# WATER, FRACTALS, AND WATERSHED PROCESSES

**MARRIN, DL-W**(1)

*(1) Water Sciences & Insights*
*Encinitas, California 92023 USA*
*marrin@watersciences.org*

## ABSTRACT

Watersheds and other real world landscapes frequently exhibit self-repeating patterns on different scales that are usually referred to as fractal. A fractal is a repeating geometric pattern that has the exact same proportions on different spatial scales. Water and ice in the form of rivers, oceans, and glaciers cut through the planet's surface in ways that create landscapes appearing random or haphazard if examined for straight edges, square corners, or perfect circles. Nonetheless, the organic patterns displayed by watersheds are so precise that those viewed from airplanes are identical to much smaller ones observed in tiny sections of the watershed. Although these patterns have been largely unrecognized or ignored in designing most man-made landscapes and altering natural ones, there is recent interest in emulating them to generate sustainable and eco-compatible creations such as green roofs, artificial wetlands, and stormwater drainage networks.

The intricate patterns created by water influence a landscape's [i] hydrologic regimes, [ii] water quality and quantity, and [iii] ability to buffer extreme natural events. This presentation explores the link between fractal-like spatial patterns and processes that either sustain natural watersheds or are emulated in designed landscapes.

**Keywords:** Water, Fractals, Networks, Connectivity, Patterns

## 1. INTRODUCTION

The mitigation or restoration of altered landscapes and the design of artificial landscapes in the post-industrial era have necessitated the recreation of watersheds that are both aesthetically and functionally similar to natural ones. There are a number of parameters that are important in designing artificial landscapes or restoring ones that have been damaged or otherwise compromised. The process of restoring natural landscapes is sometimes referred to as reclamation, which endeavors to recreate conditions that are similar (at least functionally) to those of the original watershed; however, the replacement never perfectly mimics the original because nature's intricacies are too numerous and complex to be fully understood or recreated. Nonetheless, the extent to which artificial watersheds emulate the structure and function of reclaimed ones (with respect to hydrologic regimes, vegetation types, and soil conditions) is the extent to which they serve as viable mitigation technologies.

As an example, landscape architects at Penn State University conducted a study to assess the effectiveness of mitigating compromised wetlands by comparing their functions to selected portions (e.g., depressions, slopes, floodplains) of adjacent natural wetlands (Sonntag and Cole, 2008). One of the most important parameters was the extent and duration of flooding, which had to be recreated in the artificial wetland by placing water inlets, outlets, weirs, and similar engineering control structures in a manner that best emulated the parameters. Geotextiles (as soil or sediment cover), brush, and rocks were intended to recreate the measured rates of water infiltration and evaporation, as well as to achieve a balance among the mineral, aqueous, and organic phases of the soil. Because the physics, chemistry, and biology of natural soils in every watershed are very complex, this selection process represents a formidable task. Perhaps the task could be better performed, if not simplified, by recognizing, modeling, and mimicking fractal relationships among the spatial (geometric) and temporal (cyclic or rhythmic) features of watersheds.

## 2. METHODS

As a review paper, there are no conventional methods and materials. Instead, examples and interpretations of watershed or landscape fractality were drawn from my work and from that described in the scientific literature.

## 3. DISCUSSION

Water is one of the most interesting substances on the planet because of its distinctive physical and chemical properties that result from its complex and highly dynamic molecular network, which has been described as fractal-like in terms of both its geometries (created by connections between adjacent water molecules) and its rhythms (in switching those connections). The fractal relationship between water itself and the patterns created via its sculpting landscapes on the Earth's surface is one that has been recently recognized, raising questions as to how the former gives rise to the latter. This short non-technical paper examines the fractality of watersheds and the use of fractal theories and mathematics to assess their geomorphology and the behavior of water within them. Table 1 presents the general topics that are discussed in terms of fractality.

Table 1. Watershed processes amenable to analysis or predictions using fractal relationships or mathematics and their potential applicability to landscape evaluation or decision-making.

| WATERSHED PROCESS | FRACTALITY | APPLICABILITY |
|---|---|---|
| Water flow or discharge based on runoff algorithms. | Temporal/Mathematical | Development and flooding. |
| Elevation lines delineating watershed subsections. | Spatial/Geometrical | Boundaries and land cover. |

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|---|---|---|
| Channel networks linking surface water drainages. | Spatial/Morphological | Identifying critical regions. |
| Soil properties affecting subsurface water flow. | Spatial/Structural | Infiltration and aquifers. |
| Aqueous pollutants transported through basins. | Temporal/Chemical | Toxics exposure duration. |

Researchers at China Agricultural University examined the fractal characteristics of long-term daily discharge records from both mid- and small-scale watersheds for a period of 120 to 150 days and discovered a consistent self-similarity up to a threshold limit for daily runoff (Zhao et al., 2011). Scale invariance in hydrological processes has been known for some time, assisting water researchers to understand and model watersheds in a manner that provides information about their origin and behavior—including the prediction of stream flows through time and the forecasting of extreme events such as floods. These predictions are usually stochastic in nature, meaning that the descriptions are probabilistic rather than deterministic. Hence, the laws of probability governing hydrologic predictions of flow are frequently scaled up or down when applied to discharges from different watersheds or to streams and rivers within the same watershed.

Correlations between spatial patterns of a watershed's elevation contours, land cover, and hydrologic responses exhibit fractal or fractal-like relationships over various scales. Observations that some spatial scales produce more significant correlations than do others and that some watershed subsections contribute disproportionately to hydrologic responses have encouraged the use of fractal analyses and models to quantify watershed discharge dynamics and to select practical management boundaries. The optimal spatial resolution at which watersheds are best described, modeled, and managed depends on the range of scales over which fractal relationships exist (Colby, 2002). For example, fractal characterization and hydrologic response in a tropical watershed were observed over two orders-of-magnitude (i.e., 90 meters to about 1 kilometer), beyond which differences in land cover and drainage patterns skewed the response. Alternatively, a study of thousands of different-sized random landscapes revealed a consistent self-similarity, and only the value of the fractal dimension changed over long-range correlations (Fehr et al., 2009). The spatial scales within which fractal patterns exist are important for altering or remediating natural landscapes and designing artificial ones.

Given the aforementioned self-similarity or fractality among natural landscapes over a wide range of spatial scales, topographies, land covers, and hydrologic regimes, an interesting question is which types of watersheds display similar fractal dimensions. The fractal dimension expresses the complexity or roughness of the spatial pattern, such that linear fractal dimensions vary between 1.0 and 2.0 for a smooth boundary and a very irregular one, respectively. Lathrop and Peterson (1992) studied three watersheds and found that the fractal dimension was higher for relatively complex terrains carved by fluvial processes than for structurally simpler landscapes created primarily by glacial processes. They further noted a correlation between landscape structure and ecosystem function, representing yet another way to parameterize and extrapolate from ecosystem models. One of the most important parameters for modeling and evaluating the state of ecosystems focuses on the spatial and temporal availability of surface water to both terrestrial and aquatic organisms.

Interconnected surface waters within a watershed or subsections of a watershed form networks can be analyzed and modeled in terms of fractal and morphometric data that are applicable to quantifying drainage parameters such as channel length, catchment area, and bifurcation ratio. The two analyses provide different, but related, ways to characterize the watersheds and to discern the effects of surface water networks on the morphology and hydrology of landscapes. Many real-world networks that create self-replicating patterns on different scales, such as interconnected surface waters within a landscape, may also be described and modeled as artificial neural networks (ANNs). ANNs utilize parallel processing to distribute information over the entire network and can predict a watershed's hydrology or chemistry. For example, ANNs are used to predict how soils retain water and how sediment and pollutants present on the landscape are carried into small streams during rainfall events. ANNs have also been used to predict seasonal flows, as well as changes in the clarity and amount of dissolved solids, in rivers where it is impossible to collect field measurements (Najah et al., 2009).

One reason to investigate interconnected surface waters within a landscape (according to either fractal analysis or artificial neural networks) is to document or predict the changes in hydrologic response that occur when a watershed is altered. Japanese researchers found that changes in both the peak runoff coefficient and the timing of floods were affected by modifying the course of an urban river and by installing a stormwater sewer network (Yamakawa and Ogawa, 2006). A combination of straightening the bends in the river and channeling stormwater through an impermeable network of canals, which differed appreciably from the natural drainage pattern, created a situation where less water infiltrated into the catchment soils and the peak runoff volume was greater and arrived sooner. These changes reflect the reduced fractal dimensions of the river and stormwater network, as well as the increase in impervious surface area associated with urban modifications. By contrast, natural surface water networks associated with a major river in Brazil possessed multifractal characteristics, such that the entire watershed displayed a slightly different fractal dimension than did the sub-networks within the watershed (Kobiyama and Junior, 2002). Similar network and fractal data have been used to document and predict the hydrological and ecological effects of altering a natural landscape in many regions of the world.

Perhaps the most surprising application of watershed fractality is related to the transport of natural compounds and pollutants in fluvial networks. Kirchner et al. (2000) found that the apparent travel times of conservative, (non-sorptive) compounds display a distribution based on a power law, suggesting yet another fractal property of watersheds. This also suggests that pollutants introduced to a watershed may exit it over longer time periods and at lower concentrations than those predicted by the more conventional "black-box" models, which have been used to estimate the duration of watershed flushing. It should be noted that these predictions do not include pollutants that are temporarily sorbed to soil particles or are degraded during transport. Fractal descriptions of watersheds can extend beyond surface water dynamics to include surface and subsurface soils through which groundwater and its associated pollutants are transported. Essentially, soils can be described as a fractal and fragmented porous medium that produces similar sized aggregates and pore spaces over a range of spatial scales (Rieu and Sposito, 1991). As was the case for surface waters, many of the hydraulic properties of soils conform to a power law distribution and can be described by the geometry of fractal networks. These soil properties influence the rate of groundwater infiltration and migration in watershed soils and their propensity to trap fine sediment or organic matter upon which pollutants can be sorbed or degraded. Fractal soil properties also affect the exchange of water between surface and subsurface compartments of watersheds, thus affecting their geomorphology and ability to rid themselves of pollutants.

## 5. CONCLUSION

Geographers and landscape specialists have long recognized the geometric similarity among drainages within a single watershed and the similarity of those component drainages to the overall watershed. The tools of fractal analyses and modeling have quantified such qualitative observations and extended the spatial scale over which landscapes and their components are described by fractals (see Figure 1). Fractal analyses are now applied to temporal phenomena within watersheds, facilitating the prediction of effects resulting from man-made changes and the interpretation historical processes affecting the landscape. Fractal analyses may prove to be even more important in the future as additional mathematical and observational tools are developed.

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Figure 1. Fractals describe both major landscape features and soil properties

Photos provided by the author and 123RF.

## BIBLIOGRAPHY

Colby, J. D. (2001) Resolution effects and fractals. Journal of Water Resources Planning and Management, July/August, 261.

Fehr, E., Andrade, J.S., da Cunha, S.D., da Silva, L.R., Herrmann, H.J., Kadau, D., Moukarzel, C.F. and E.A. Oliveira (2009) New efficient method for calculating watersheds. Journal of Statistical Mechanics 2009, P09007.

Kirchner, J.W., Feng, X.H. and C. Neal (2000) Fractal stream chemistry and its implications for contaminant transport in catchments. Nature 403, 524.

Lathrop, R.G. and D.L. Peterson (1992) Identifying structural self-similarity in mountainous landscapes. Landscape Ecology 6, 233.

Najah, A., Elshafie, A., Karim, O.A. and O. Jaffar (2009) Prediction of Johor River water quality using artificial neural networks. European Journal of Scientific Research 28, 422.

Rieu, Michel and Garrison Sposito (1991) Fractal fragmentation, soil porosity, and soil water properties. Journal of the Soil Science Society of America 55, 1231.

Sonntag, Daniel, and Charles Cole (2008) Determining the feasibility and cost of an ecologically-based design for a mitigation wetland in central Pennsylvania, USA. Landscape and Urban Planning 87, 10.

Yamakawa, Shun and Susumu Ogawa (2006) Runoff change with urbanization in Tama Newtown watershed and its fractal geometry, in: Proceedings of the Asian Association on Remote Sensing, AARS, Tokyo, Japan, p. 31.

Zhao, H., Guo, S.Y., Xie, M.S. and T.W. Lei (2011) Fractal characteristics of daily discharge in different scaled watersheds. Ying Yong Sheng Tai Xue Bao 22(1), 159.

## BIOGRAPHY

D.L. Marrin is an applied scientist, educator, and founder of Water Sciences & Insights, a forum for exploring diverse perceptions of water and assisting environmental, entrepreneurial, and educational groups on water-related projects. He has authored three books (*Universal Water*, *Altered Perceptions, Hydromimicry*) and a range of scientific papers addressing water and biogeochemistry. He is a former Adjunct Professor at San Diego State University and holds B.S. and M.S. degrees in the biological and environmental sciences from the University of California, as well as a Ph.D. in water resources from the University of Arizona.