Title
Is Scarcity a Real Driver for Water Reuse ?

Author
Hermanowicz, S W

Publication Date
2006-07-01

Is Scarcity a Real Driver for Water Reuse?

Slawomir W. Hermanowicz
Department of Civil and Environmental Engineering
University of California, Berkeley, CA 94720-1710
hermanowicz@ce.berkeley.edu

Water Resources and Water Reuse

Conventional knowledge suggests that water reclamation and reuse is implemented as a response to scarcity of natural water resources. According to this scenario, as water demand increases driven by increasing population, agriculture or industry, natural water resources (surface waters or groundwater) become insufficient and individual communities or larger regions turn to water reuse to meet an increasing fraction of their needs. Such image is often supported by intensive water reuse in the western US, a region known for its periodic droughts and extensive water resources infrastructure. However, the analysis of data on water consumption and water reuse collected by the US Geological Survey indicate that water scarcity is perhaps only one factor behind water reuse. Every five years, USGS publishes data on water use in the United States. Until 1995, these data included quantities of reclaimed water (the data for year 1995 are available at http://water.usgs.gov/watuse/spread95.html). The latest survey, for 2000, does not include water reclamation. For the purpose of this analysis, annual average reclaimed water flows were divided by wastewater returns also reported in the same source. When aggregated by states, water reclamation was reported in sixteen states in the contiguous US. The quantities of reclaimed water (as a fraction of total wastewater returns) varied from less than 0.1% for Tennessee to more than 80% for Arizona. In the remaining 32 states, no water reuse was reported.

The extent of water reuse was then compared to the available water resources. USGS published a map showing the quantities of "*renewable water supplies*" and "*consumptive use*" for 21 water-resources regions in the United States (http://water.usgs.gov/watuse/misc/consuse-renewable.html). According to this source, renewable water is defined as "*the sum of precipitation and imports of water, minus the water not available for use through natural evapotranspiration and exports*". Based on these data, the consumptive use was expressed as a percentage of renewable supplies. This ratio varied from 0.7 and 0.8% for the Tennessee River and New England regions to 103% for the Lower Colorado River region. Fig. 1 shows the comparison between water reuse and the consumptive use for the contiguous United States. Although water reuse was aggregated by states and water consumption by water-resources regions, an interesting picture emerges. While water reuse is practiced in many of the western states where consumptive use constitutes a substantial portion of renewable resources, significant reuse occurs also in the regions with much lower consumptive use in relation to the renewable resources. Among those seemingly water-abundant regions, water reuse is implemented in the southeast, especially in Florida and, to a lesser extent, in Georgia and the Carolinas.

Even in the west, there are significant differences in the extent of water reuse between the states with similar consumptive uses. For example, in Arizona, 87% of wastewater returns is reclaimed while in neighboring New Mexico, this value is much lower, at 0.6%. For both states, the consumptive use is very high (70% for New Mexico and 103% for Arizona, assuming the values for Rio Grande and Lower Colorado River, respectively).

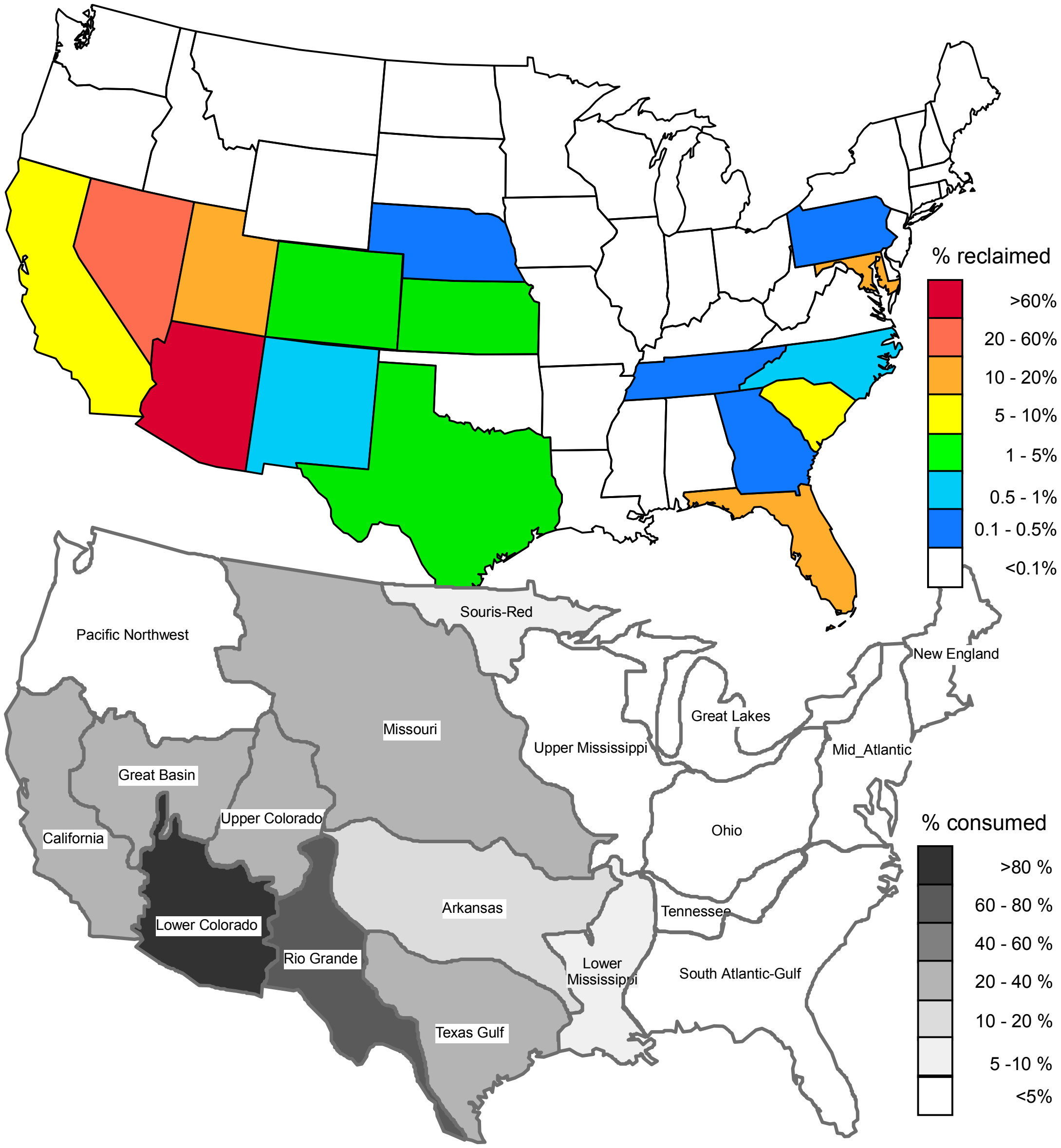
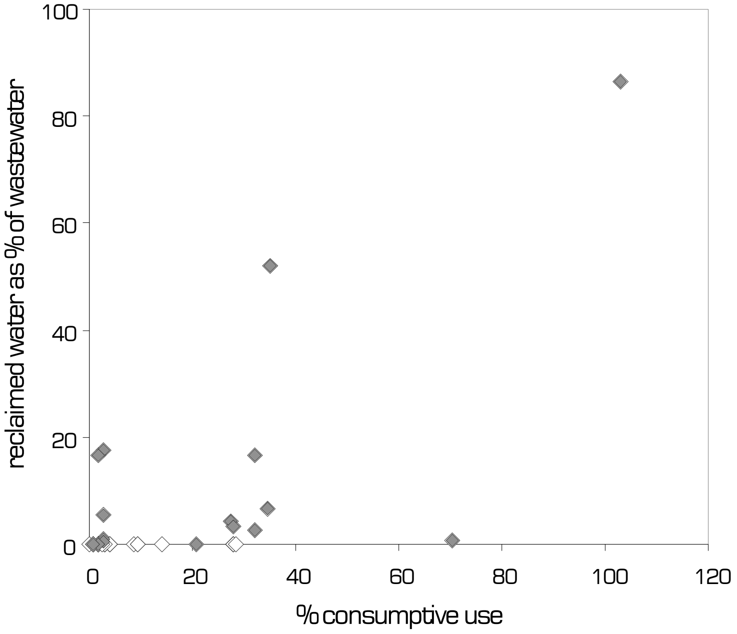


Figure 1 Water reuse as percent of wastewater returns (top map) and consumptive use as percent of renewable water resources (bottom map). *Source: USGS*

Further comparison between available water resources and water reuse is shown in Figure 2. The extent of water reuse is plotted as a function of either relative consumptive use or average annual rainfall. Rainfall is a major component of renewable water resources. On a regional scale, rainfall replenishes water supplies, affects evapotranspiration, and controls the need for artificial urban and agricultural irrigation. Thus, it can be used as a proxy for water supply, especially since the availability of complete water supply data on smaller temporal and spatial scales is very limited. In contrast, rainfall data are available for 70 years from the National Climatic Data Center (maintained by the US NOAA) for individual meteorological stations and aggregated by climate divisions and states (a selection of various datasets is at http://www5.ncdc.noaa.gov/). For our analysis, area-weighted state monthly precipitations (file HCS4-2) were used.



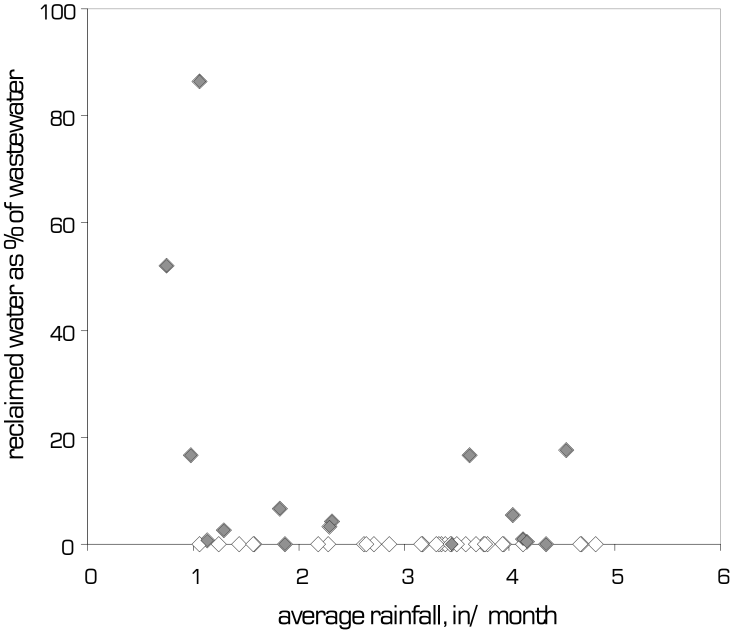


Figure 2 Water reuse as percent of wastewater returns *versus* percent consumptive use (top) and annual average state rainfall (bottom). Dark symbols show states with reported water reuse. *Sources: NOAA, USGS*

Although large water reuse is associated with high relative consumptive use and low rainfall, the association is not complete as significant water reuse occurs also in other areas as shown previously in Fig. 1.

Variability of Water Supply

The lack of clear association between water scarcity and the extent of water reuse suggests that other factors are also responsible, perhaps even to a larger extent for implementation of water reuse projects. We postulate that variability and control of water supplies may be that the real (and perhaps unacknowledged) driver behind substantial water reuse. This motivating force for water reuse was implicitly postulated by Hermanowicz and Asano (1999) in their analysis of "metabolism of cities", the term first coined by Abel Wolman in his seminal paper in 1965. Hermanowicz and Asano considered water contained in urban wastewater as "*a valuable resource ready for reuse and under local control*". This idea can be further expanded by examining the spatial and temporal scales of different parts of a hydrologic cycle. Natural hydrologic processes are characterized by large variabilities associated with large scales. For example, the range of daily flows (difference between the maximum and the minimum) for Colorado River is approximately 16 times its average flow. In contrast, engineered systems have much smaller variability. For dry-weather wastewater flows, the range-to-average ratio of daily flows is typically smaller than 1. Larger variation occur in systems exposed to stormwater influx (e.g., in combined sewers) but these changes are somewhat outside of the realm of engineering control.

We suggest that water reuse becomes a significant portion of water supplies when spatial and temporal scales of natural and engineered cycles do not overlap. For example, if a local watershed is "irrigated" by rain every few days, water reuse is less needed and possibly superfluous. However, when time scale of the natural cycle is measured in years or decades and stretches over a large area (like drought conditions in the western US), while water demand occurs on much smaller local scales on shorter times, this disjunction promotes water reuse - "*closing hydrologic cycle on smaller scales*" as discussed by Hermanowicz and Asano (1999).

To test this hypothesis in a quantitative manner, we use average monthly rainfall as a convenient proxy for water supply. Again, the reason for using this meteorological parameter is its obvious association with renewable water supplies, especially on a regional scale, and the availability of high quality, long-term data. Unlike long-term averages used in Figure 2, we examine changes in monthly rainfall for individual states over 70 years (1931-2000). Variability of this parameter can be characterized in two ways: with the coefficient of variation, and the Hurst exponent. From each state record, we calculated the coefficient of variation (equal to the ratio of the standard deviation to the average) for each calendar month over the seventy years. The *average* coefficient of variation C was then defined as the arithmetic average of the twelve monthly coefficients. We feel that this way of averaging reflect better the variability associated with the yearly hydrologic cycle rather than a simple coefficient of variation derived from the whole seventy-year long record. However, when the simple coefficient of variation was used, the results were quite similar. The calculated values of C were from 0.336 for New York to 0.772 for California.

The coefficient of variation describes the overall variability of the time series (rainfall in our case) but does not describe the dynamics of the series. With respect to water supplies, persistence of the series seems to be of importance. The time series is called persistent (or long-memory) if high values of the variable are likely to be followed by high values and low values by low values. In contrast, if low values are likely to occur after high values and *vice versa*, the series is anti-persistent (or short memory). In the boundary case, where there is no correlation between subsequent values, the series is (neutrally) random. This attribute of a time series may be described by its autocorrelation function but Hurst exponent H provides a more robust characteristics. The exponent was named after E.H. Hurst, a hydrologist who applied this analysis to river flows (especially the Nile). The value of H can be estimates using the R/S analysis. This method is based on the following relation

$$\frac{\langle R(t) \rangle}{\langle S(t) \rangle} \propto t^H$$

where $R(t)$ is the range of the time series (i.e., maximum - minimum) within a window of length t, $S(t)$ is the standard deviation, and < > denotes an average. To estimate H, the time series is divided into segments of length t. For each segment, R and S are calculated and averaged over all segments. The procedure is repeated for several values of t and H is calculated as the slope of log($<R>/<S>$) *versus* log(t). If $H > 1/2$, the series is persistent, if $H < 1/2$ - it is anti-persistent.

Most of natural time series exhibit linearity of the R/S log-log plot only over a limited range of time periods. An example of such a plot is shown in Fig. 3 for monthly rainfall data for Utah. The plot is linear up to t values of roughly 48 months with the Hurst exponent of 0.220. Almost all records showed a similar pattern, with H (for up to 48 months) spanning the range from 0.187 for Georgia to 0.291 for Washington.

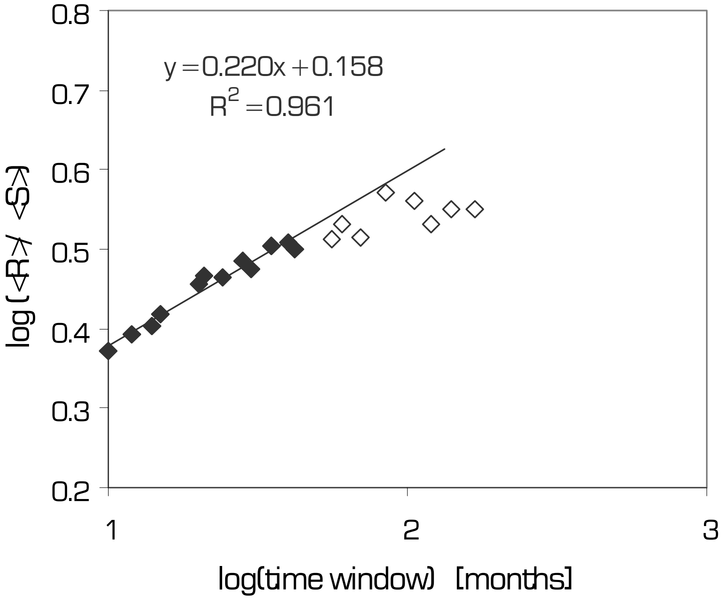


Figure 3 R/S plot for monthly rainfall data for Utah. Dark points were used to estimate H.

The physical meaning of the Hurst exponent can be demonstrated by comparing the rainfall records of Arizona, California and New Mexico. The average annual rainfalls are 13.6 in for Arizona, 21.8 in for California, and 13.6 in for New Mexico. All three states have close coefficients of variation: 0.75 for Arizona, 0.77 for California, and somewhat smaller 0.60 for New Mexico. However, the series look quite different (Fig. 4).

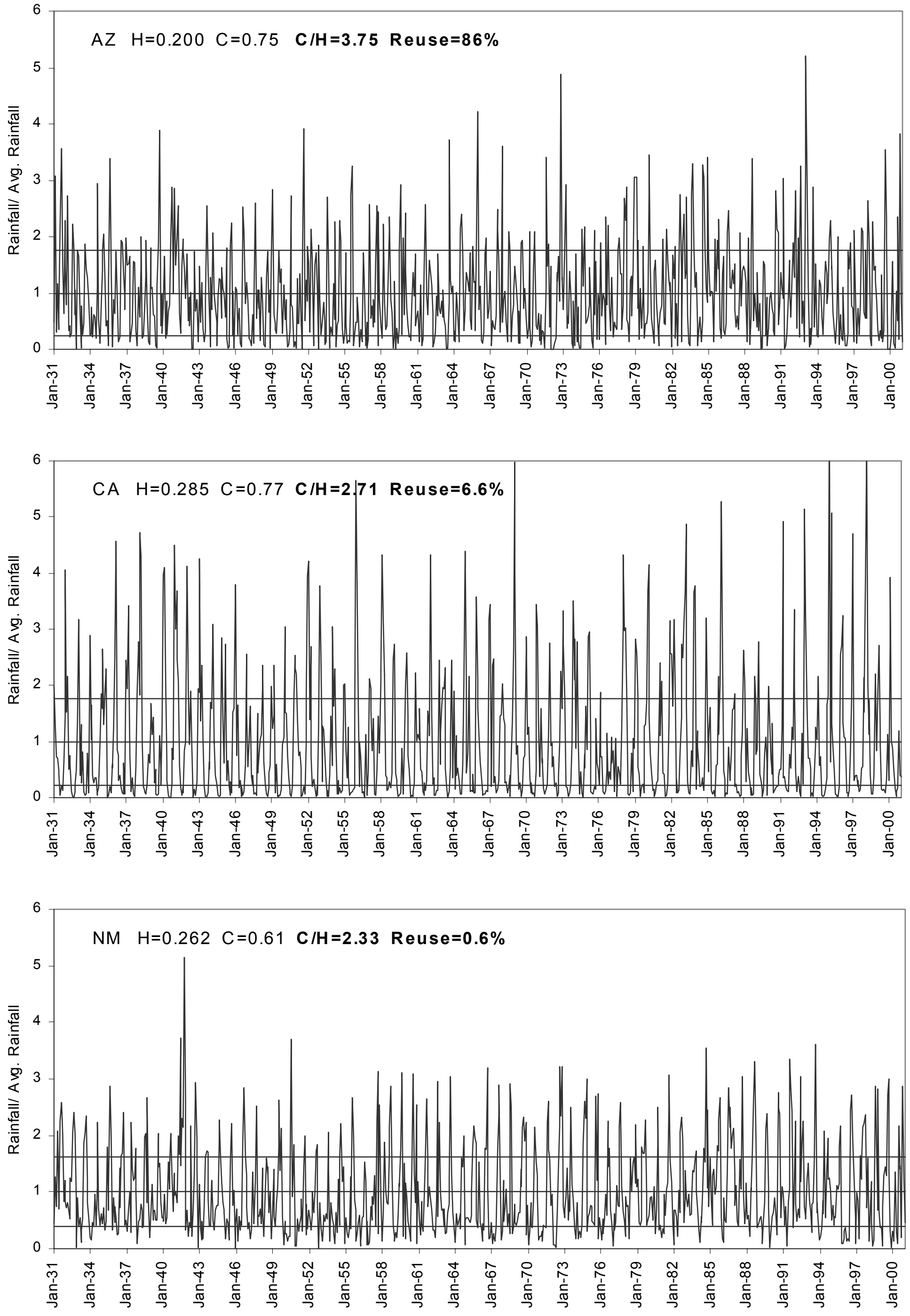


Figure 4 Monthly rainfall records for Arizona, California and New Mexico

The range of rainfalls in California is larger that in Arizona and the series itself is more persistent (or less anti-persistent) in accordance with different Hurst exponents (0.285 for California and 0.200 for Arizona). New Mexico has similar degree of persistence as California (with Hurst exponent of 0.262) but the range of values is somewhat smaller, in line with smaller *C*. As seen in this example, both *C* and *H* provide information about the dynamics of the time series.

Reclaimed Water as a Local Resource

We have developed two measures of variability of renewable water supply through its proxy, the rainfall. The average coefficient of variation *C* describes the magnitude of its deviation from the average while the Hurst exponent *H* characterizes the degree of persistence (or anti-persistence) in time. We propose to create a simple index of variability by taking the ratio of these two parameters *C/H*. Large values of this index indicate large variability and, in some sense, larger uncertainties of water supply. Hence, these conditions should promote water reuse. To examine this possibility, the extent of water reuse (as percent of wastewater returns) was plotted *versus* the *C/H* index (Fig. 5).

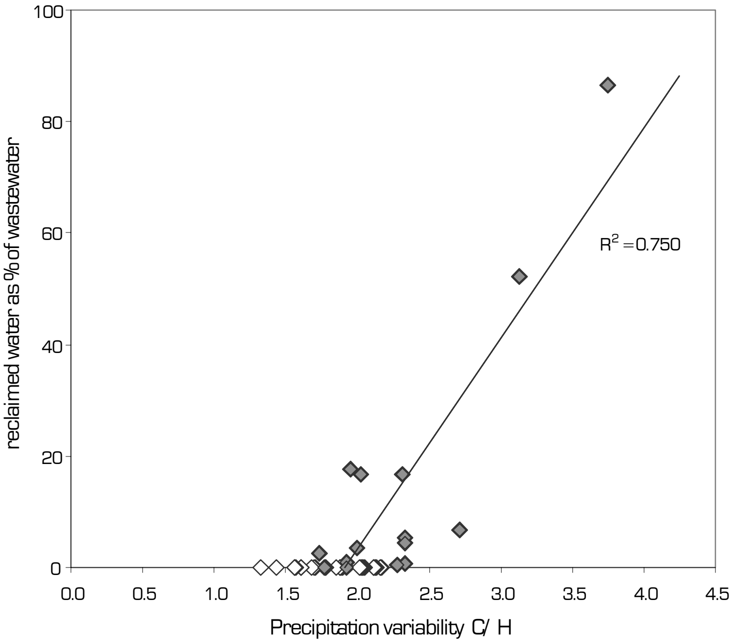


Figure 5 Water reuse for different variability index

It appears that the extent of water reuse is significantly correlated with the variability index. The correlation is much stronger than with any other parameter such as relative consumptive use or simple rainfall (Fig. 2). As the index reaches approximately 2, water reuse seems to take off quite dramatically. Although correlation does not necessarily imply causality, we believe that the developed relation may point to an important (and hopefully) universal link between *variability* of water supply and the extent of water reuse.

The following two examples demonstrate the meaning of the *C/H* index. In the first example, we compare three western state already shown in Fig. 4: Arizona, California and New Mexico. All three states are located in the arid or semi-arid region and receive little rainfall although California has almost twice as much as Arizona or New Mexico. However, the extent of water reuse varies greatly, from less than 1% in New Mexico to 6.6% in California to over 80% in Arizona (1995 USGS survey data). We suggest that these differences can be correlated with differences of their respective variability index *C/H*: 2.3 for New Mexico, 2.7 for California, and 3.75 for Arizona.

The second example, water supply variability (expressed as *C/H* index) in Utah and Florida are examined. Unlike Utah, Florida has abundant rainfall (54.5 in/yr compared with 11.6 in/yr). A similar difference exists for the consumptive use of water. In the South Atlantic Gulf region, where Florida is located, the average consumptive use is merely 3% of the renewable water resources. For Utah, that straddles the Upper Colorado River and the Great Basin regions, the consumptive use is larger than 30%. Despite these very large differences in water supply, the extent of water reuse is very similar: 16.7% in Utah and 17.5% in Florida. We believe that these similarities are associate with similar values of the *C/H* index, close to 2 (for Utah 2.3 and for Florida 1.96). Figure 6 shows in the top panel actual monthly rainfall data for both state that clearly are much different. However, when the rainfall data are rescaled by their average (bottom panel of Fig. 6), both series are almost indistinguishable.

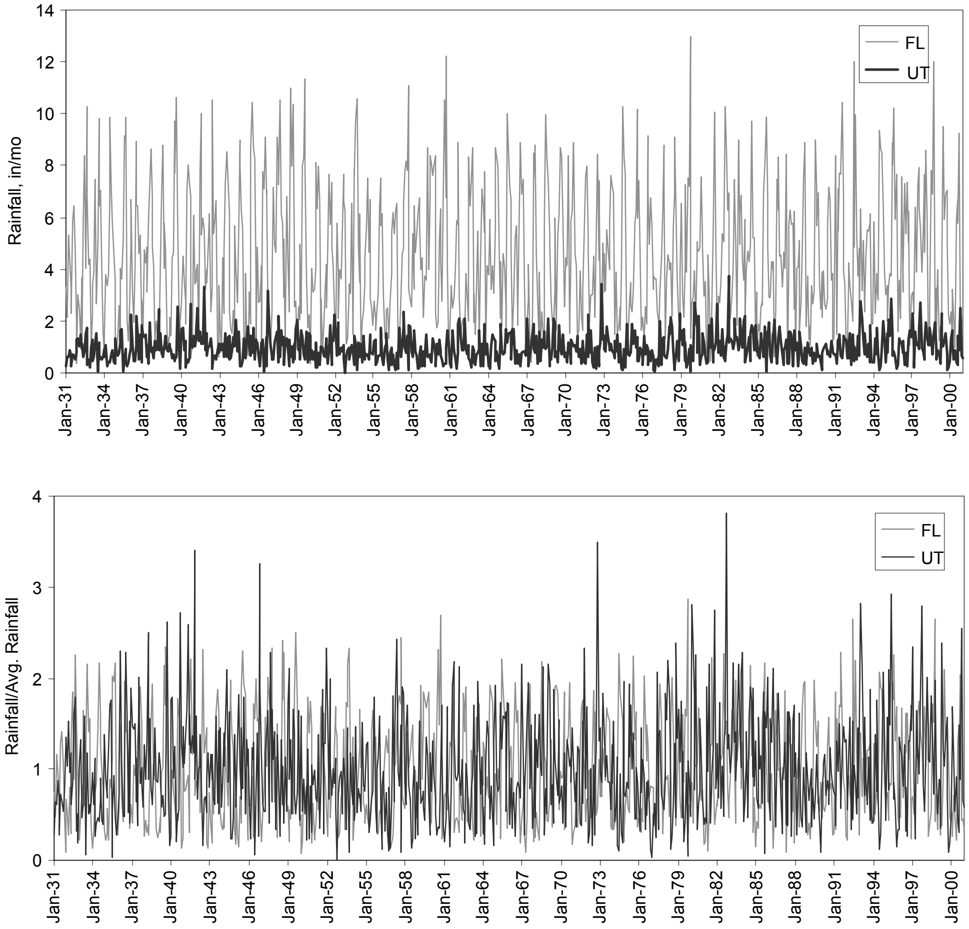


Figure 6 Actual monthly rainfall data for Florida and Utah (top) and rescaled by the respective averages (bottom)

As shown in these specific examples and in Fig. 4 for all contiguous United States, a strong correlation exists between the extent of water reuse and the variability of water supply, in this work measured by the rainfall variability index *C/H*. We postulate that the *variability* of water supply rather than its absolute level is a good quantitative determinant of water reuse extent. In areas with large variabilities, there is a trend to use reclaimed water as a locally controlled resource to supplement uncertain natural sources.

Obviously, in some cases other issues constitute the main impetus for water reuse. For example, limitation in discharge and disposal of treated wastewater may foster water reclamation and reuse. An example of such is the souther region of the San Francisco Bay (San Jose - Santa Clara) where a large portion of consumed water is brought from outside the natural watershed or extracted from underground. A substantial portion of this water becomes wastewater that is treated in a large tertiary treatment plant. In the past, the treated effluent was discharged without particular limits at the southern tip of the Bay. However, as the discharged flow significantly exceeded the natural quantity of water historically draining to the Bay, it began to affect its saline ecosystem including a few endangered species. As a result, discharge limits of treated effluent were instituted promoting reclamation and reuse of the excess flow. However, these isolated instances do not materially affect regional (state-wide) situation where water supply variability seems to be an overall driver.

Further Work

So far, we examined water reuse and supply on the state-by-state basis with consumptive use evaluated for hydrologic regions as defined by the USGS. Dynamics of water supply was approximated by monthly rainfall data. This approach was primarily dictated by the availability of data on these spatial and temporal scales. Further work is planned to examine our hypothesis on different spatial scales. Instead of administrative units, a more logical choice would be to apply our analysis to areas of similar meteorological and hydrologic conditions. Climate divisions (as delineated by NOAA) could be a possible choice of such unit. Ideally, the dynamics of water imports and exports should be also included beside rainfall.