SPATIAL PATTERNS OF ANOMALOUS RUNOFF TO PRECIPITATION RATIOS FOR WATERSHEDS WITHIN THE CONTIGUOUS UNITED STATES ARRANGED BY LEVEL ONE ECOREGIONS

by

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Abstract: Mean annual runoff to precipitation (R/P) ratios were generated for 966 watersheds within the contiguous United States. The watersheds were plotted using Arc View GIS and used as part of an overlay analysis with Level 1 U.S. ecoregions. The ratios were statistically evaluated to determine anomalous R/P conditions within the ecoregions. Anomalous conditions are defined as any watershed that has a mean R/P greater than two standard deviations from the mean R/P for the ecoregion in which it lies. The highest mean R/P ratios were found to correlate positively with regions that are characterized by significant topographic relief. Anomalous R/P conditions were consistently found in the higher elevations of each ecoregion. This may indicate that precipitation volume may play a greater role in governing the R/P ratio for a region than it's evapotranspiration regime.

Introduction

Geographic Climatology consists of applied studies that combine geomorphology, hydrology, ecology, and statistics. Spatial analysis is the common thread combining these disciplines into a unique field of geographic study. The purpose of this paper is to display this researchers accomplishments in two subfields of geography, cartography and climatology.

Objectives

This project will contribute to the field of climate mapping by presenting an annual perspective of R/P distribution at the synoptic scale. The objectives of this paper are the production of maps displaying spatial patterns of (1) mean annual runoff to precipitation ratios for the period of 1960 -1991 (2) anomalous runoff to
precipitation ratios by ecoregion (3) estimated actual evapotranspiration to precipitation ratios and (4) observations on the spatial distribution of these variables.

This project will define anomalous R/P conditions of watersheds within seven ecoregions of the contiguous U.S., determine their spatial distribution, attempt to explain their occurrence and elucidate interregional trends of R/P values. To accomplish this both qualitative and quantitative methods will be undertaken. The quantitative component will involve mapping the regional distribution of runoff to precipitation ratios with the aid of GIS software. The map will be used as an analysis tool to assist in the statistical determination of anomalous R/P conditions. The qualitative component is an analysis of the distribution of R/P ratios and their comparison with estimated Actual Evapotranspiration/Precipitation values (AET/P) for the same region.

Climate mapping is a pragmatic means to display and summarize the spatial distribution of phenomena such as temperature, soil moisture content, precipitation and runoff. Maps are an efficient means of communication and have great utility to natural resource planners and managers. Climate maps are used for a variety of problem solving efforts such as climate change studies, flood control mitigation, and acid rain deposition.

Climate maps expressing a ratio of climatic variables are relatively rare in literature. Examples of climate ratio mapping includes consumptive use/precipitation for the United States by Hidore (1966), runoff/precipitation for the northeastern U.S. by Church (1994), and global runoff/precipitation by Wendland (1987) (Bishop and Church 1994).
Runoff to precipitation (R/P) ratios provide a convenient tool to compare the hydrologic response of basins that receive different amounts of total annual precipitation. Total evapotranspiration will be greater in wet areas and lower in dry areas, but tends to be a similar proportion of precipitation across a range of precipitation regimes. R/P ratios, therefore, will be less variable than other climate proportions such as P-R. For example, adjacent watersheds A and B have R/P ratios of 20%. Watershed A receives 100cm of precipitation and has 20cm of runoff. Watershed B receives 10cm of precipitation and has 2cm of runoff. Using P-R to represent the watersheds would produce values of 80cm and 8cm respectively. The watersheds have similar evapotranspiration responses but P-R values do not accurately describe the hydrologic response of the two watersheds.

This paper focuses on anomalous R/P ratios because they represent either areas where evapotranspiration conditions are unusual or areas that are not represented accurately by the data used for this research. Accurate R/P information is necessary for agricultural and landuse planning applications. Farmers can use R/P data to assess the irrigation requirements of a region. Developers can use R/P to assist in estimating hazardous building conditions.

This project builds upon the work of previous researchers such as Daly, Vogel, and Wilson. Professor Chris Daly is currently undertaking climate-mapping research at Oregon State University in Corvallis Oregon. Professor Daly’s work includes producing maps at different scales with data generated from the PRISM climate model. Examples of his work include maps of mean annual precipitation, mean annual temperature, mean annual dew point, and runoff to precipitation ratio
maps for the northeastern U.S. Vogel and Wilson calculated the R/P for various hydrologic units within the U.S. (Vogel 1996).

Background

Hydrologic Cycle

Climate is the result of the distribution and interaction of water and energy over the surface of the earth. Differential heating of the earth's surface combined with the rotation of the earth is responsible for distributing energy and water to different regions of the earth. This process of energy and water transfer is referred to as the hydrologic cycle (Figure 1). Water exists in the atmosphere in three phases; solid (ice), liquid, and vapor. The hydrologic cycle describes the process of water flowing from one location to another and one phase to another. Water in a liquid form (lakes, rivers, and dew) is converted to a gas by evaporation and transpiration. The converted liquid, now airborne as a gas, can travel to a new geographic location via atmospheric conductance. The next phase of the cycle is when the gas condenses back into a liquid and falls to the earth as precipitation and if it is cold enough then snow will form. After landing on the earth's surface the liquid water will be trapped in lakes and streams, frozen as snow, or begin to flow downward as overland flow or subsurface percolation. It flows to a point where it will again be evaporated and transported as a gas.

The hydrologic cycle represents the interface for the exchange of mass and energy between terrestrial and atmospheric systems. The terrestrial component of this process is runoff (Brook 1997).
Water Balance

The hydrologic cycle describes the condition of water between the earth and its atmosphere. The amount of water available at a terrestrial surface for a given time interval is expressed by the water balance equation (1):

\[ P = R + ET + \Delta S. \]

\( P \) is the amount of precipitation received by the surface, \( R \) is the amount of water that leaves the surface by overland or subsurface flow, \( ET \) represents the amount of water leaving via evapotranspiration, and \( \Delta S \) represents the change in storage at the site. Storage refers to water stored as ice, in lakes, or as soil moisture within the watershed. For long-term analysis the change in storage of a watershed is considered to be negligible and will be 0 for the purposes of this analysis (Church et al. 1994). Runoff is the water leaving a watershed that is considered to be available.
for human use. Evapotranspiration and runoff are the two dominant means by which precipitation may leave a watershed. When averaged over long periods of time the amount of water entering a terrestrial system will equal the amount leaving. (Dingman 1994)

**Evapotranspiration**

Evapotranspiration (ET) is the collective loss of water from soil, plants, and other surfaces within a watershed (Figure 1). It is a combination of evaporative and transpirative processes. Evaporation is the loss of water from a surface as a result of water changing from a liquid to a gas. Transpiration is the loss of water from plants as they evaporate water through their stomata (Brook 1997). It determines how much water will be left over to leave the watershed as runoff. The amount of evapotranspiration that occurs within a watershed is dependent upon several factors. The geology, soil porosity, vegetation, climate, available water, and land use practices all effect the rate of evapotranspiration. Evapotranspiration is an important hydrologic process that is directly influenced by land use practices. 70% of the United State's precipitation leaves as evapotranspiration (Gay 1993).

Evapotranspiration can be expressed by rewriting the water balance equation as (2):

$$ET = P - R + \Delta ST.$$  

In order for evapotranspiration to occur three processes are required; an influx of water, an energy source to drive the process, and an outflow of vapor from the system.
Evapotranspiration acts on the water stored in a system. This water can be stored as ice, surface water, or soil moisture. Evaporation is the transfer of water as a gas from surface storage such as snow and lakes while transpiration is the transfer of water through the vascular system of plants.

The moisture influx for evapotranspiration begins as precipitation. Water flows as a liquid through soils to the roots of plants (Figure 2). In general plants with deeper more developed root systems have more access to soil moisture deposits. Water transfer in soils can be explained by the existence of a pressure gradient between the soil and the roots. In unsaturated soils roots draw up water from adjacent soil pores. As the pores dry a pressure gradient is created between the soils and the surrounding saturated soils. This gradient then provides moisture to

![Figure 2](image_url)

**Figure 2.** Evapotranspiration. Moisture is conveyed from ground water storage through the vascular system of plants to the stomata of the foliage. It is then transmitted back to the atmosphere as a gas.
the roots, as long moisture is available. The rate of moisture conductance is a product of several components such as gradient length, gradient degree, soil resistance and hydraulic conductivity. In saturated soils the flow of water is similar except that gravity, osmotic pressure and thermal potential of the soil and the water exert additional control over the flow of water (Brook et.al. 1997).

The amount of evapotranspiration that occurs from a terrestrial surface is determined in part by the net energy (Rn) available to that surface. The sun provides the energy that drives the hydrologic cycle. Energy is divided into two categories, short wave, wavelengths less than four micrometers and longwave, wavelengths greater than four micrometers. Solar radiation is the primary source of short-wave radiation for surfaces. The amount of short-wave radiation absorbed by a surface is offset by the albedo of a surface. Albedo refers to the amount of reflectance maintained by a surface. Surfaces with high albedos, such as snow, reflect more solar radiation than surfaces with low albedos such as black pavement. All objects emit longwave radiation, which in many cases is short-wave solar radiation that has been converted to longwave. The sum of longwave and short-wave radiation are the net energy available for terrestrial surfaces.

Rn fluctuates insignificantly over long periods of time. The net gain and loss of energy available to the earth’s surface is described by the energy balance equation (3):

\[ Rn = Qs (1 - \text{albedo}) + (Qlo - Qli). \]

Where Qs refers to cumulative total short-wave radiation available multiplied by the albedo value for that surface. The short-wave radiation is added to the net longwave
radiation, Qlo - Qli. The energy budget can be positive or negative depending on the time interval. When the budget is positive, there is energy available for evapotranspiration. The budget can then be expressed as (4):

$$ Rn = LE + H + G. $$

$Rn$ is net radiation, $LE$ is a combination of the latent heat of vaporization and evaporation, $H$ is energy lost as sensible heat, and $G$ is energy conducted to the ground. $LE$ is the energy used for evapotranspiration. With unlimited water available, $LE$ can comprise 80% – 90% of the energy budget. In snow dominated systems the majority of the energy budget goes to melting and sublimating snow.

Vapor flow from the surface is also required in order for evapotranspiration to take place (Brook 1994). After water has passed from the soil to the roots and through the plants vascular system to it’s foliage it will be transmitted to atmosphere through openings on the underside of the foliage called stomata. Water diffuses from a liquid to a gas at the boundary layer, a thin layer of air directly adjacent to the leaf. The water vapor is then transmitted to the atmosphere via atmospheric turbulence. In order for the flow of vapor to continue the vapor pressure at the surface of the foliage must be greater than the vapor pressure of the surrounding atmosphere. The vapor pressure gradient is usually a result of the temperature and humidity of the surrounding atmosphere.

**Evapotranspiration Controls**

Vegetation cover type plays an important role in the amount of ET that can occur from a surface. Plants possess different root patterns, stomata behavior, and albedo rates; all of which have a direct effect on the rate of ET. Vegetation density,
type, and structure effect the degree with which the plant interacts with atmosphere. Tall, coarse vegetation in a multi-layered canopy possesses more foliage surface than flat, smooth cover such as grass. The difference in surface area creates more turbulent airflow and is more conducive to ET as a result. There is more ET potential from a mature forest than young grassland. Deep-rooted species also have better chances at producing ET because their deep roots can access water after the surface soil layers have desiccated. This allows ET to occur long after precipitation has passed (Bishop and Church 1995).

Interception refers to the process where precipitation is captured by vegetation before it reaches the surface of the earth. This can occur as snow and rain piling up on trees. Intercepted precipitation usually results in a loss of water conveyed to the atmosphere by transpiration. The plant energy that would normally be used for transpiration is evaporating precipitation that has accumulated on foliage. The amount of evaporation is usually greater than the rate of evapotranspiration prior to the interception occurring. The result is a net gain in water conveyed to the atmosphere.

Stomata response varies greatly among plant species. Light intensity, temperature, soil moisture, vapor pressure, wind, and diurnal parameters govern stomata activity.

Measurement of Evapotranspiration

Despite playing such an integral role in the hydrologic cycle evapotranspiration is very difficult to measure. Quantifying the ET rate for a region would be of great value to watershed managers and scientists. Physically
measuring the amount of water vapor leaving an ecosystem, however, is nearly impossible (Brook et. al. 1994).

Potential evapotranspiration (PET) is the amount of evapotranspiration that could occur from a surface not constrained by limited water availability. This term was introduced by Thornthwaite and is used to describe the capacity of a surface to displace precipitation back to the atmosphere (Thornthwaite et al. 1958). It was designed for agricultural purposes to estimate water losses from crops. This method is good only as a reference when assessing the hydrologic nature of a surface because energy rates (Rn) vary greatly among differing surfaces. Methods used to estimate PET include pan evaporation and empirical methods such as those developed by Thornthwaite and Penman (Vorosmarty et. al. 1998).

Actual evapotranspiration (AET) is the amount of water actually emitted by a surface. Attempts to measure the emitted water include the use of lysimeters. Lysimeter measurement lacks utility because it is only practical for small-scale measurement of ET from short vegetation. Applying the water balance equation is another method to estimate AET (1). If all other variables are known except ET then ET will equal P – R. Other successful methods involve applying an empirical estimate of PET and estimating the AET based on the amount of water available (5).

**Runoff**

The amount of water that does not infiltrate into the earth or leave as evapotranspiration is referred to as runoff. Runoff is equal to the sum of the amount of precipitation that leaves a watershed as overland flow, subsurface flow and water intercepted by the stream channel. Runoff for a watershed is determined by
measuring the streamflow from gauging stations along the outlet of the studied watershed. Runoff is often referred to runoff depth. It is calculated by measuring the volume of water discharged from a stream for a given time interval and dividing it by the surface area of the contributing watershed (Bishop and Church 1995).

Runoff sources can vary spatially and temporally. Subsurface flow usually arrives to the stream channel much slower than overland flow. Subsurface flow is water that has infiltrated into the substrate of the watershed and slowly travels to the stream channel in subsurface capillaries. Overland flow results when the field capacity of a soil is reached and precipitation can no longer infiltrate through the soil. At this saturated state precipitation begins to collect and flow quickly across the surface to the active channel. Storm frequency, duration and intensity, and vegetation characteristics of the receiving surface affect short-term runoff magnitude. Long term runoff such as mean annual magnitudes is a product of regional climate and precipitation characteristics (Brook et al. 1994).

Runoff to Precipitation Ratio

R/P is the ratio of runoff to precipitation for a given time interval and spatial extent. For extended time periods this ratio reflects the amount of ET that is occurring in a watershed. R/P is an indicator of a landscapes response to precipitation. It is a valuable tool when assessing the impacts of landuse, climate change or other phenomena on the watersheds. Assessing the distribution of R/P can aid in predicting the regional response of impacts to the hydrologic cycle (Bishop and Church 1995).
Methods

The primary objective of this analysis is to determine the spatial distribution of R/P ratios and the spatial variance of anomalous R/P conditions across the contiguous United States. This was accomplished by comparing the R/P ratios of hydrologic units within and between U.S. level one ecoregions. This required the compilation of data from several sources in order to get the necessary runoff, precipitation, ecoregion boundary, and estimated actual evapotranspiration data. This analysis can be used to assess the accuracy of the PRISM generated precipitation data used for the R/P derivation.

R/P ratios were obtained from previous work done by Ian Wilson, Richard Vogel of Tufts University, and Chris Daly of the Oregon Climate Service. Their work for the article "Regional Regression Models of Annual Streamflow for the United States" submitted to the Journal of Irrigation and Drainage Engineering in July of 1998 was used to generate watershed R/P values for basins within the contiguous U.S. The data set includes runoff, precipitation, mean basin elevation, and drainage area values for 1,556 hydrologic units within the conterminous U.S. U.S.G.S. hydrologic units (HUC's) were chosen as the analysis units because they represent the most complete set of runoff data available for the U.S. When viewed collectively HUC's illustrate regional variations of runoff and precipitation.

Mean annual runoff values for these watersheds were obtained from the U.S.G.S. Hydroclimatic Data Network (HCDN). The HCDN data provides averaged daily streamflow data for streams within the U.S. and can be obtained from the U.S.G.S. website at,http://www.rvares.er.usgs.gov/hcdn_cdrom/1st_page.html.
Watershed selection was limited to the following criteria. Each stream has at least 20 years of flow records deemed "good" by U.S.G.S. standards. In an effort to represent "natural" runoff conditions streams were limited to those with no diversions or augmentations of flow upstream of the gauging station within each watershed. No estimated or reconstructed flow data was used for the analysis.

Precipitation values for the Tufts data set is was derived from PRISM generated grids of mean annual precipitation from 1961 – 1990. The PRISM data is 2.5 minute (4 km) resolution grids of the lower 48 states. The precipitation values are calculated from data gathered from 7,000 National Weather Service stations, 500 SNOTEL stations, and 2,000 additional state and local climate observation sites. Each basin was given a precipitation value based upon the corresponding values of overlaid precipitation grids. The PRISM (Parameter-elevation Regressions on Independent Slopes Model) is a climate analysis system using point climate data, a digital elevation model, and other spatial data to generate climate information. It has proven very useful in estimating climate conditions between point station data and in areas of non-uniform terrain. It's capabilities include extrapolation of data vertically beyond the highest climate observations and accounting for gradients caused by rainshadowing, coastal influences, and uneven topographic relief. PRISM data can be obtained by contacting the Oregon Climate Service at their website; http://www.ocs.orst.edu/prism_new.html.

The United States is well represented by the 1,556 HUC's except for regions within the Southwest and the Great Basin. A lack of useable runoff data for these areas makes comparative analysis difficult.
Watershed English units were converted to metric units using Excel spreadsheet software. Latitude, longitude, and datum elevation values were added to each gauging station within each basin.

Of the 1,556 basins 966 were chosen to perform the R/P analysis. It was observed that several watersheds would often fall within one U.S.G.S hydrologic unit. When this occurred the basins were consolidated into the hydrologic unit with the largest drainage area. The largest watershed for a particular hydrologic unit contains all other smaller watersheds within the hydrologic unit.

The 966 HUC's were plotted with Arc View GIS and used to estimate regional conditions for the contiguous U.S. See Plate 1. Cartographically each basin is represented by its HUC obtained from the Hydroclimatic Data Network at the U.S.G.S. website. In some cases the representative HUC covers a larger area than the actual basins used for analysis. This was considered to be acceptable due to the coarse scale of the analysis.

Grid coverages of estimated potential evapotranspiration (PET) for the contiguous United States were obtained from C.J. Vorosmarty, C.A. Federer, and Annette Schloss of the University of New Hampshire. The grid resolution is 5-degree cells. Despite the large cell size the values are still useful for comparison with the R/P values of regional basins because the average basin size is close to 5 degrees. Vorosmarty et al. used 11 contemporary methods to calculate potential evapotranspiration and applied them to a global scale water balance model. The 11 models were then compared against each other and against calculated runoff to see which method was the most robust. Each method was constrained by parameters
set by the authors such as a uniform rooting depth for cover vegetation. Data was averaged over 24 hour periods and then summed to derive annual values. Input variables to simulate the water balance for the global scale water balance model (WBM) included; vegetation cover, precipitation, soil texture, air temperature, rooting depth, solar radiation, wind speed, and vapor pressure. The WBM considered averaged monthly climatic conditions. The model also incorporated snowmelt conditions. The Hamon method produced the lowest mean absolute error and Vorosmarty recommended its use. (Vorosmarty et al. 1998).

Estimated actual evapotranspiration was calculated by taking the Hamon grided data and using it as the PET input into a Hortonian derived formula for estimating AET (5):

\[
\frac{AET}{PET} = \frac{P}{PET} \left[1+\left(\frac{P}{PET}\right)^2 \right]^{1/2}
\]

This formula as modified by Pike (1964) expresses AET as a function of precipitation and PET (Dooge, 1992). The Hamon data was used to generate the estimated actual evapotranspiration grids of the U.S. used in this analysis. The simulated AET grid values were then employed to qualitatively validate R/P values from the polygon coverage.

Plotted R/P ratios were compared to evapotranspiration (ET) data for each ecoregion. According to the water balance equation R/P is equivalent to ET for a given watershed (2). Comparing the R/P ratios to the AET/P ratios aids in determining the accuracy of data representing the watersheds.

The Environmental Protection Agency's ecoregion taxonomy was selected as a framework to separate the watersheds into regions. Level 3 ecoregion data for the United States was downloaded and aggregated to Level 1 ecoregions using Arc
View GIS. Level 1 ecoregion data is coarser than Level 3 ecoregion data and its borders closely resemble the trends of R/P data (Plate 2).

Ecoregions are not topographic basins but rather zones of similar ecosystem processes. They are multipurpose regions emphasizing the interrelated nature of ecosystem variables rather than one element. This taxonomy is intriguing because the factors that affect the distribution and nature of R/P ratios are also varied and not dependent upon one process. R/P is a product of multiple processes and ecoregion taxonomy attempts to combine these processes into a common zone. The results are regions based upon such variables as climate, geology, biota, agriculture, and wildlife are more similar internally than they are to surrounding regions (Omernik and Bailey, 1997).

Current resource management paradigms advocate a holistic approach to resource management. The regions were designed as spatial framework for the assessment, analysis, monitoring and management of ecosystems. The ecoregions were not designed for the analysis of one variable and emphasis on input variables are sometimes weighted. For instance vegetation may be considered more important for The Northern Forests classification than the regions climate. Regardless, the watershed response to precipitation (R/P) within one region should be similar to other watershed responses within the region but different from the responses of the surrounding regions (Omernik and Bailey, 1997).

An overlay analysis was performed on the R/P coverage and the ecoregion coverage. Seven ecoregions were used to represent the contiguous U.S. for the analysis (Plate 2). The Arid Highlands and the Temperate Sierra were aggregated
into the North American Deserts ecoregion. The Tropical Dry Forest ecoregion, was omitted due to a dearth of data for this region. Statistical analysis was performed on each of the regions to determine the mean, the standard deviation, the variance, and the range of R/P values. The results of the statistical analysis were used to define anomalous watersheds, watersheds with R/P values greater than two standard deviations from the mean (Table 1).

Discussion

The primary objective of this analysis is to assess the regional and interregional distributions of the R/P ratios of the contiguous United States in order to determine spatial variance of anomalous R/P conditions. The analysis consists of two parts, a quantitative assessment of the statistical variation of R/P ratios between and within ecoregions and a qualitative assessment of the R/P ratios compared to estimated AET values. The statistical assessment describes the existing conditions for each region and identifies individual basins with anomalous R/P conditions. The R/P to AET/P analysis is a means of checking the accuracy of the R/P ratios.

According to the water balance equation (1) the sum of the R/P value and the AET/P value should equal one (Brook 1997). If the R/P ratio and the corresponding AET percentages are correct then their values will compliment each other. If the values do not compliment each other then it indicates either a geographic anomaly where runoff or evaporation and transpiration conditions are unusual, or it indicates errors in the data used to create the ratios.
Premises for Discussion

Runoff is the portion of the water balance that is not lost to evapotranspiration. Evapotranspiration controls the R/P ratio. Average R/P values for the United States vary from approximately 30% to 40% (Loaiciga 1997). This means that about one third of the U.S. total precipitation results in runoff. Regionally water balances within the contiguous United States vary considerably. There are a myriad of factors that create unique hydrologic conditions for each region. The hydrologic regime of a watershed can be evaluated by assessing it's PET and AET components.

PET describes the amount of evapotranspiration that would be produced from a region if it had unlimited water supply to be acted upon by it's annual energy budget. AET refers to the amount of ET that is actually evaporated on average from the regional environment. The constraints upon the ET regime of a region can be expressed as moisture limited or energy limited (Dooge 1992). In energy limited regions with an abundance of water (ie. from excessive precipitation or abundant ground water supplies) ET is limited by available energy and AET will equal PET. In arid regions AET is a product of available moisture and tends to be less than it's PET. The factors that control the ET regime have varying degrees of impact that can compound or offset each other. The factors can be divided into primary and secondary controls (Thornthwaite et al. 1958).

The primary regional controls of ET are incident radiation (solar energy) and available moisture (precipitation). Incident radiation varies across the United States. The largest variation is between northern and southern latitudes. Southern latitudes
typically receive more solar energy than do northern regions (Trewartha and Horn 1968). Areas with more solar energy have greater evaporative potential and generally transpire more water than energy deficient regions.

Water availability is also a primary control of the evapotranspiration regime of a region. Arid regions have less water available and as a result transpire less but evaporate relatively more. Tropical regions, such as those found in Florida, have the potential to evapotranspire more water.

Secondary controls of evapotranspiration include such features as elevation, topography, aspect, precipitation type, and proximity to water. Evapotranspiration is the product of an amalgam of ecosystem processes working together. Rarely does one process dictate a region's water balance. The influence of secondary controls can vary from watershed to watershed but generalizations can be drawn regarding their influence on evapotranspiration and hence runoff to precipitation ratios.

As elevation increases, precipitation generally increases creating more moisture available for evapotranspiration (Brook et al. 1997). In addition, temperature decreases with elevation resulting in less energy for evaporation. The orographic effect can offset the presence of additional moisture creating a system that is energy limited (Figure 3 page 21). In mountainous regions one would expect higher R/P and lower AET percentages.

Aspect also reflects evapotranspiration trends. North slopes tend to receive less solar radiation and evapotranspire less then south facing slopes.

A region's dominant precipitation type can determine the nature of the region's water balance. Snow dominated systems use a greater proportion of available...
energy to melt snow (Brook et al. 1997). Rain dominated systems use less energy to melt snow and as a result have more energy to evaporate water than do snow dominated systems. Therefore one would expect more AET from a rain-dominated system.

![Diagram of Orographic Precipitation]

**Figure 3.** Mountain ranges can lift air masses creating more precipitation. This process is referred to as the orographic effect.

Arid regions with sparse vegetation and high average temperatures will not transpire as much as mesic regions. Evaporation is usually greater for arid regions than for mesic regions. Evaporation claims a large percentage of the water leaving little for runoff resulting in a small R/P ratio.

Regions characterized by high humidity will transpire less in total than areas of low humidity. Saturated air has a greater vapor pressure than dry air at the same temperature (Dingman 1994). Plants require a strong pressure gradient between plant stomata and their surrounding atmosphere in order to transpire. When the surrounding atmospheric vapor pressure is higher than the vapor pressure of the plant stomata then plants transpire less (Dingman 1994). Greater vapor pressures in humid regions acts to inhibit transpiration from plants.
Vegetation type and density have a significant impact on evapotranspiration rates. In general, a region with more vegetation per unit area and plants with deeper root systems such as trees, will transpire more. Trees can access soil moisture stored deep below the surface and have greater foliage surface area with which to transpire moisture. Shallow rooted vegetation, such as grasses, cannot access this water and as a result have less potential to transpire water.

Landuse practices that replace or remove vegetation within specific watersheds can have drastic impacts on runoff conditions (Jackson 1998). Removing vegetation and replacing it with urban development features, such as houses and roads, greatly increases the measured runoff recorded at stream gages.

These factors are interrelated and can have varying degrees of impact. Generalizations about their collective influence can be drawn and used to predict evapotranspiration and runoff conditions. Regions that have high amounts of precipitation with low temperatures and sparse vegetation will transpire less and produce more runoff relative to the incident precipitation. R/P is a comparative term describing the nature of a landscape's response to precipitation. Two watersheds may have the same R/P ratio but this could be the result of different climatic and biotic conditions.

**Sources of Error**

Throughout this research, efforts to eliminate sources of error were strictly adhered to but due to the nature of the subject matter sources of error still exist. Precipitation data is gathered at point locations. Despite contemporary efforts to
convert point data to a continuous surface, the results still involve interpolation. Stream gage data is also subject to error either from extreme events exceeding gage capacities or poor maintenance and record keeping. Actual evapotranspiration is extremely difficult to measure and the best efforts usually result only in an estimation of AET. In order to minimize these effects the data was assessed at a mean annual temporal scale. Short-term erroneous data values will create small perturbations in the long-term data sets.

**Results of Statistical Analysis**

For the purpose of this analysis, anomalous R/P conditions will refer to any watershed that has an R/P value greater than two standard deviations away from the mean R/P value for the region in which it lies. Anomalous watersheds that cross the boundary between two regions will not be considered for this analysis. Watersheds on the edge of ecoregions often reflect the hydrologic influence of neighboring ecoregions and are not considered to be representative samples.

The analysis will address three questions for each region:
- Where do anomalous R/P conditions occur within each ecoregion?
- Do anomalous conditions occur because there are errata in the data or are there unusual runoff and precipitation conditions for that region?
- How does the mean R/P compare to surrounding ecoregions?
**Marine West Coast Forest**

The Marine West Coast Forest region (MWCF) has the greatest runoff to precipitation response with a mean R/P of 71% (Table 1). This region is characterized by mountainous terrain that is in close proximity to the Pacific Ocean. The Coast Range Mountains, extending up to 4000 feet, intercept prevailing westerly storms and increase precipitation through orographic enhancement. This combination of elevation and moisture create strong runoff conditions. R/P values here range from 40% to 98%. The marine climate enhances runoff conditions by creating a persistent cloud cover that reduces annual solar energy reception that in turn reduces the actual evapotranspiration.

Anomalous watersheds occur here along the coast and can be attributed to the exorbitant amounts of precipitation received by the region. In addition to receiving large amounts of precipitation some watersheds receive significant amounts of moisture from condensation. Dense forests intercept clouds coming from the ocean and this moisture condenses on the foliage. This moisture is conveyed to stream networks increasing the runoff without increasing measured precipitation. (Brook et. al. 1997)

**Northwest Forested Mountains.**

The Northwest Forested Mountains ecoregion (NWF) is a spatially discontinuous compilation of western U.S. mountain ranges. It includes the Rocky Mountains, the Cascade Range, and the Sierra Nevada Mountains. Elevations in north-south trending ranges can exceed 14,000 feet. The marked topographic relief of this region reveals a great deal of climatic variation over relatively short distances.
The watersheds are snow dominated systems and much of the incident radiation is used to melt snow rather than drive evapotranspiration processes. The mean R/P for this region is 52%. The region also exhibited the greatest variance with a value of .048. (Table 1.)

Table 1. Statistical results for analysis of runoff to precipitation ratios of Level 1 U.S. ecoregions.

<table>
<thead>
<tr>
<th>Ecoregion</th>
<th>Mean</th>
<th>S.D.</th>
<th>Variance</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest Forested Mountains</td>
<td>0.52</td>
<td>0.22</td>
<td>0.048</td>
<td>.04 - .99</td>
</tr>
<tr>
<td>Mediterranean California</td>
<td>0.36</td>
<td>0.21</td>
<td>0.043</td>
<td>.09 - .73</td>
</tr>
<tr>
<td>Marine West Coast Forest</td>
<td>0.71</td>
<td>0.15</td>
<td>0.023</td>
<td>.4 - .98</td>
</tr>
<tr>
<td>North American Deserts</td>
<td>0.27</td>
<td>0.19</td>
<td>0.041</td>
<td>.01 - .99</td>
</tr>
<tr>
<td>Great Plains</td>
<td>0.12</td>
<td>0.22</td>
<td>0.012</td>
<td>.01 - .72</td>
</tr>
<tr>
<td>Eastern Temperate Forest</td>
<td>0.35</td>
<td>0.11</td>
<td>0.013</td>
<td>.03 - .99</td>
</tr>
<tr>
<td>Northern Forests</td>
<td>0.51</td>
<td>0.09</td>
<td>0.009</td>
<td>.25 - .68</td>
</tr>
<tr>
<td>United States</td>
<td>0.34</td>
<td>0.19</td>
<td>0.04</td>
<td>.01 - 1.07</td>
</tr>
</tbody>
</table>

S.D. = Standard Deviation

Despite the high variance and the lack of climatic homogeneity there are few anomalous watersheds in this region (Plate 3). The anomalous watersheds have an R/P value of 74% to 107% and occur near the coast. An R/P value greater than 100% indicates that runoff is exceeding the precipitation for that watershed. This is possible in this region due to the great deal of condensation produced runoff that is generated from the persistent low cloud cover.

The NWF’s high mean R/P is most likely a product of the ecoregion classification scheme for this area. The Northwest Forested Mountains ecoregion is
based on vegetation and wildlife that flourishes in high elevation, mountainous terrain and as such does not include low elevation areas. The lower elevation areas were included in neighboring ecoregions. The mountainous regions will experience higher R/P conditions.

_Mediterranean California_

This region is comprised of the Central Valley of California, it's surrounding foothills and the western mountains of southern California. The mean R/P for this region is 36%. It has a Mediterranean climate where most of the precipitation is received in the cooler, winter months.

The one anomalous watershed for this region has an R/P value of 74% and it is located on the coast (Plate 3). This value is probably erroneous due to the arid nature of the watershed and possible HUC delineation errors by the U.S.G.S.

Due to the high variance in California and the lack of usable data for this region, results from this region should be interpreted with caution (Table 1).

_North American Deserts_

The region is comprised of the Great Basin, the Colorado Plateau and arid regions that extend south to the U.S./Mexico border. The North American Deserts mean R/P is the lowest of the U.S. ecoregions with a value of 27 percent. It has an arid climate characterized by low annual precipitation and severe rainshadowing by the Sierra Nevada and the Cascade mountain ranges. The region is fairly homogenous in terms of R/P values as evidenced by its low variance of .04 (Table 1). This region has few rivers to transmit runoff and it is covered with sandy soils that yield fast infiltration rates further reducing the amount of runoff. AET/P would be
exceptionally high for this region due to the lack of vegetation, low annual precipitation, and warm annual temperatures. The region often experiences high intensity precipitation events that could increase the recorded precipitation but due to the rapid infiltration of the sandy soils the runoff variable could remain quite low.

The few anomalous watersheds in this region are located in the center of the Great Basin (Plate 3). They are more than two standard deviations greater than the mean for this region. The anomalous watersheds have higher mean basin elevations that could explain their higher R/P response.

*The Great Plains*

The Great Plains are characterized by low elevations and a semi-arid climate created by the rainshadow of the Rocky Mountains. Northern reaches of this region are subject to cold continental air masses while the southern reaches are subject to more mesic conditions. Despite the disparity in precipitation sources the region has a low variance of R/P values, .01. The mean R/P for this region is 12% (Table 1). There are no anomalous R/P values for this region (Plate 3).

*Eastern Temperate Forest*

The Eastern Temperate Forest (ETF) region is spatially the largest region in the ecoregion taxonomy. As a result it aggregates R/P ratios by not separating significant topographic features that affect runoff. Despite this lack of separation the ETF exhibits the most consistent interregional distribution of R/P ratios in the U.S as illustrated by it's variance of only .01. The mean R/P for the East is 35% (Table 1). Topographically this region is fairly homogenous except for the Appalachians and
the Catskill's. The flat terrain and lack of orographic enhancement is conducive to producing similar runoff conditions throughout the region.

Anomalous watersheds are located primarily in the Appalachian and Catskill Mountains (Plate 3). The spatial occurrence of the anomalous R/P watersheds is consistent with the orographic effects upon precipitation. The higher elevations of the mountains receive more precipitation than the surrounding watersheds resulting in higher R/P ratios. Several of the anomalous watersheds are located in the northern reaches of the region. AET decreases at these latitudes further enhancing runoff conditions.

**Northern Forests**

The Northern Forests region is one of the smaller, more discontinuous regions of the ecoregion taxonomy. It is a colder region dominated by continental polar air masses. Statistically the Northern Forest has little variance and a range of R/P values from 25% to 68%. The mean R/P for the Northern Forests region is 51%, the second highest of the U.S. ecoregions (Table 1).

Colder annual temperatures and less incident solar radiation inhibit AET and create higher runoff conditions for this region. R/P ratios may not be accurate indicators of the region's hydrologic regime. Western portions of this region near the Great Lakes are generally flat and characterized by karst topography and shallow depths to bedrock. The soils in the region are porous and there are large bodies of standing water with no surface inlet or outlet. (Omernik 1994) A great deal of water is stored in these standing water bodies and may skew runoff to precipitation results. Surface runoff does not represent the dominant mechanism for
removing water from the system. Eastern reaches of this region are more mountainous and illustrate the high mean R/P (Plate 1).

**Results of AET/P and R/P Comparison**

The qualitative portion of the analysis is to ascertain if there are significant discrepancies between the plotted R/P conditions and the estimated AET/P for the ecoregions. Discrepancies (i.e., the R/P and AET/P for a region are greater than 1) could indicate errors exist in the data for that region. A good fit between the R/P and the AET/P reinforces the data and adds strength to conclusions drawn from the analysis.

The R/P and AET/P match up well for ecoregions within the contiguous United States. Inconsistencies were expected in complex terrain with high elevations such as the Rocky Mountains, the Sierra Nevada, the Cascade Range, and the Coast Range Mountains yet the AET/P and the R/P seem to fit for these areas (Plate 1 and Plate 4).

Evaluation of Plate 1 reveals spatial patterns in the regional distribution of R/P ratios. In general R/P is less consistent for the Western U.S. than the Eastern U.S. R/P increases with elevation and proximity to marine sources of precipitation. The more arid conditions and complex topography that represents large portions of the Western U.S can explain this. Plate 3 and Table 1 further illustrate this pattern.

Assessment of Plate 3 reveals spatial patterns in the distribution of anomalous R/P ratios. Anomalous R/P watersheds tend to occur in areas with high elevation or in mesic areas. The enormous topographic relief of the West produces a great deal of anomalous R/P watersheds (Plate 3). The East has less topographic
relief and produces more stable R/P ratios. The highest anomalous R/P watersheds occur at high elevations near the coast. This is evidenced in the mountainous Marine West Coast Forest (MWCF) ecoregion that has several watersheds with R/P values greater than 90%. High precipitation and very low AET conditions exacerbate R/P conditions here. The Northwest Forested Mountains and Northern Forests ecoregions also possess watersheds with high R/P ratios (Plate 3).

Regions with low mean R/P ratios have fewer anomalous hydrologic units than ecoregions with high mean R/P ratios. The Great Plains and the North American Deserts ecoregions have mean R/P ratios less than .28. They are spatially the largest ecoregions but they lack significant amounts of anomalous watersheds. The majority of all anomalous watersheds possess R/P ratios that are more than +2 standard deviations from the mean.

Projections about specific watersheds were omitted from this analysis because the U.S.G.S. hydrologic units used to represent a basin do not always spatially represent the entire watershed. See "Methods" page 15.

**Conclusion**

The purpose of this research is to create maps of the following phenomena; mean annual R/P ratios for watersheds of Level 1 ecoregions, anomalous R/P ratios of Level 1 ecoregions, and estimated AET/P. These maps were produced in order to make observations on the spatial distribution of R/P conditions for the contiguous U.S.
Mean annual runoff data for 966 watersheds was procured from the U.S.G.S. Mean annual precipitation data was derived from PRISM precipitation grids. The runoff to precipitation ratio for each watershed was plotted in its corresponding U.S.G.S. hydrologic unit. Estimated AET was calculated using Turc's version of the Horton AET equation. Inputs for this formula came from gridded estimates of PET (Vorosmarty et al.) and PRISM precipitation data. Ecoregion boundaries were obtained from the Environmental Protection Agency.

All of the data was plotted using ArcView GIS. The mean R/P for each ecoregion was determined from statistical analysis and anomalous watersheds were determined to be any watershed with an R/P ratio more than two standard deviations from the mean R/P for the ecoregion.

According to the water balance equation the mean annual runoff and the mean annual AET for a watershed should equal its mean annual precipitation. The R/P ratios were compared to corresponding AET/P ratios to check the accuracy of the data. Based upon the prevailing climate research regarding evapotranspiration controls, it was determined that the R/P distributions are accurate.

This research suggests that watersheds with anomalous R/P conditions tend to occur in areas that experience extremely high precipitation. Arid regions tend to have fewer anomalous watersheds. The Marine West Coast Forest and the Northwest Forested Mountains receive substantial precipitation from marine sources and orographic enhancement and they have significant amounts of anomalous R/P watersheds. The Temperate Eastern Forest ecoregion, despite its low mean R/P of
35%, has anomalous watersheds almost exclusively in its wetter, mountainous terrain.

Flatter, topographically homogenous ecoregions tend to exhibit more stable and predictable R/P ratios than complex terrain. This phenomenon is clearly represented in the difference between the R/P ratios of the eastern U.S and the western U.S. The east is generally flatter and has lower mean annual R/P ratios and fewer anomalous R/P watersheds than does the higher, mountainous west. The west is also subject to greater rainshadow effects from the tall mountain ranges, which enhances the R/P differences between local watersheds.

This research provides a new perspective for studying the distribution and relationships of hydrologic variables at the synoptic scale. The analysis elucidates the role of evapotranspiration in determining the annual R/P distribution among watersheds. It reinforces the paradigm that evapotranspiration governs the magnitude of R/P ratios. In addition it was noted that anomalous R/P ratios coincide with areas of extremely high precipitation. This could indicate the presence of a possible threshold where precipitation magnitude may play a greater role than evapotranspiration in governing the R/P ratio. Further R/P research at smaller basin scales could clarify this phenomenon.
Bibliography


