. John Wiley and Sons, New York.
Odum, H.T., 1987. Living with complexity. In: Crafoord Lectures: The Crafoord Prize in the Biosciences. The Royal Swedish Academy of Sciences, Stockholm, pp. 19–85.
Odum, H.T., 1988. Self-organization, transformity, and organization. Science 242, 1132–1139.
Odum, H.T., 1996. Environmental Accounting: Emergy and Environmental Decision Making. Wiley, New York.
Odum, H.T., Odum, E.C., 2001. A Prosperous Way Down. University Press of Colorado, Boulder, Colorado.
Romitelli, M.S., 1997. Emergy Analysis of Watersheds, Ph.D. Dissertation, University of Florida, Gainesville, Florida.