# Influence of Hydroclimate on Characteristics of Hydrograph Evolution in Snowmelt-Dominated River Systems

Margaret A. Matter[1]
Civil Engineering Department, Colorado State University, Fort Collins

Luis Garcia
Civil Engineering Department, Colorado State University, Fort Collins

Darrell Fontane
Civil Engineering Department, Colorado State University, Fort Collins

**Abstract.** Earlier and more accurate water supply forecasts for the Colorado River Basin (CRB) could help reduce uncertainty and risk when making decisions and lengthen lead time for planning more efficient and effective water supply strategies. The approach presented quantifies characteristic hydrograph responses to interannual variations in hydroclimatic conditions in snowmelt-dominated river systems. Results for the CRB indicate that beginning in fall (4-6 months prior to April forecasts), differences in timing, magnitude and form of seasonal hydrographs and amount of streamflow variability correlate closely with relative magnitude and timing of upcoming snowmelt runoff. These results suggest and recent advances in understanding effects of ocean/atmosphere interactions on precipitation in the CRB support, that essential hydroclimatic conditions that drive snowpack development and snowmelt establish by fall and persist into spring. The use of teleconnections to develop characteristic streamflow responses in the CRB provides insight into atmosphere/land processes that influence snowpack development and runoff characteristics.

## 1. Introduction

The Colorado River system is a major source of water supply for seven states. Rapid development, high population growth rates, expanding types of demands, and limited accuracy and short lead time of water supply forecasts require efficient and effective water resource planning and management. Earlier and more accurate forecasts could help reduce uncertainty and risk in water management decision-making and lengthen the time period for planning more efficient and effective water use strategies. The goal of this research is to increase the lead time for snowmelt runoff hydrograph estimation by 4-6 months (from spring to the preceding fall), and at the same time, increase the accuracy of snowmelt runoff estimates in the Upper Colorado River Basin (UCRB).

Snow comprises 50 to 80 percent of the water supply in the Colorado River Basin (CRB; Woodhouse 2003), so the total volume of streamflow during the peak snowmelt runoff period, April to September, represents most of the water supply for the water year (WY). Total April-September flow is pre-

[1] Department of Civil Engineering
Colorado State University
Fort Collins, CO 80523-1372
Tel: (970) 491-7620
email: matter@lamar.colostate.edu

dicted based on precipitation from December through February (or March), when snowpack is most extensive (Gutzler and Rosen 1992). However, total precipitation over a longer period of time, October through March, is positively correlated with April-September streamflow (Cayan et al. 1999; Gutzler et al. 2002; Hidalgo and Dracup 2003). This suggests that precipitation and temperature regimes that establish in the fall are related to the same hydroclimatic conditions that persist through winter and into early spring, and thus, beginning in fall, streamflow hydrographs may be expected to reflect influences of precipitation and temperature signals associated with hydroclimatic conditions that will drive snowpack development through winter and influence snowmelt in early spring.

Hydroclimatic conditions (e.g., average, wet or dry) are accompanied by characteristic temperature and precipitation regimes. In general, wet years tend to be colder and dry years tend to be warmer than average, since moisture moderates air temperature (Trenberth and Guillemot 1996). Nevertheless, effects of interannual or long-term climate variations on temperature and precipitation in a river basin are often difficult to quantify. Streamflow integrates and amplifies the effects of changes in temperature and precipitation over the basin (Cayan et al. 1999; Dettinger and Diaz 2000), and hence streamflow is a stronger indicator of hydroclimatic change than variations in temperature or precipitation. Timing and magnitude of seasonal flow volumes (i.e., total amount of flow to pass a stream gage in a period of time) are sensitive to changes in physical conditions of a river basin, such as land use (Court 1962) or climate trends (Hodgkins et al. 2003). Hodgkins and others (2003) examined effects of increased temperatures related to long-term climate change on fall and winter/spring seasonal flow volumes for river basins of the northeastern U.S. All of the stream gages were listed in the USGS Hydro-Climatic Data Network (HCDN), a database of streamflow records relatively unaffected by anthropogenic activities and therefore suitable for climate studies (Slack and Landwehr 1992). Results were significant for winter/spring seasonal flow volumes, indicating that temperature increases caused the center of winter/spring flow volume to occur earlier than average in the season.

In addition to seasonal hydrographs, diurnal hydrograph development over the snowmelt season in rivers throughout the Western U.S. exhibits effects of long-term climate change (Lundquist and Cayan 2002), as well as effects due to interannual climate variations (Lundquist and Dettinger 2003), though the effects are different. Similarly, Hannah and others (1999) demonstrated that characteristics of diurnal glacier-fed hydrographs are also related to hydroclimatic conditions (i.e., a wet, dry or average year) and timing of peak flows, which provide water managers and hydropower generators with advance information about magnitude and timing of glacier runoff. Seasonal and diurnal hydrograph techniques have not been applied to interannual variations in hydroclimate to determine effects on hydrograph evolution between fall and early spring in snowmelt-dominated river systems for purposes of improving forecast accuracy and increasing lead time. In addition, since seasonal flow volume methods are often unable to detect significant changes in fall hydrograph development, different methods are required that are more sensitive and can reveal subtle changes in streamflow patterns, such as rate of change (i.e., slope) of hydrographs and patterns in daily flow. Differences in fall hydrograph characteristics that are indicative of driving hydroclimatic conditions (i.e., future water supply), increase lead time for planning and managing water resources by 4-6 months prior to April forecasts.

Timing of when hydroclimatic conditions establish and become persistent also affects characteristics of hydrograph evolution. Recent advances in understanding influences of ocean/atmosphere interactions on precipitation and streamflow in the CRB agree with the observation that October-March precipitation is positively correlated with April-September streamflow, and support the assertion that snowpack development and melt in the UCRB are influenced by hydroclimatic conditions that set up in the fall.

Three of the major climate modes affecting precipitation and streamflow in the CRB are El Niño/Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) (e.g., Enfield et al. 2001; McCabe et al. 2004; Webb et al. 2004). AMO is the most slowly evolving of the three climate modes, with a cycle of approximately 65-80 years (Enfield et al. 2001), and PDO evolves over about 20-30 years (Staudenmaier 2003). ENSO evolves over a shorter time period, approximately 6-18 months (Staudenmaier 2003). ENSO modes are phase locked meaning they evolve with the seasons (Neelin et al. 2000). In about July, ENSO conditions begin to set up, and by October, conditions tend to persist and can be predicted several months in advance (Gutzler et al. 2002; Gershunov and Cayan 2003). ENSO events persist and influence precipitation (e.g., Ropelewski and Halpert 1986; Redmond and Koch 1991; Cayan and Webb 1992; Kayha and Dracup 1993; McCabe and Dettinger 1999) and streamflow (e.g., Cayan et al. 1999; Hidalgo and Dracup 2003) in Western U.S. rivers between fall and spring. Yet predictability in how ENSO modes will be expressed in the CRB is modulated by atmospheric circulation, weather, orographic effects, and other climate modes, such as the PDO and AMO, that evolve over longer timescales (McCabe and Dettinger, 1999; Gutzler et al., 2002; Gershunov and Cayan, 2003) and are important drivers of climate signals with or without contemporaneous ENSO extremes (Gershunov and Cayan 2003). Since ENSO conditions are persistent between fall and early spring and the slow-evolving PDO and AMO do not change appreciably during the same time period, it is reasonable to assume that combined effects of the three climate modes remain relatively constant between fall and early spring. Thus, fundamental hydroclimatic conditions are set in the fall that will determine relative magnitude of the snowpack, or the water supply (i.e., average, wet or dry) for the water year.

Initial water supply forecasts for the CRB are issued in January, and although they have high predictive skill (i.e., level of accuracy; NRC, 1999) initial forecasts are more uncertain than those made later in the snowmelt season. Yet even forecasts as late as April are subject to change, and by April, planning time and options are limited for many water users in the CRB. If fall hydroclimatic conditions remain relatively unchanged through winter and into early spring, then effects of temperature and precipitation signals associated with fall hydroclimatic conditions should be reflected in characteristic patterns in seasonal and diel hydrograph development. The characteristic patterns provide earlier (4-6 months) and reasonably reliable indications of the relative volume of snowmelt runoff and timing of peak flows.

## 2. Methods of Analysis and Data

Seasonal hydrograph methods and new techniques are used to quantify changes in magnitude, timing, and rate of change of seasonal hydrograph evolution and patterns in daily flow fluctuations between fall and early spring. Identifying significant changes in timing and magnitude of fall/early winter seasonal hydrographs in response to long-term climate change is more difficult than for late winter and early spring seasons (Hodgkins et al. 2003), so methods were developed to quantify other hydrograph characteristics over shorter time increments than seasons, such as rate of change in flows and patterns in daily flow variability, that are indicative of longer-term trends in hydrograph evolution.

Each water year gage records are categorized according to hydroclimatic conditions (i.e., average, dry or wet) based on annual basin yield (ABY), or the total flow volume to pass a gage in a year. Methods are applied to periods of record at each gage, and correlations between each variable in a water year and corresponding ABY are estimated using Spearman's Rho rank correlation method. For example, November ICDF/DCDF ratios, flow variability indices, for the period of record at the GRG gage are correlated with corresponding values of ABY. The correlation relationships for each gage, which were developed posteriori, may be used a priori with different gage data to predict relative magnitude snowmelt runoff and timing of peak flows.

### 2.1. Data

The three gages used for seasonal analysis are the Gunnison River near Gunnison, CO., East River near Almont, CO., and the Colorado River at Lees Ferry, AZ... Streamflow data for the three gages was obtained from the USGS. Two of the gages, the Gunnison River near Gunnison, CO. (GRG) and East River near Almont, CO. (ERA), are listed in the USGS Hydro-Climate Data Network (HCDN) as having periods of streamflow record that are reasonably unimpaired, and thus suitable for climate studies. The Colorado River near Less Ferry, AZ. (CRLF), is not listed in the HCDN, however the period of record begins in the early 1900's when land and water resource development was limited. Gage information and periods of record are summarized in Table 1. Early streamflow records are often affected by factors including frequency and method of measurement. Consequently, ice flow data were examined to ensure that the streamflow records were representative and appropriate for analysis. For example, periods of record with the same value reported for every day of the month are not representative of actual flow variability, and thus are not suitable for some analyses. The period of record for the ERA is comprised of individual years and series of consecutive years because years where daily flows remained unchanged for a month at a time were not suitable for analysis, and thus were omitted. Between water years 1911 and 1917 for the GRG, only one reading of river stage was made per day to estimate daily mean flow, after which two readings per day were made through water year 1928. Periods of records for the GRG and ERA are discontinuous. No flow estimates were made between water years 1929 and 1944 for the GRG, and in 1937, a dam was built upstream on the Taylor River. The unregulated period of record, water years 1911 to 1928, is the "unimpaired" record of analysis for the GRG. The ERA data record is discontinuous between water years 1923 and1935, so in order for the unimpaired record to be of similar length, water years 1911-1922 and 1936-1949 wee selected for analysis. A coffer dam was built upstream of the CRLF gage in 1959 in preparation for construction for the Glen Canyon Dam, which was completed in 1963. Temperature and precipitation data was obtained from the National Climatic Data Center (NCDC) for gages at or near the stream gages, and are associated with hydroclimatic conditions.

**Table 1.** Summary of USGS Gage Information and Periods of Record

| | **Station Name** | | |
|---|---|---|---|
| | Gunnison R. nr. Gunnison, CO. | East R. nr. Almont, CO. | Colorado R. at Lees Ferry, AZ. |
| | **Station Number** | | |
| | 09114500 | 09112500 | 09380000 |
| **Type of Record** | **Period of Record (Water Years)** | | |
| Unimpaired | 1911-1928 | 1911-1912, 1917-1920, 1936-1949 | 1921-1938 |
| | **Length of Record (years)** | | |
| Unimpaired | 18 | 20 | 18 |

## 2.2. Methods of Analysis

Season flow volume methods are commonly used to determine effects of increased temperature due to long-term climate change on streamflow. Temperature or precipitation signals accompanying variations in hydroclimate alter magnitude and timing of seasonal or annual flow volumes or the total volume of flow to pass a gage in a season or year. Magnitude and time of occurrence (i.e., timing) of one-third and one-half of fall/early winter and late winter/early spring seasonal flow volumes are calculated for unimpaired records at each gage.

Temporal shifts in flow volume and variations in magnitude change hydrograph shape and slope, or rate at which flows rise or recede. Changes in hydrograph slope for fall/early winter and late winter/early spring seasons are determined over 10-15 day and at monthly intervals, for each year of record at each gage.

Increasing or decreasing hydrograph trends are typically not gradual changes in the CRB, but rather occur as flow fluctuations that incrementally increase or decrease flow volume over time. Frequency, magnitude and sign of fluctuations in streamflow reflect changes in precipitation and temperature associated with variations in hydroclimatic conditions. Increasing trends in seasonal flow occur through more frequent and/or higher magnitude increases in daily flow, and the opposite is true for decreasing seasonal trends. Ratios of running totals of increasing changes in flow to decreasing changes in flow (ICDF/DCDF) are calculated for each year of record to indicate sign (i.e., increasing or decreasing) and magnitude of trends in flow.

## 3. Results and Discussion

The goal of this research is to demonstrate that in the UCRB between fall and early spring, hydrograph features evolve characteristically according to hydroclimatic conditions that set up by fall and influence snowpack development and melt, and thus these features indicate relative magnitude and timing of snowmelt runoff 4-6 months in advance of April forecasts. For some analysis, it was necessary to use a subset of the unimpaired period of record for the Gunnison River near Gunnison, Colorado (GRG). Only one measurement of river stage was used to estimate daily mean flow between WY1911 and 1917, which was not sufficient to capture actual variability in daily flow. Two daily measurements of river stage were taken to estimate daily mean flow from WY1918-WY1928, and using this subset increased correlations by an order of magnitude.

Magnitude of fall/early winter one-third flow volume (OTFV) for WY1918-WY1928 is plotted against corresponding annual basin yield (ABY) in Figure 1. Fall/early winter OTFV tends to be larger when hydroclimatic conditions are drier than when they are wetter. Correspondingly, in Figure 2

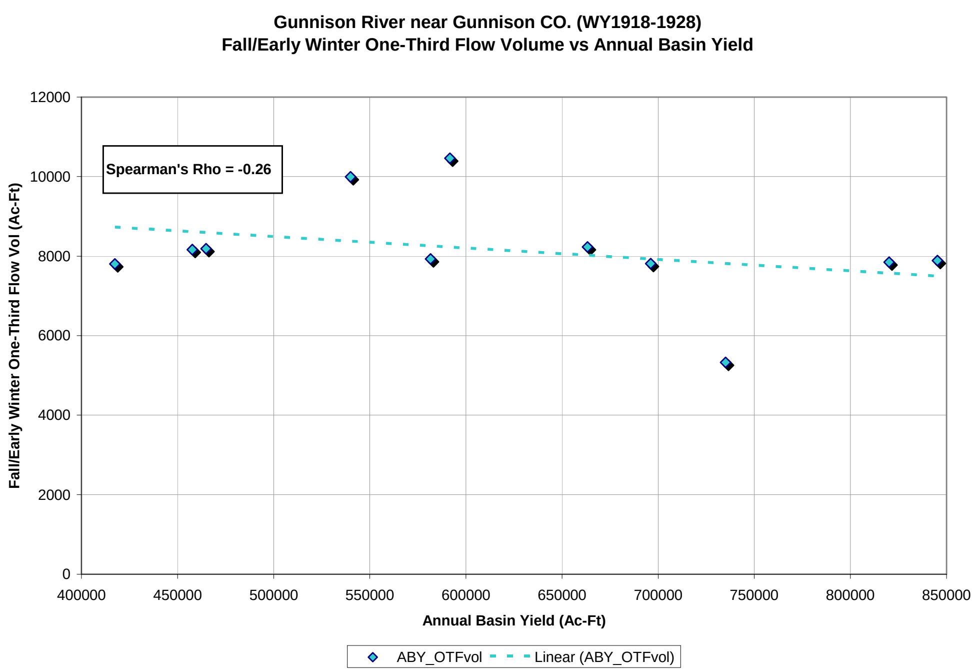


**Figure 1.** Fall/early winter one-third flow volume decreases in magnitude as annual basin yield increases.

the one-third flow date (OTFD), or the date by which the OTFV occurs, is earlier in drier years than in wetter years. Fall/early winter flow volume tends to be lower in magnitude and arrives later in wetter years than in drier years.

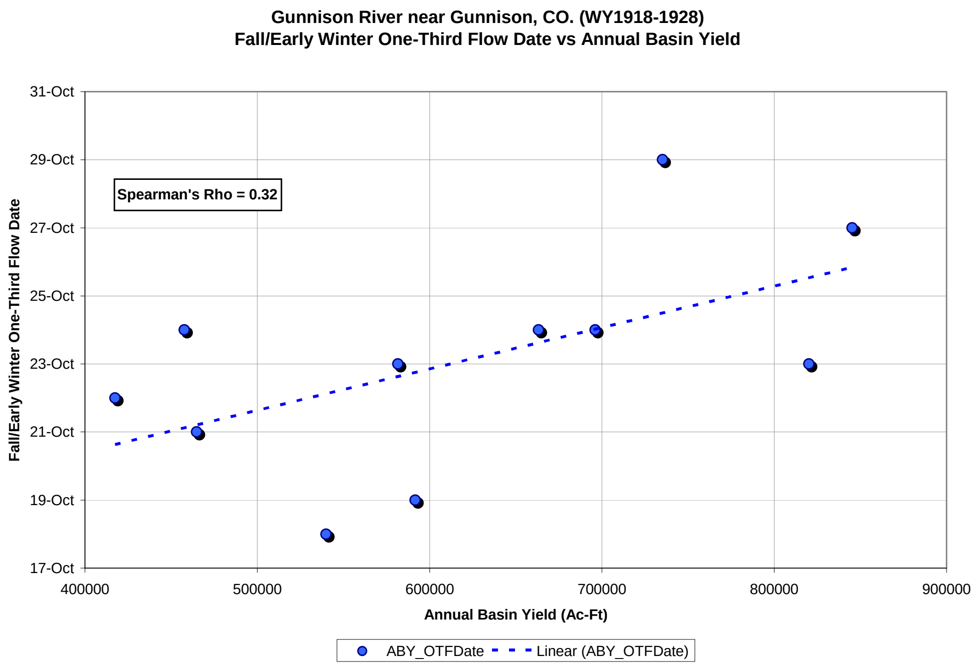


**Figure 2.** The fall/early winter one-third flow date, or the date by which the one-third flow volume occurs, is earlier in drier years and later in wetter years.

Antecedent conditions and characteristics of historical data may be factors contributing to the amount of variability and lower correlations. Effects of temperature change tend to be more easily detected in spring seasonal volumes (e.g., Hodgkins et al. 2003).

The water year one-third flow date (OTFD), or the date by which one-third of the total flow for the year passes a gage, also shifts according to hydroclimatic conditions. Annual basin yield and corresponding water year OTFD for the entire unimpaired period of record, WY1911-1928, are plotted in Figure 3. In drier years, OTFV for the year passes the gage earlier in the spring, and conversely in wetter years, the OTFV occurs later. During average hydroclimatic conditions (i.e., average ABY), the OTFV occurs around the average one-third flow date for the period of record. Earlier timing of the OTFD may be due to the fact that snowmelt depends on temperature (Williams and Tarboton 1999) and incident solar radiation (Leavesley et al. 1983; Gurnell et al. 1992), so in drier conditions, there may be fewer clouds along with warmer temperatures, and thus snow may melt at a faster rate than in wetter years when it is cooler and cloudier.

As seasonal flow volumes change in magnitude and shift temporally, the rate at which flow changes varies accordingly. Figure 4 illustrates how rate of change in streamflow, or hydrograph slope, varies with magnitude and timing of late winter/early spring flow volumes. Warm, clear conditions increase the rate of snowmelt, in turn increasing runoff and rate of change in streamflow.

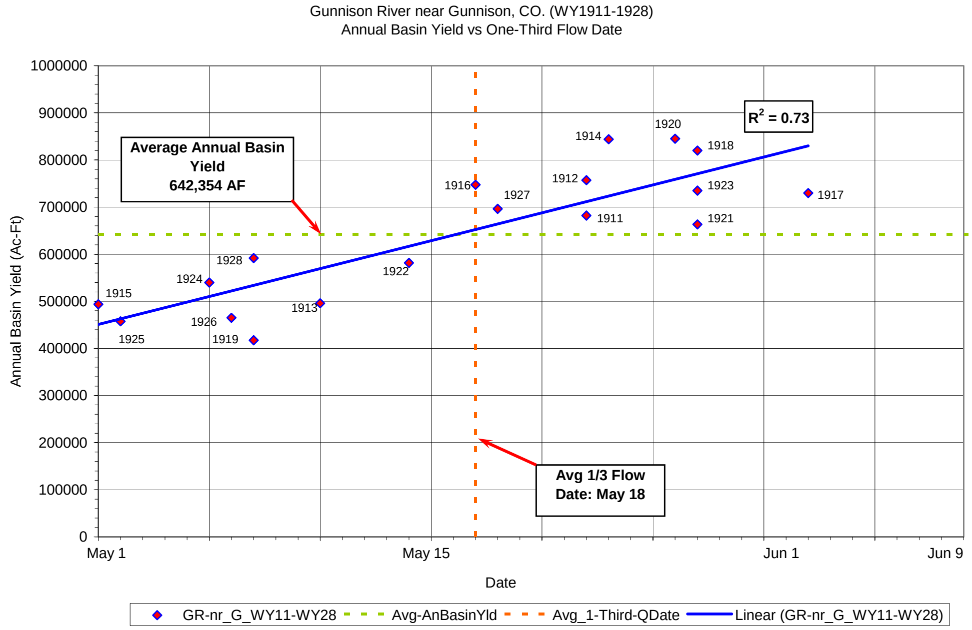


**Figure 3.** Water year one-third flow date for the GRG occurs earlier in drier years (i.e., lower ABY) compared to wetter years (i.e., higher ABY).

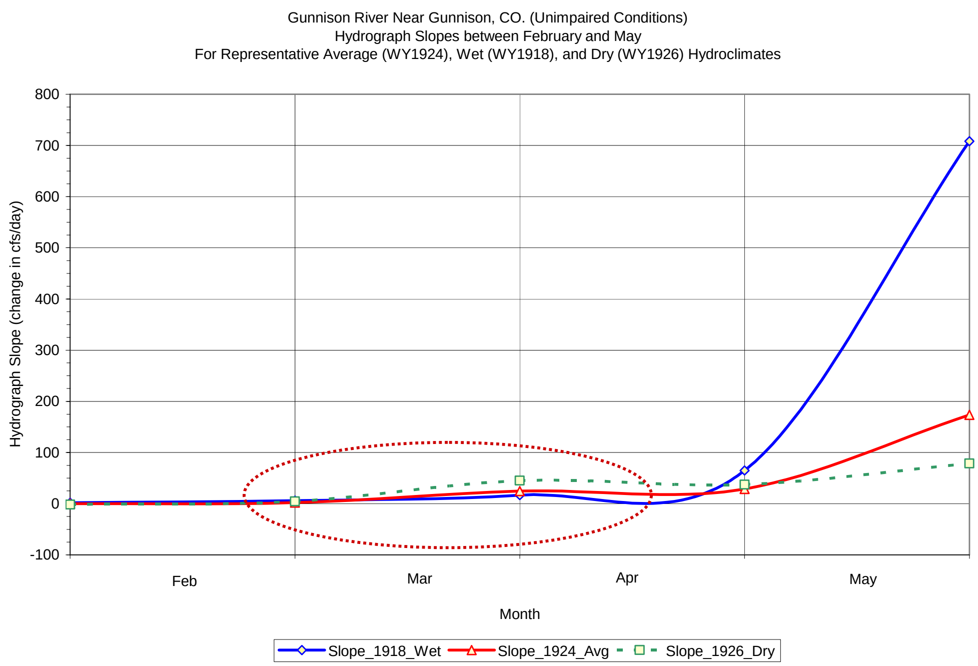


**Figure 4.** Monthly slope of hydrographs, or the rate of change in streamflow, between Feb and May, is steepest in drier years and least steep in wet years, corresponding with shifts in late winter/early spring flow volume to earlier in the season.

Snowmelt rate is lower under colder, cloudier conditions, and thus the rate of increase in streamflow would also be lower. Consistent with earlier OTFD in drier conditions, peak snowmelt runoff for the GRG also tends to be earlier in dry to below average years than in wet conditions

Streamflow response to changes in temperature and precipitation signals associated with interannual variations in hydroclimate is also observed in patterns of daily flow fluctuations beginning in the fall. Ratios of running totals of increasing changes to decreasing changes in daily flow (ICDF/DCDF) for the subset of unimpaired flows are plotted in Figure 5. The ICDF/DCDF ratios on the y-axis begin at zero and become increasingly negative because the denominator is decreasing (i.e., negative) change in daily flow. Beginning in

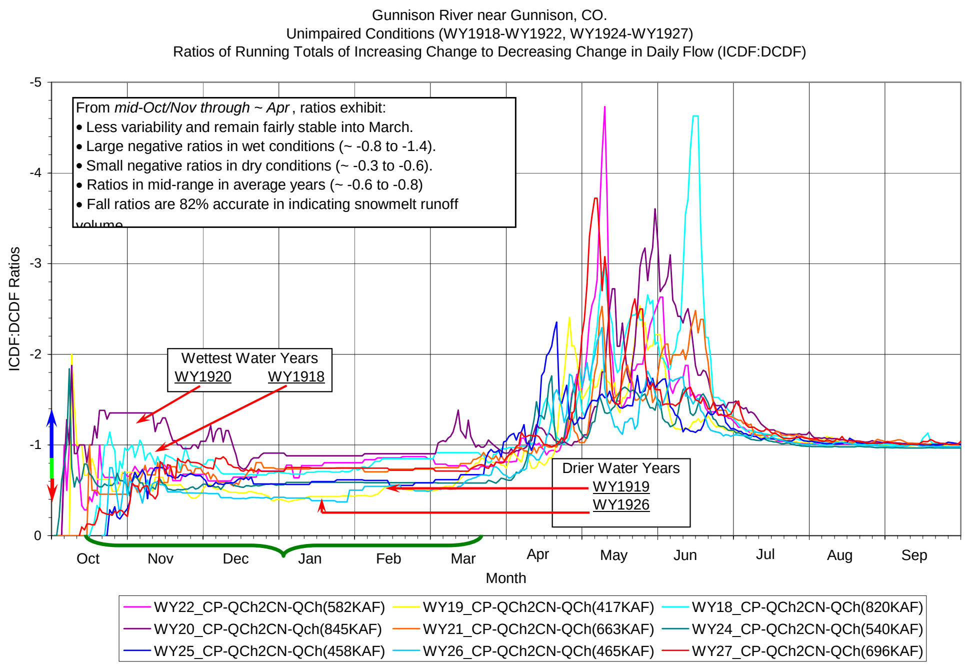


**Figure 5.** Daily ratios of running totals of daily increases in flow to decreases in flow plotted for 9 of 11 water years of the unimpaired show that between Oct and Mar, increasing changes in flow are higher and/or more frequent in wetter hydroclimatic conditions than in average or drier conditions.

about mid-October or the beginning of November, variation in the ratios subsides and the ratios are relatively stable into March. The order in which the ratios plot is directly related to relative magnitude of ABY; large negative ratios in wetter years and small negative ratios in drier years. Ratios for two years, WY1923 (wetter year) and WY1928 (below average year) are not plotted because the ratios initially exhibited inconsistencies compared to the rest of the record. In both cases, characteristics of data explained inconsistencies. For example, in WY1923 there was no rain at the beginning of October, so ratios remained low until it began to rain in mid-October. Ratios increased and were consistent with patterns for the rest of the record for the remainder of the year. By November, ICDF/DCDF ratios correctly predict ABY nine out of eleven years of record, or 82 percent, and by mid-November, ABY for 10 out of 11 years (91 percent) were correctly predicted. Average ratios for November are plotted against ABY in Figure 6, and the plot illustrates a reasonably strong

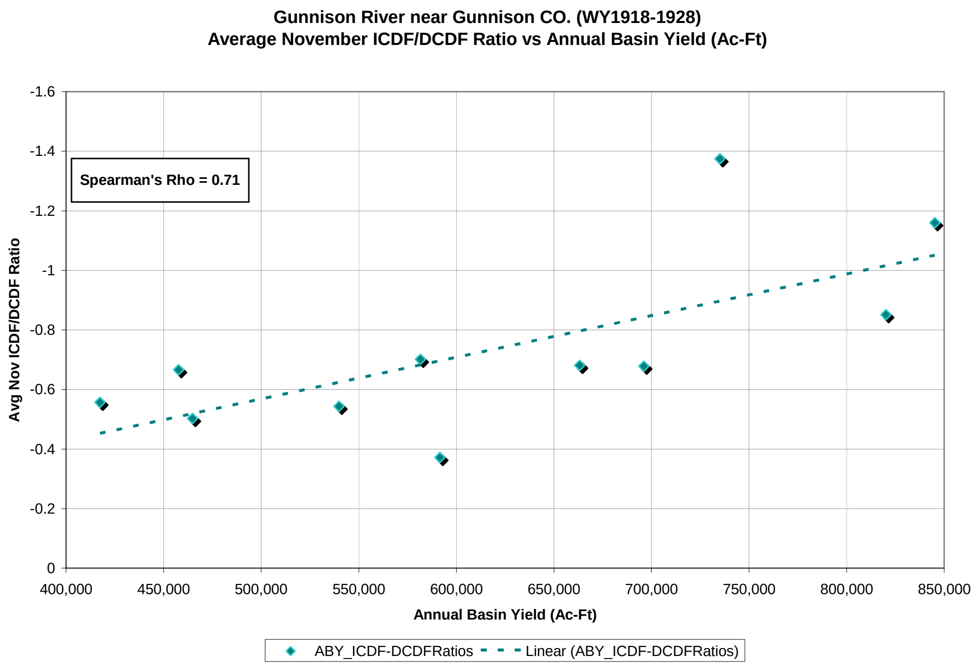


**Figure 6.** Average ICDF/DCDF ratios for November tend to range from smaller negative ratios in drier years to larger negative ratios in wetter conditions.

relationship (Spearman's rho = 0.71) between average November ratios and ABY, indicating that by November, ICDF/DCDF ratios can predict snowmelt relative magnitude of spring snowmelt runoff. Although fall/early winter flow volumes are higher and occur earlier in dry versus wet conditions, flow fluctuations indicate greater increases in flow volume early in the fall in wet hydroclimatic conditions compared to dry conditions. Antecedent conditions, ground water contributions and differences in distribution of precipitation between wet and dry hydroclimatic conditions may explain the observations.

## 4. Conclusions

In this paper we investigated streamflow records for the UCRB for largely unimpaired basin conditions to determine relationships between hydroclimatic conditions and hydrograph evolution from fall to early spring in snowmelt-dominated river systems. Recent advances in understanding influences of climate modes, including ENSO, PDO and AMO, on precipitation and streamflow in the CRB suggest that hydroclimatic conditions that drive snowpack development may actually set up by fall. However, the relationship between fall/early winter precipitation and snowpack development, the major source of water supply in the CRB, has been mostly ignored primarily because December-February (or March) is the main snow accumulation period.

The consistent patterns in streamflow response to interannual variations in precipitation and temperature signals in the UCRB has application in skilled water supply forecasting to improve accuracy and increase lead time.

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## References

Cayan, D.R., and Webb, R.H., 1992. El Nino/Southern Oscillation and Streamflow in the Western U.S. In H.F. Diaz and V. Markgraf (eds.). Historical and Paleoclimatic Aspects of the Southern Oscillation. Cambridge University Press, 29-68.

Cayan, D.R., Redmond, K.T., and Riddle, L.G., 1999. ENSO and Hydrologic Extremes in the Western United States. American. Meteorological. Society. 12: 2881-2893.

Court, A. 1962. Measures of Streamflow Time. Journal of Geophysical. Research. 67(11): 4335-4339.

Dettinger, M.D. and Diaz, H.F., 2000. Global Characteristics of Stream Flow Seasonality and Variability. Journal of Hydrometeorology. 1: 289-310.

Enfeld, G. Mestas-Nunez, A., and Trimble P. 2001. The Atlantic Multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. Geophysical Research Letters. 28: 2077-2080.

Gershunov, A. and Cayan, D.R., 2003. Heavy Daily Precipitation Frequency over the Contiguous United States: Sources of Climatic Variability and Seasonal Predictability. Journal of Climate. 16: 2752–2765.

Gurnell, A.M., Clark, M.J., and Hill, C.T. 1992. Analysis and interpretation of patterns within and between hydroclimatological time series in an alpine glacier basin. Earth Surface Processes and Landforms 17: 821-839.

Gutzler, D.S. and Rosen, R.D., 1992. Interannual Variability of Wintertime Snow Cover across the Northern Hemisphere. Journal of Climate. 5: 1441-1447.

Gutzler, D.S., Kann, D.M., and Thornbrugh, C., 2002. Modulation of ENSO-Based Long-Lead Outlooks of Southwestern U.S. Winter Precipitation by the Pacific Decadal Oscillation. Weather and Forecasting 17: 1164-1172.

Hannah, D.M., Gurnell, A.M., and McGregor, G.R., 1999. A Methodology for Investigation of the Seasonal Evolution in Proglacial Hydrograph Form. Hydrological Processes. 13: 2603-2621.

Hidalgo, H.G. and Dracup, J.A., 2003. ENSO and PDO Effects on Hydroclimatic Variation of the Upper Colorado River Basin. Journal of Hydrometeorology. 4: 5-23.

Hodgkins, G.A., Dudley, R.W., and Huntington, T.G., 2003. Changes in the Timing of High River Flows in New England over the $20^{th}$ Century. Journal of Hydrology, 278, 244-252.

Kayha, E., and Dracup, J.A., 1993. U.S. Streamflow Patterns in Relation to the El Nino/Southern Oscillation. Water Resources Research. 29: 2491-2503.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983. Precipitation – Runoff Modeling System – Users Manual. U.S. Geological Survey, Water Resources Investigations Report 83-4283, 207 pp.

Lundquist, J.D., and Cayan, D.R. 2002. Seasonal and Spatial Patterns in Diurnal Cycles in Streamflow in the Western United States. American Meteorological Society. 3: 591-603.

Lundquist, J. and Dettinger, M. 2003. Linking diurnal cycles of river flow to interannual variations in climate. $83^{rd}$ Meeting of the American Meteorological Society. $17^{th}$ Conference. on Hydrology. Long Beach, California.

McCabe, G.J. and M.D. Dettinger, 1999. Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States. International Journal Climate. 19: 1399-1410.

McCabe, G.J. Palecki, M.A., and Betancourt J.L. 2004. Pacific and Atlantic Ocean influences on Multidecadal drought frequency in the United States. Proceedings of the National Academy of Sciences. 101: 4136-4141.

National Research Council, 1999. Making Climate Forecasts Matter, P.C. Stern and W.E. Easterling, Eds., NAP, p. 9.

Neelin, J.D., Jin, F., and Syu, H., 2000. Variations in ENSO Phase Locking. Journal of Climate. 13:2570-2590.

Redmond, K.T. and Koch, R.W., 1991. Surface climate and streamflow variability in the western United States and their relationship to large scale circulation indices. Water Resources Research. 27: 2381-2399.

Ropelewski, C.F., and Halpert, M.S., 1986. North American Precipitation and Temperature Patterns Associated with El Niño-Southern Oscillation (ENSO). Monthly Weather Review. 27: 2352-2362.

Slack, J.R., Landwehr, J.M., 1992. Hydro-climatic Data Network (HCDN): A USGS streamflow data set for the United States for the study of climate variations, 1874-1988. U.S. Geological Survey Open-File Report 92-129, 193 pp.

Staudenmaier, M. 2003. National Oceanic and Atmospheric Administration (NOAA). "What is the Pacific Decadal Oscillation?" Http://www.wrh.noaa.gov/Flagstaff/science/pdo.php.

Trenberth, K.E., and Guillemot, C.J., 1996. Physical Processes Involved in the 1988 Drought and 1993 Floods in North America. Journal of Climate 9: 1288-1298.

Webb, R.H., McCabe, G.J., Hereford, R., and Wilkowske, C., 2004. Climatic fluctuations, drought, and flow on the Colorado River: U.S. Geological Survey Fact Sheet 3062-04.

Williams, K.S., and Tarboton, D.G., 1999. The ABC's of snowmelt: a topographically factorized energy component snowmelt model. Hydrological Processes 13: 1905-1920.

Woodhouse, C.A., 2003. A 431-Yr Reconstruction of Western Colorado Snowpack from Tree Rings. Journal of Climate. 16:1551-1561.