DISSERTATION

CHARACTERIZING HYDROCLIMATIC VARIABILITY IN TRIBUTARIES OF THE UPPER COLORADO RIVER BASIN – WY 1911-2001

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY MARGARET ANN MATTER ENTITLED CHARACTERIZATION OF HYDROCLIMATIC VARIABILITY IN TRIBUTARIES OF THE UPPER COLORADO RIVER BASIN – WY 1911-2001 BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

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Mountain snowpack is the main source of water in the semi-arid Colorado River Basin (CRB), and while the demands for water are increasing, competing and often conflicting, the supply is limited and has become increasingly variable over the 20th Century. Greater variability is believed to contribute to lower accuracy in water supply forecasts, plus greater variability violates the assumption of stationarity, a fundamental assumption of many methods used by water resources engineers in planning, design and management. Thus, it is essential to understand the underpinnings of hydroclimatic variability in order to effectively meet future water supply challenges.

A new methodology was applied to characterize time series of temperature, precipitation, and streamflow (i.e., historic and reconstructed undepleted flows) according to the three climate regimes that occurred in CRB during the 20th Century. Results for two tributaries in the Upper CRB show that hydroclimatic variability is more deterministic than previously thought because it entails complementary temperature and precipitation patterns associated with wetter or drier conditions on climate regime and annual scales.

Complementary temperature (T) and precipitation (P) patterns characterize climate regime type (e.g., cool/wet and warm/dry), and temperatures increase or decrease

and precipitation changes magnitude and timing according to the type of climate regime. Accompanying each climate regime type, are complementary T and P patterns on annual scales that are associated with upcoming precipitation and annual basin yield. Annual complementary T and P patterns: (a) establish by fall; (b) are detectable as early as September; (c) persist to early spring; (d) are related to the relative magnitude of upcoming precipitation and annual basin yield; (e) are unique to climate regime type; and (f) are specific to each river basin. Thus, while most of the water supply in the Upper CRB originates from winter snowpack, statistically significant indictors of relative magnitude of upcoming precipitation and snowmelt runoff are evident in the fall, well before appreciable snow accumulation.

Since natural and anthropogenic external forcings, including solar variability, anthropogenic climate change, and modifications to land use, land cover and water use, influence the climate modes that shape climate regimes, the external forcings also influence the complementary temperature and precipitation patterns accompanying each climate regime. Consequently, although complementary temperature and precipitation patterns are similar for climate regimes of the same type (e.g., cool/wet climate regimes), they also differ and the differences may be associated with anticipated or observed effects of external forcings.

In summary, this research shows that hydroclimatic variability during the 20th Century is more deterministic than previously thought, and includes: (a) a series of alternating patterns in temperature and precipitation corresponding with changes in climate regimes; and (b) effects of anthropogenic external forcings on the complementary temperature and precipitation patterns accompanying the climate regimes. Results of this research suggest alternative strategies to incorporate into existing water supply forecasting methods to improve forecast accuracy and increase lead time up to six months, from April 1 to October 1 of the previous year. Based on the relationships revealed by this research, the physical mechanisms behind the relationships may be determined and used to improve models for water supply forecasting and water management; develop long-range forecasts; and downscale climate models. In addition, the research results may also be used : (a) to improve application of or develop alternatives to engineering and hydrologic methods based on the assumption of stationarity; (b) in developing science-based adaptive management strategies for natural and cultural resource managers; and (c) in developing restoration, conservation and management plants for fish, wildlife, forest, and other natural resources.

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DEDICATION

To my mother, for her friendship and love; encouragement, support, enthusiasm and inspiration; and to my father for his support and inspiration.

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CHAPTER 1: INTRODUCTION

1.1 Background and Rationale

Water supply forecast accuracy for the Colorado River Basin decreased over the 20th Century due to increasing hydrologic and climatic variability in the system (Pagano et al., 2004, and Jain et al., 2005). Winter mountain snowpack is the primary source of water supply of the Colorado River Basin (CRB), and the limited and highly variable water supply must be allocated among diverse, increasing and often conflicting demands. Greater hydrologic variability also violates the assumption of stationarity, thereby invalidating many standard tools used in water resources planning, design and management (McCabe et al., 2007; Garfin et al., 2008; and Milly et al., 2008). Therefore, identifying natural and anthropogenic sources of hydroclimatic variability in the CRB is central to accurately anticipating and adapting to the impacts on water supplies due to climate change (Chen and Grasby, 2009) and other anthropogenic activities. Most endeavors to improve forecast accuracy have involved advances in computing and new datasets, and while forecast accuracy has increased in some regions, such as the Northwest, accuracy has decreased in other regions over the 20th Century (Pagano et al., 2004). Fresh approaches and methods that will garner new insights are required to improve water supply forecast accuracy and increase lead time, as well as develop new tools for water resource planning, design and management.

Increases in hydroclimatic variability are attributed primarily to anthropogenic climate change (e.g., Pagano and Garen, 2005; Garfin et al., 2008; Milly et al., 2008), but variability also arises from other sources, such as climate regimes and other forms of internal climate variability; air pollution (e.g., sulfate aerosols), modifications to land use, land cover and water use, and annual variability (Milly et al., 2008), as well as solar cycles (Kerr, 2009). In addition, sources of variability interact with one another, confounding detection and interpretation of variations in temperature and precipitation, as well as accurate representation of hydroclimatic processes in models of the CRB. Natural external forcings, such as solar cycles, and anthropogenic external forcings, including climate change and modifications to land use, land cover and water use, influence climate cycles (Wang and Schimel, 2003), or climate regimes. Effects of increasing greenhouse gas emissions since the advent of the Industrial Revolution are particularly evident later in the 20th Century (Stott et al., 2000; Balling and Goodrich, 2007; and Rosenzweig et al., 2008). Throughout the 20th Century, the CRB went through extensive changes in land use, land cover and water use, and during the same period, three climate regimes also occurred in the CRB (Hereford et al., 2002; Hidalgo and Dracup, 2003; McCabe et al., 2004; and Balling and Goodrich 2007). Given that the three climate regimes during the 20th Century are influenced by climate change and modifications to land use, land cover and water use, it is reasonable to use climate regimes as a basis upon which to characterize hydroclimatic variability. In this way, changes in the hydroclimatic variables may be compared between climate regimes, as well as over the century.

Climate regimes and annual variations in the CRB are shaped by the combined effects of internal climate variability, including climate modes; natural external forcings (e.g., solar variations); and anthropogenic external forcings (e.g., anthropogenic climate change; modifications to land use, land cover and water use; and air pollution, including sulfate aerosols and soot). Climate modes influencing hydroclimate in the CRB include the Pacific Decadal Oscillation (PDO), Atlantic Mulidecadal Oscillation (AMO) and Pacific North American (PNA) (e.g., Hereford et al., 2002; Wang and Schimel, 2003; Woodhouse, 2003; Hidalgo, 2004; McCabe et al., 2004; and Quiring and Goodrich, 2008). On annual scales, El Niño-Southern Oscillation (ENSO) affects hydroclimate in the CRB between fall and spring (e.g., Gershunov and Cayan, 2003; Hidalgo and Dracup, 2003; Balling and Goodrich, 2007; and Kim et al., 2007). Yet expression of ENSO is modulated by factors including PDO and AMO, which evolve over longer time periods (McCabe and Dettinger, 1999; Gutzler et al., 2002; and Gershunov and Cayan, 2003) and are influential drivers of hydroclimate in the CRB with or without contemporaneous ENSO extremes (Gershunov and Cayan, 2003). Because PDO and AMO evolve over long time periods, for example 20-30 years (Mantua et al., 1997) and 50-80 years (e.g., Kerr, 2000; Enfield et al., 2001; McCabe et al., 2004; and Quiring and Goodrich, 2008), respectively, they are unlikely to change substantially between fall and early spring. In contrast, ENSO evolves over shorter time periods (i.e., 2-7 years) and is also phase-locked with the seasons. ENSO conditions begin to set up in July; are established by about October and persist into early spring (Neelin, 2000).

It is then reasonable to assume that combined effects of major climate modes influencing hydroclimate in the CRB are essentially unchanged between fall and early spring, meaning that temperature and precipitation patterns influencing snowpack development and snowmelt establish by fall and are detectable by October or earlier. This assumption is consistent with Hidalgo and Dracup (2003) and Archer and Fowler (2008) who found that April-September streamflow for the upper CRB and the River Jhelum in Pakistan, respectively, is more correlated with total precipitation for October-January than with any other time period (e.g., October-March, December-March, January-March, or October-September). The upper CRB and the River Jhelum are both snowmelt-dominated river systems and are influenced by ENSO at least during the winter months (e.g., Gershunov and Cayan, 2003; Hidalgo and Dracup, 2003; Balling and Goodrich, 2007; Kim et al., 2007; Archer and Fowler 2008). Thus, similar to climate regimes which are characterized by prevailing temperature and precipitation patterns (e.g., cool/wet and warm/dry climate regimes), combined effects of major climate modes influencing annual hydroclimate in the CRB also entail complementary temperature and precipitation patterns that establish by fall, persist to early spring, and are associated with total upcoming precipitation and annual basin yield (ABY).

Since combined effects of internal climate variability and external forcing shape and influence climate regimes, the complementary temperature and precipitation patterns accompanying wetter or drier hydroclimatic conditions on climate regime and annual scales are also shaped and influenced by internal climate variability and external forcings. Internal climate variability occurs on all time scales from instantaneous to thousands of years, involving atmospheric and oceanic processes, and coupled interactions between the ocean and atmosphere include climate modes such as ENSO, PDO and AMO (Hegerl, et al., 2007). Combined effects of climate modes influencing hydroclimate and water resources in the CRB (e.g., PDO and AMO) shape cool/wet or warm/dry climate regimes lasting approximately 30 years. In turn, ENSO conditions combine with AMO and PDO to influence hydroclimate in the CRB on annual scales (e.g., Gershunov and Cayan, 2003; Hidalgo and Dracup, 2003; Balling and Goodrich, 2007; and Kim et al., 2007).

Variations in the 11-year solar cycle, a natural external forcing, affect ENSO conditions. The solar maxima gives rise to La Niña-like and lagged El Niño-like conditions in the Pacific region, which may amplify or dampen true La Niña and El Niño conditions (Meehl, et al., 2009). Effects of anthropogenic external forcings may vary temporally and spatially, depending on characteristics of the forcing and site specific conditions, such as location and climate. For example, urban and agricultural irrigation may depress maximum daily temperatures locally or regionally, and the effects may be seasonal or longer (e.g., Pielke and Avissar, 1990; Stohlgren et al., 1998; Chase et al., 1999; Bounoua et al., 2000; Bounoua et al., 2002; Marland et al., 2003; Feddema et al., 2005; and IPCC, 2007). Hence, natural and anthropogenic external forcings influence and change details of characteristic complementary temperature and precipitation patterns associated with climate regimes so that complementary temperature and precipitation patterns for climate regimes of the same type (e.g., cool/wet climate regime) may be similar but not alike.

Detecting climate signals in temperature, precipitation and streamflow records depends on factors including: (a) length and starting point of data records, (b) elevation of data gauges, and (c) level of impairment of the river basin above the gauge. As a guideline for minimizing misleading results, the length of hydrometeorological time series should be at least as long as the most prominent climate mode influencing hydroclimate in the area of interest, and the starting point of analysis in the time series relative to the phase of cyclic hydroclimatic component affects interpretation of results (Chen and Grasby, 2009). The most prominent climate mode is the AMO, and the collective effects of the phase of AMO and other climate modes give rise to climate regimes. The three climate regimes of the 20^{th} Century in the CRB are: (1) a cool/wet climate regime, from about 1905 to 1941; (2) a warm/dry climate regime, from about 1942 to 1977; and (3) a second cool/wet climate regime, from approximately 1978 to 1998 (e.g., Hereford et al., 2002; Hidalgo and Dracup, 2003; McCabe et al., 2004; and Balling and Goodrich, 2007). Thus selecting time series for analysis that encompass most or all of the 20^{th} Century would include the three main climate regimes of the Century and approximately two AMO cycles.

Previous studies have demonstrated that site elevation is an important factor in detecting climate signals. June-November ENSO conditions only correlate highly with October-March precipitation from high elevation sites in the upper CRB (Hidalgo and Dracup, 2003), and some models, such as snowmelt runoff models, may be improved significantly by including precipitation and temperature data from high elevation sites (Colle, et al., 2000; Reed et. al., 2001; and Dracup, 2005). Other corroborating evidence includes tree ring data from higher elevation areas in China that exhibit less variability than trees at lower elevations (Wang et. al., 2005). A large amount of the variability is associated with the planetary boundary layer (PBL), the lower troposphere ranging between the earth's surface and approximately 300 to 10,000 feet in elevation. Within the PBL, air masses and transport processes are influenced by surface features (e.g., trees, mountains, buildings and water bodies) and by surface processes (e.g., evaporation, transpiration, diurnal temperature variations; Stull, 1988), as well as by effects of land surface modifications (Chase et al., 1999) and water use changes, which confound detection of climate signals. Above the PBL is the free atmosphere where air masses and transport processes are less affected by surface features, processes and modifications.

Thus confounding effects of the PBL on climate signals are minimized by selecting gauges located at higher elevations.

Amount and spatial extent of modifications to land use, land cover and water use are greater at lower elevations than at higher elevation sites. The USGS Hydro-Climatic Data Network (HCDN) lists streamflow gauges with data records that are sufficiently unaffected by anthropogenic activities, and thus suitable for climate studies (Slack and Landwehr, 1992). Since land and water development tend to decrease with elevation, most of the HCDN gauges in the CRB are above 1,829 meters (6,000 feet), and the related drainage basins are relatively small [i.e., between 518 and 3,108 square kilometers (200 and 1,200 square miles)]. Basins at higher elevations tend to be more sensitive to change than basins at lower elevations for reasons including thinner soils, cooler temperatures, steeper terrain, higher UV radiation, and shorter growing seasons (Diffenbaugh, 2005; Brandt and Townsend, 2006). Type of modification in a basin at higher elevations is at least as important as spatial extent of the modification (Dow, 2007), and the magnitude of effects of modifications correlates positively with elevation and correlates inversely with basin size (Monaghan et al., 2000; and Brandt and Townsend, 2006). However, modifications to land use, land cover, and water use (e.g., irrigated agriculture) that occur at lower elevations also affect climate regionally, including adjacent mountain areas (e.g., Pielke and Avissar, 1990; Stohlgren et al., 1998; Chase et al., 1999; Bounoua et al., 2000; Bounoua et al., 2002; Marland et al., 2003; Feddema et al., 2005; and IPCC, 2007). Nonetheless, higher elevation gauges may be better suited for detecting climate signals because confounding effects of the PBL may be less than at lower elevations.

The objectives of my research are to examine hydrometeorological time series for three climate regimes during the 20th Century for two gauges in the Upper CRB to: (a) identify patterns in the time series accompanying climate regimes; (b) identify changes in climate regime patterns over the century which may potentially be effects of anthropogenic external forcings; (c) identify complementary patterns in temperature and precipitation between September and March that are associated with upcoming precipitation and ABY; and (d) develop multiple linear regression models, based on the complementary T and P patterns, to predict ABY for each of the three climate regimes of the 20th Century.

1.2 References

Archer, D.R, Fowler, H.J., 2008. Using meteorological data to forecast seasonal runoff on the River Jhelum, Pakistan. Journal of Hydrology 361, 10-23.

Balling, R.C., Jr., Goodrich, G.B., 2007. Analysis of drought determinants for the Colorado River Basin. Climate Change 82, 179-194.

Bounoua, L., Collatz, G.J., Los, S.O., Sellers, P.J., Dazlich, D.A., Tucker, C.J., Randall, D.A., 2000. Sensitivity of Climate to Changes in NDVI. Journal of Climate 12, 2277-2292.

Bounoua, L., Defries, R., Collatz, G.J., Sellers, P., Khan, H., 2002. Effects of Land Cover Conversion on Surface Climate. Climate Change 52, 29-64.

Brandt, J.S., Townsend, P.A., 2006. Land use–land cover conversion, regeneration and degradation in the high elevation Bolivian Andes. Landscape Ecology 21, 607–623.

Chase, T.N., Pielke, R.A., Sr., Kittel, T.G.G., Baron, J.S., Stohlgren, T.J., 1999. Potential impacts on Colorado Rocky Mountain weather due to land use change on the adjacent Great Plains. Journal of Geophysical Research 104, 16673-16690.

Chen, Z., Grasby, S.E., 2009. Impact of decadal and century-scale oscillations on hydroclimatic trend analyses. Journal of Hydrology 365, 122-133.

Colle, B.A., Mass, C.F., Westrick, K.J., 2000. MM5 Precipitation Verification over the Pacific Northwest during the 1997-99 Cool Seasons. Weather and Forecasting 15, 730-744.

Diffenbaugh, N.S., 2005. Atmosphere-land cover feedbacks alter the response of surface temperature to CO_2 forcing in the western United States. Climate Dynamics 24, 237-251.

Dow, C.L., 2007. Assessing regional land-use/cover influences on New Jersey Pinelands streamflow through hydrograph analysis. Hydrological Processes 21, 185-197.

Dracup, J., 2005. Climate Change and Water Supply Reliability. Public Interest Energy Research Program (PIER), Publication Number CEC-500-2005-053. California Energy Commission. California Climate Change Center Series # 2005-014. Page 3. Online at: Online at: http://www.energy.ca.gov/pier/project_reports/CEC-500-2005-053.html.

Enfield, D.B., Mestas-Nuñez, A.M., Trimble, P.J., 2001. The Atlantic multidecadal oscillation and its relations to rainfall and river flows in the continental U.S. Geophysical Research Letters 28(10), 2077-2080.

Feddema, J.J., Oleson, K.W., Bonan, G.B., Mearns, L.O., Buja, L.E., Meehl, G.A., Washington, W.M., 2005. The Importance of Land-Cover Change in Simulating Future Climates. Science 310, 1674-1678.

Garfin, G., Jacobs, K., Buizer, J., 2008. Beyond Brainstorming: Exploring Climate Change Adaptation Strategies. EOS, Transactions of the American Geophysical Union 89(25), 227.

Gershunov, A., 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.

Gutzler, D.S., Kann, D.M., 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.

Hegerl, G.C., Zwiers, F.W., Braconnot, P., Gillett, N.P., Luo, Y., Marengo Orsini, J.A., Nicholls, N., Penner, J.E., Stott, P.A., 2007. Understanding and attributing climate change. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds), Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, p. 667.

Helsel, D.R., Hirsch, R.M. 2002. Statistical Methods in Water Resources, US Geological Survey Techniques of Water Resources Investigations, book 4. Online at: http://water.usgs.gov/pubs/twri/twri4a3/. Feb 2009.

Hereford, R., Webb, R.H., Graham, S., 2002. Precipitation History of the Colorado Plateau Region, 1900-2000. U.S. Geological Survey Fact Sheet 119-02, 1-4.

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

Hidalgo, H.G., 2004. Climate precursors of multidecadal drought variability in the western United States. Water Resources Research 40, W12504, doi: 10.1029/2004WR003350.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jain, S., Hoerling, M., Eischeid, J., 2005. Decreasing Reliability and Increasing Synchroneity of Western North American Streamflow. Journal of Climate 18, 613-618.

Kerr, R.A., 2000. A North Atlantic climate pacemaker for the centuries. Science 288, 1984-1986.

Kerr, R.A., 2009. Joining forces to pump up a variable sun's climate effects. Science 325, 1058-1059.

Kim, T-W, Chulsang, Y., Ahn, A-H, 2007. Influence of climate variation on seasonal precipitation in the Colorado River Basin. Stochastic Environmental Research and Risk Assessment 22, 411-420.

McCabe, G.J., Dettinger, M.D., 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., 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.

McCabe, G.J., Betancourt, J.L., Hidalgo, H., 2007. Associations of decadal and multidecadal sea-surface temperature variability with Upper Colorado River flow. Journal of the American Water Resources Association 43, 183-192.

Mantaua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78, 1069-1079.

Marland, G., R.A. Pielke Sr., M. Apps, R. Avissar, R.A. Betts, K.J. Davis, P.C. Frumhoff, S.T. Jackson, L. Joyce, P. Kauppi, J. Katzenberger, K.G. MacDicken, R. Neilson, J.O. Niles, D.D.S.

Meehl, G.A., Arblaster, J.M., 2009. A lagged warm event-like response to peaks in solar forcing in the Pacific Region. Journal of Climate 22, 3647-3660.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R., Kundzewicz, Z., Lettenmaier, D., Stouffer, R., 2008. Climate Change: Stationarity is Dead: Whither Water Management. Science. 319(5863), 573-574.

Monaghan, K.A., Peck, M.R., Brewin, P.A., Masiero, M., Zarate, E., Turcotte, P., Ormerod, S.J., 2000. Macroinvertebrate distribution in Ecuadorian hill streams: The effects of altitude and land use. Archiv für Hydrobiologie 149, 421-440.

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

Pagano, T.P., Garen, D., Sorooshian, S., 2004. Evaluation of Official Western U.S. Seasonal Water Supply Outlooks, 1922-2002. Journal of Hydrometeorology 5, 896-909.

Pagano T., Garen, D., 2005. A Recent Increase in Western U.S. Streamflow Variability and Persistence. Journal of Hydrometeorology 6, 173-179.

Pielke, R.A., Avissar, R., 1990. Influence of landscape structure on local and regional climate. Landscape Ecology 4, 133-155.

Quiring, S.M., Goodrich, G.G., 2008. Nature and causes of the 2002 to 2004 drought in the southwestern United States compared with the historic 1953 to 1957 drought. Climate Research 36, 41-52.

Reed, S., King, S., Koren, V., Smith, M., Zhang, Z., Wang, D., 2001. Parameterization Assistance for NWS Hydrology Models Using ArcView, Proceedings of the 21 Annual ESRI International User Conference, San Diego, CA, July 9-13, 2001.

Rosenzweig, C., Karoly, D. Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T.L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S., Imeson, A., 2008. Attributing physical and biological impacts to anthropogenic climate change. Nature 453, 353-358.

Slack, J.R., Landwehr, J.M., 1992. Hydro-Climatic Data Network: A U.S. Geological Survey streamflow data set for the United States for the study of climatic variations. U.S. Geological Survey Report 92-129, 193 pp.

Stohlgren, T.J., Chase, T.N., Pielke, R.A., Sr, Kittel, T.G.F., Baron, J.S., 2003. Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas. Global Change Biology 4, 495-504.

Stott, P.A., Tett, S.F.B., Jones, G.S., Allen, M.R., Mitchell, J.F.B., Jenkins, G.J., 2000. External Control of 20th Century Temperature by Natural and Anthropogenic Forcings. Science 290, 2133-2136.

Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers. Dordrecht, The Netherlands. Pps. 1-2.

Wang, G., Schimel, D., 2003. Climate Change, Climate Modes, and Climate Impacts. Annual Review of Environmental Resources, 28: 1-28.

Wang, T., Ren, H., Ma, K., 2005. Climatic signals in tree ring of *Picea schrenkiana* along an altitudinal gradient in the central Tianshan Mountains, northwestern China. Trees 19, 735-741.

CHAPTER 2: METHODS

2.1 Site Description

Tributaries and associated weather and streamflow gauges in the Upper CRB were selected according to the following considerations:

a) Sites have concurrent temperature, precipitation and flow data;
b) Data records encompass all or the majority of each climate regime of the 20th Century;
c) Data are at daily time increments;
d) Large-scale climate modes influencing climate at each site;
e) Gauge elevation [i.e., over 1,524 m (5,000 ft)];
f) Availability of reconstructed undepleted (natural) flow records for the flow gauges.

Weather and flow data for two sites in the Upper CRB, the Gunnison River near Gunnison, CO and the Yampa River at Steamboat Springs, CO, are used for analysis; locations of the sites are indicated in Figure 2.1.

The Gunnison River flows approximately east to west through the central Upper CRB and joins the Colorado River near Grand Junction, CO. The weather and stream gauges are located on the east side of the basin near the city of Gunnison, below the junction of the East and Taylor rivers, the two main tributaries forming the Gunnison River. North of the headwaters of the Gunnison River, is the Yampa River which flows west-southwest through Colorado and joins the Green River, a major tributary to the Colorado River, in Utah. Table 1 summarizes gauge and river basin information for the

Gunnison and Yampa rivers. Both gauges are at elevations over 1,829 m (6,000 feet), and both drainage basins are relatively small, although the basin above the Yampa River gauge is about half the area of the basin above the Gunnison River gauge (see Table 1).

Since the streamflow records for the gauges, Gunnison River near Gunnison, CO (GRG) and Yampa River at Steamboat Springs, CO (YRS) are both part of the USGS HCDN, they are considered relatively unaltered by anthropogenic activities, and thus suitable for climate studies (Slack and Landwehr, 1992). However, the drainage basins above the GRG and YRS sites experienced land and water resource development over the 20th Century. Histories of the Gunnison and Yampa river basins include mining, timber harvesting, livestock grazing and agriculture during the first half of the 20th Century, and during the second half, the economies of both river basins depended largely on industries such as agriculture, grazing, coal mining, tourism, and recreation, including alpine skiing. In addition, because of local deposits of high-grade coal in the Yampa River Basin, large coal-fired power plants were built in the upper basin during the latter part of the century to generate electric power. River diversions, including transbasin diversions, for purposes including agriculture occur throughout the 20th Century, and later in the Century, diversions are also used for snowmaking at ski areas. In 1936, Taylor Park dam and reservoir was completed upstream of the GRG gauge on the Taylor River, one of the main tributaries forming the Gunnison River. Taylor Park dam was built during the part of the GRG period of record that is discontinuous, and transbasin diversions from the Gunnison River Basin above the GRG gauge to the Colorado Front Range began in 1914. Thus the WY 1911-1928 streamflow record does not include upstream reservoir operations but does include transbasin diversions. Taylor Park Reservoir has no carryover storage, so inflow is released primarily during the growing season for crops. In contrast, about six dams were built on the Yampa River upstream of the YRS gauge during the 20th Century, however most of the dams are small and the water uses include agricultural irrigation, recreation, and municipal water supply.

2.2 Data and Methods

Streamflow data were obtained online from the USGS National Water Information System at http://waterdata.usgs.gov/usa/nwis/sw, and meteorological data were obtained online at http://www.ncdc.noaa.gov/oa/climate/stationlocator.html from the National Climate Data Center. Streamflow records for the Gunnison River near Gunnison and the Yampa River at Steamboat Springs are HCDN gauges. The periods of record for meteorological and streamflow data for the sites in the upper Gunnison and Yampa river basins begin in the early 1900's and continue through the present. The period of record for the YRS gauge is continuous, but the streamflow period of record for the GRG gauge is discontinuous between October 1928 and September 1944. Despite the discontinuity, the period of record for the Gunnison River site is used because the early part of the flow record includes much of the cool/wet climate regime at the beginning of the 20th Century and the warm/dry climate regime during the mid-century, and the remainder of the record is of good quality. Plus the Gunnison River is uniquely situated relative to the boundaries of climate modes that influence hydroclimate in the Upper CRB. Woodhouse (2003) describes hydroclimatic conditions in the Gunnison River basin as among the most variable in the CRB, due in part to the basin location, which is near the border of the bipolar effects of ENSO and near the boundary of the PNA. In that regard, the Gunnison River basin may represent a "worst case scenario" for detecting climate signals. In contrast to the Gunnison River basin, the Yampa River basin is influenced more by La Niña conditions (Woodhouse, 2003).

Three climate regimes occur during the 20th Century in the CRB, and the research period of record, water year WY 1911 to 2005, is divided into three sub-periods of record, each coinciding approximately with a climate regime. In addition, the sub-period of record defining each climate regime also corresponds to different levels of development of land and water resources, or alteration, in the basins. Accordingly, each of the three sub-periods of record is named for the prevailing climate regime and relative level of basin alteration. The Unaltered Basin (UB)-Cool/Wet climate regime is the sub-period of record that encompasses the cool/wet climate regime during the first third of the century, and involves a period of relatively limited development in the Gunnison and Yampa river basins (i.e., relatively unaltered). Next, during the middle of the century is the Altered Basin (AB)-Warm/Dry climate regime, this sub-period of record mainly entails the warm/dry climate regime, and is also a period of water and land resource development, or basin alteration. During the last third of century is the Altered Basin (AB)-Cool/Wet climate regime, the sub-period of record which encompasses the second cool/wet climate regime and includes further alteration of basin of water and land resources. Table 1 summarizes information about the climate regime periods of record for the GRG and YRS sites.

During several years near the end of the WY 1911-2005 period of record, the climate regime changed from the AB-Cool/Wet to another warm/dry regime (i.e., AB-Warm/Dry-21). The reasons for incorporating the period of transition are: (a) the assumption that the transition period between climate regimes, which began in about 1998, would not substantially impact the analysis results; (b) the sub-periods of record would be about the same length, and (c) to include more recent years of record.

In addition to historic gauge streamflow data, the research evaluated whether climate signals are also evident in reconstructed undepleted, or "natural" or naturalized, flows. Reconstructed undepleted streamflow data are historic gauge flow records adjusted for anthropogenic activities, such as irrigation diversions, transbasin imports, exports of water, reservoir operations, and estimated return flows. Reconstructed undepleted flows are used in water supply forecasting and other water resource management activities. Several entities develop reconstructed undepleted flow datasets, but the same gauges are not used by each of the entities and most of the data are developed at average monthly time increments. Daily data are required for this research and available from the Colorado Water Conservation Board (CWCB) for the GRG and the YRS sites. Although the CWCB does not develop water supply forecasts, they use reconstructed undepleted flow data for other water supply-related purposes. The undepleted flow records for the GRG and YRS sites correspond to gauge data for 1975-present, which is the calibration period of record for CWCB models. CWCB reconstructed undepleted flow datasets were developed by adjusting historic mean monthly streamflow data for diversions, return flows, transbasin imports and exports of water, and reservoir storage. Monthly undepleted flows are disaggregated to daily values using the pattern gauges, Yampa River at Steamboat Springs, CO for the YRS site, and the East River at Almont, CO for the GRG site (CWCB, 2004a and 2004b). Undepleted flow data for the YRS and for the GRG sites are available for WY 1975-2005, which coincides with the AB-Cool/Wet climate regime.

Temperature, precipitation and flow variables include mean and median monthly values (e.g., mean and median September maximum daily temperature), seasonal variables (e.g., Jan-Mar total cooling degree-days or Sep-Dec total precipitation), and annual variables for flow volume, or ABY. Heating and cooling degree-days are based on 0° C (32° F). One-third and one-half dates for quantities, including total annual and seasonal flow volumes, total precipitation, total seasonal heating degree-days and total cooling degree-days, are the dates by which one-third or one-half of the quantities occur. For example, the Jan-Mar one-third precipitation date is the date by which one third of the total Jan-Mar precipitation arrives. Table 2 summarizes temperature, precipitation and flow variables used in the analysis.

Unique attributes of the methodology include: (a) analyses are conducted from September through March, rather than the main snowpack accumulation months (i.e., December to March, DJFM), or the main snowmelt runoff period (April to September); (b) rather than using one long period of record (e.g., WY 1911-2005) for analysis, the research period of record is divided into three sub-periods of record, each corresponding approximately to one of the main climate regimes of the 20th Century; (c) results for each climate regime may be compared to identify potential effects of external forcings on the climate regimes; (d) the sites are at higher elevations, minimizing confounding effects, such as from the PBL and development at lower elevations in the basin; (e) methods are applied to reconstructed undepleted and actual gauge streamflow records; and (f) analyses are conducted at individual sites to determine whether the climate signal at a point is representative of the associated basin.

Nonparametric methods are included because the sub-periods of record are relatively short and some of the data are skewed. The methods are applied to temperature, precipitation and historic and undepleted flow between September and March for each year of the three climate regime periods of record. Two seasons are defined for the Sep-Mar time period; Fall-Early Winter is Sep-Dec and Oct-Dec, and Winter-Early Spring is Jan-Mar. The Fall-Early Winter season is defined by two time periods because the current research suggested that climate signals are detectable earlier than October. Quartile analysis includes the mean, in addition to the median, and is applied to temperature, precipitation and streamflow time series for each climate regime period of record to examine differences in patterns of hydroclimatic variables between climate regimes of different types (e.g., cool/wet vs. warm/dry) and between climate regimes of the same type (e.g., UB-Cool/Wet vs. AB-Cool/Wet) to identify differences in climate regime patterns that may be associated with external forcings (e.g., climate change or modifications to land and water use).

Means and medians for each variable are compared using the Kruskal-Wallis Test ($\alpha = 0.05$; Helsel and Hirsch 2002) to test whether the means and medians are the same for the climate regime periods of record and for the reconstructed undepleted flows. Spearman's ρ Rank Correlation ($\alpha = 0.02$; Helsel and Hirsch 2002) is used to examine temperature associations with precipitation, flow and other temperature variables for September to March for each year of each climate regime period of record.

Key components of the Sep-Mar complementary temperature and precipitation patterns were used to develop demonstration multiple linear regression models for Sep-Dec and Sep-Mar to predict ABY for each climate regime of the 20th Century. Since the proposed research methods and the demonstration regression models expand or are an enhancement to existing National Weather Service (NWS) water supply forecasting procedures, which include regression methods, the demonstration models are referred to as the Enhanced Water Supply Prediction, or Enhanced WSP, models. The AB-Cool/Wet climate regime period of record originally included several years of the warm/dry climate regime which began near the turn of the 21st Century (Shoennagel et al., 2007). Because the transition from the AB-Cool/Wet climate regime to the warm/dry climate regime of the 21st Century was estimated to occur over about 3 years, the AB-Cool/Wet climate regime record was truncated to WY 1975-2001 for the Enhanced WSP models.

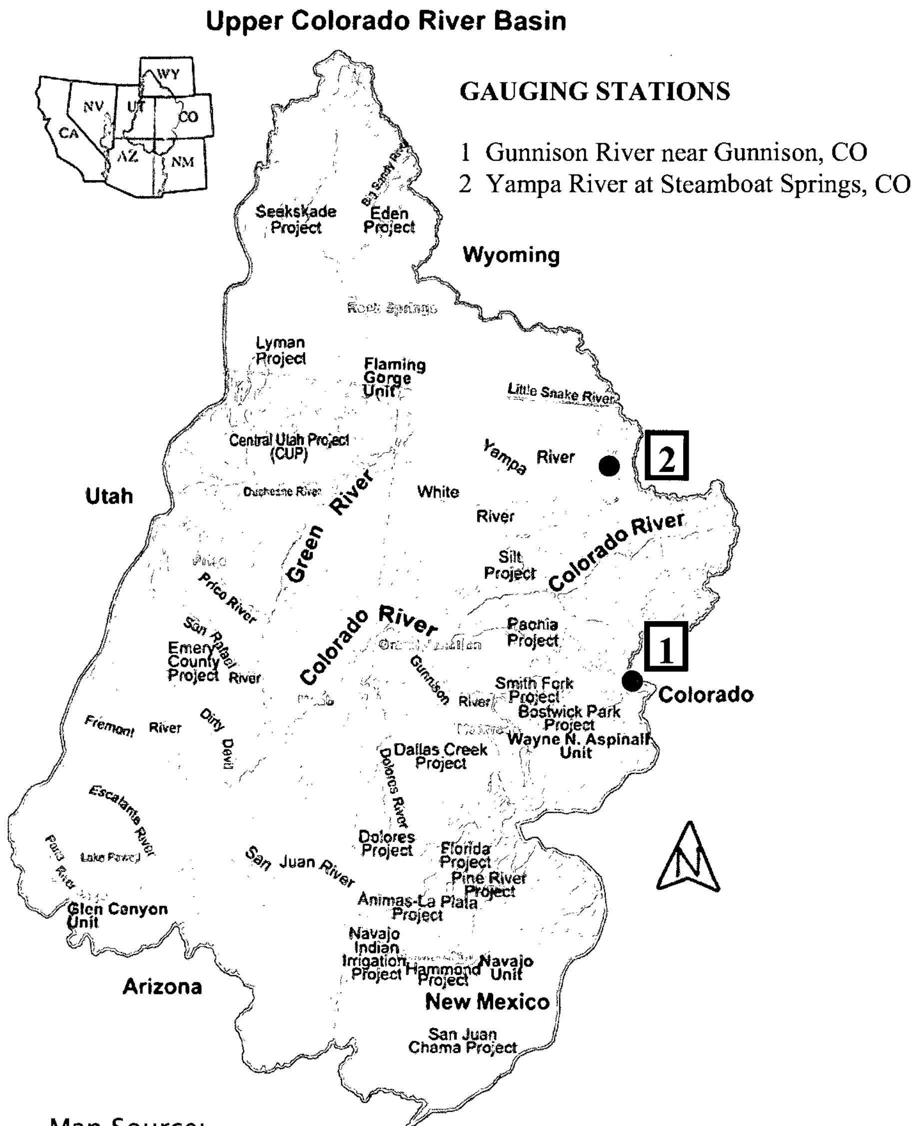
2.3 References

Colorado Water Conservation Board (CWCB), 2004a. Yampa River Basin Water Resources Planning Model User's Manual. Colorado Water Conservation Board, p C-4. Accessed October 10, 2009 from ftp://dwrftp.state.co.us/cdss/swm/in/yampausers_20040601.pdf

Colorado Water Conservation Board (CWCB), 2004b. Gunnison River Basin Water Resources Planning Model User's Manual. Colorado Water Conservation Board, p 8-7. Retrieved October 10, 2009 from ftp://dwrftp.state.co.us/cdss/swm/in/GunnisonUsers_200407.pdf

Helsel, D.R., Hirsch, R.M. 2002. Statistical Methods in Water Resources, US Geological Survey Techniques of Water Resources Investigations, book 4. Online at: http://water.usgs.gov/pubs/twri/twri4a3/. Feb 2009.

Woodhouse, C.A., 2003. A 431-yr reconstruction of Western Colorado snowpack from tree rings. Journal of Climate 16, 1551-1560.



Map Source:
http://www.usbr.gov/uc/rm/crsp/crbMap.html

Figure 2.1 The map of the Upper Colorado River Basin shows approximate locations of the two research gauges, the Gunnison River near Gunnison, CO [1] and Yampa River at Steamboat Springs, CO [2].

Table 2.1 River Basin and Gauge Information and Periods of Record for the YRS and GRG Sites

USGS Gauge Name	USGS Gauge No.	NWS Gauge COOPID	Gauge Elev (ft)	Basin Area (sq mi)	Period of Record (in Water Years)		
					UB[1] Cool/Wet (n yrs)	AB[2] Warm/Dry (n yrs)	AB Cool/Wet (n yrs)
Gunnison River near Gunnison, CO	09114500	53662	7,655	1012	1911-1928 (18)	1945-1974 (30)	1975-2005 (31)
Yampa River at Steamboat Springs, CO	09239500	57936	6,695	568	1911-1942 (32)	1943-1974 (32)	1975-2005 (31)

[1]UB = Unaltered Basin
[2]AB = Altered Basin

Table 2.2 Summary of Acronyms and Abbreviations

Term	*Acronym or Abbreviation*
Altered Basin	AB
Annual Basin Yield	ABY
Atlantic Multidecadal Oscillation	AMO
Colorado River Basin	CRB
Colorado Water Conservation Board	CWCB
Complementary temperature and precipitation patterns	Complementary T and P patterns
December, January, February and March	DJFM
El Niño/Southern Oscillation	ENSO
Gunnison River near Gunnison, CO	GRG
Hydro-Climatic Data Network	HCDN
Maximum daily temperature	Tmax
Minimum daily temperature	Tmin
Mean/Median daily temperature	Tdaily
Pacific Decadal Oscillation	PDO
Pacific North American	PNA
Unaltered Basin	UB
Water Year	WY
Yampa River at Steamboat Springs, CO	YRS

CHAPTER 3: RESULTS

3.1 Comparison of Median Values between Climate Regimes -- Introduction

The results of applying the Kruskal-Wallis Test to compare median values of temperature, precipitation and streamflow between climate regimes are summarized in Tables 3.1-3.3, and the corresponding Kruskal-Wallis critical and K-values are summarized in Tables 3.4-3.9. In general, temperature and precipitation patterns and seasonal flow volumes for the GRG and YRS sites change cyclically in concert with changes in climate regimes, but long-term changes are also evident over the 20th Century. Characteristics of the UB-Cool/Wet and AB-Cool/Wet climate regimes at the YRS and GRG sites include: (a) cooler temperatures overall; (b) lower precipitation in the Fall-Early Winter season; and (c) precipitation shifts earlier in the Fall-Early Winter season, from November/December to September/October. Distinctions between patterns for the two sites include differences in Winter-Early Spring precipitation. Total precipitation for the Winter-Early Spring season during the cool/wet climate regimes tends to be lower at the GRG site but is higher at the YRS site. Alternatively, during the AB-Warm/Dry climate regime, the prevailing temperature and precipitation patterns are generally opposite of those during UB-Cool/Wet and AB-Cool/Wet climate regimes.

Comparing median values in temperature, precipitation and streamflow over the 20th Century, or between the UB-Cool/Wet and the AB-Cool/Wet climate regimes, the changes include: (a) temperatures generally increase in the Fall-Early Winter and Winter-Early Spring seasons at both sites; (b) median annual precipitation decreases at both sites, but the decrease at each site occurs at a different time during the century; (c) median

ABY decreases at both sites between the UB-Cool/Wet and the AB-Warm/Dry climate regimes; and (d) Fall-Early Winter and Winter-Early Spring seasonal flow volumes decrease significantly at the YRS site, but not at the GRG site.

Overall, results of comparing median values show that variations in temperature, precipitation, and streamflow during the 20th Century entail cyclic patterns accompanying changes in climate regimes, as well as long-term changes over the 20th Century. While patterns in temperature, precipitation, and flow accompanying climate regime type exhibit similarities between the YRS and GRG sites, the patterns also differ, perhaps due to the unique physiography of each basin. Long-term changes may be due to anthropogenic external forcings, such as climate change, air pollution (e.g., sulfate aerosols), and modifications to land use, land cover and water use.

3.2 Changes in Median Flow Volumes between Climate Regimes

Median ABY decreased during the first part of the 20th Century at the GRG and YRS sites; between the UB-Cool/Wet and the AB-Warm/Dry climate regimes, which may be expected during a warm/dry climate regime if streamflow volumes changed cyclically with climate regimes (see Table 3.1). But instead of ABY increasing during the AB-Cool/Wet climate regime, lower ABY persisted through the 20th Century. Although the decreases in ABY coincide with the warm/dry climate regime, flows may also have been affected by and persisted due to changes in land use, land cover and water use in the upper Gunnison and Yampa river basins over the 20th Century.

The WY 1/3-Flow Date, or the date by which one-third of the total annual flow passes a gauge, correlates positively with ABY. So the WY 1/3-Flow Date occurs earlier when conditions are drier, and conversely, occurs later when conditions are wetter. When median ABY decreased during the first part of the century, timing of annual flows did not change until later in the century, between the AB-Warm/Dry and AB-Cool/Wet climate regimes. The WY 1/3-Flow Date shifted significantly earlier at the GRG site, but shifted later at the YRS site (see Table 3.1).

Reasons explaining the delay in change of the WY 1/3-Flow Date may be related to the cumulative effects of anthropogenic external forcings (e.g., climate change and modifications to land use, land cover and water use) on the relationship between hydroclimatic conditions and the magnitude and timing of flows. The WY 1/3-Flow Date showed no discernible change between the UB-Cool/Wet and AB-Warm/Dry climate regimes, a period of relatively low development of water and land resources in the upper Yampa and Gunnison river basins. Relationships between magnitude and timing of annual flow volumes may be relatively invariant to changes in climate regimes if the magnitudes and rates of other concurrent changes are also sufficiently low. But cumulative combined effects of modifications to land use, land cover and water use; plus anthropogenic climate change, climate regimes and solar variability over the century, may have altered the correspondence between magnitude and timing of annual flow volumes, shifting the timing either earlier or later, depending on the external forcings and internal climate variability affecting basin hydrology.

Cyclic changes in seasonal flow volumes between climate regimes are clearly evident for the GRG site, but not for the YRS site (see Tables 3.1 and 3.9). At the GRG site, changes in seasonal flow volumes include: (a) Oct-Dec and Jan-Mar median flow volumes change directly with changes in climate regime type; increasing during cool/wet regimes and decreasing during the warm/dry regime; (b) median Sep-Dec flow volume varies opposite to the climate regime type; decreasing during cool/wet regimes and increasing during warm/dry regime; (c) the Oct-Dec 1/3-Flow Date is significantly later at the end of the 20th Century, and (d) seasonal flow volumes at the GRG site exhibit no net significant change over the 20th Century. Although the Fall-Early Winter and Winter-Early Spring seasonal flow volumes exhibit no long-term trends over the century, ABY decreased significantly during the same period, suggesting that decreases in spring and summer flows contributed to lower ABY.

Changes in seasonal flows between climate regimes at the YRS site are often in contrast to those at the GRG site. For example, the Fall-Early Winter (Sep-Dec and Oct-Dec) and Winter-Early Spring (Jan-Mar) seasonal flow volumes decreased over the 20th Century at the YRS site, although the decreases did not occur during the same time period. The Sep-Dec total flow volume decreased during the earlier part of the 20th Century, but the Oct-Dec total flow volumes decreased later in the century. On the other hand, the Jan-Mar total flow volumes decreased fairly steadily over the 20th Century. Decreases in Sep-Dec flow volumes may be due in part to the transition to the AB-Warm/Dry climate regime, but cumulative effects of external forcings over the 20th Century may have contributed to decreases in seasonal flow volumes for Oct-Dec and Jan-Mar.

Timing of seasonal flow volumes did not change extensively over the century see Tables 3.1 and 3.9. The Winter-Early Spring 1/3-Flow Date at the YRS site advanced significantly during the earlier part of the century, so the Winter-Early spring flows at the

YRS site are lower and arrive earlier. Decreases in the Winter-Early Spring seasonal flow volumes may contribute to lower median ABY at the YRS site.

3.3 Comparisons between Reconstructed Undepleted Flows and Gauge Flows

Results for the CWCB reconstructed undepleted were compared to actual gauge flows to determine whether the temperature and precipitation signals associated of the AB-Cool/Wet climate regime were also evident in the undepleted flows. In general, the climate signals are evident in the reconstructed undepleted flows on annual scales, but not on seasonal scales for the Fall-Early Winter and Winter-Early Spring seasons. Differences in results between reconstructed undepleted and actual gauge flows are summarized in Tables 3.1 and 3.10, and the differences include: (a) median reconstructed undepleted ABY is higher than actual median ABY at both sites; (b) actual median ABY for the UB-Cool/Wet climate regime, a period of relatively low basin development, was higher than the median reconstructed undepleted ABY for the AB-Cool/Wet climate regime; and (c) median undepleted seasonal flow volumes for the Fall-Early Winter and Winter-Early Spring are often lower than actual seasonal flow volumes during all three climate regimes at both sites.

In summary, although the magnitude of reconstructed undepleted flows may be relatively representative of "natural" flows on annual scales, but not seasonal scales, during the AB-Cool/Wet climate regime. Plus, annual and seasonal reconstructed undepleted flow volumes are lower than actual gauge flow volumes during the UB-Cool/Wet climate regime at the GRG site, indicating that: (a) the reconstructed undepleted flows may under-estimate "natural" flow conditions in the upper Gunnison

River basin, and (b) incorporating the influence of climate regime type and other relevant factors are also important in developing reconstructed undepleted flows.

3.4 Changes in Precipitation between Climate Regimes

Like annual flow volumes, 20th Century trends in median annual precipitation decrease, as shown in Tables 3.2 and 3.7. Median annual precipitation decreases over the 20th Century at the GRG and YRS sites, but the decreases at each site are not in synchrony and are in contrast to increasing trends globally (Wang and Schimel, 2003). Median annual precipitation decreases significantly at the YRS site earlier in the 20th Century, between the UB-Cool/Wet and AB-Warm/Dry climate regimes, as might be expected during changes to warm/dry climate regimes. However, median annual precipitation does not increase again during the following AB-Cool/Wet climate regime. The persistently lower precipitation at the YRS site may be related to anthropogenic climate change, as well as other regional anthropogenic sources, such as sulfate aerosols derived from sulfur dioxide in vehicular and coal fired power plant emissions (Jacobson, et al., 2007; Unger et al, 2009).

While precipitation at the YRS site decreases earlier in the century and remains lower through the century, median annual precipitation at the GRG site decreases significantly in the later half of the 20th Century, between the AB-Warm/Dry and AB-Cool/Wet regimes, which may be contrary to expectations for a cool/wet climate regime. Decreases in median annual precipitation at the GRG site may be related to anthropogenic climate change, or similar to the YRS site, may also be influenced by sulfate aerosol concentrations in the region.

Seasonal flow volumes and precipitation often vary inversely to one another between climate regimes at the two sites, which is opposite to the relationship between annual precipitation and flow volumes (see Tables 3.1 and 3.2). For example, between the UB-Cool/Wet and AB-Warm/Dry climate regimes:

(a) Median precipitation increases for the Fall-Early Winter season at the GRG site (Oct-Dec) and at the YRS site (Sep-Dec and Oct-Dec), but corresponding seasonal flow volumes tend to decrease at both sites; and similarly,

(b) Median precipitation for the Winter-Early Spring season increases significantly at the GRG site, but seasonal flows are significantly lower.

Fall-Early Winter seasonal flow volumes and precipitation may vary inversely due to temperature and the form of precipitation. For example, Fall-Early Winter flows may be higher when temperatures are warmer and precipitation falls as rain. But when temperatures are colder and precipitation falls as snow, flows may be lower because runoff is delayed until snowmelt. Likewise, lower seasonal flows during the Winter-Early Spring may be explained by precipitation falling as snow and lower temperatures, but may also be affected by lower precipitation, as well as upstream reservoir storage.

Over the 20^{th} Century (i.e., between the UB-Cool/Wet and AB-Cool/Wet climate regimes), changes in seasonal precipitation include:

(a) Median precipitation for Fall-Early Winter season (Oct-Dec) decreases at the GRG site;

(b) At the YRS site, median precipitation for the Fall-Early Winter season exhibits an increasing trend, but decreases in the Winter-Early Spring season.

Changes in median seasonal precipitation between climate regimes involve redistribution of precipitation among months of the season, and monthly precipitation typically changes in concert with climate regimes (see Tables 3.2, 73. and 3.8). During the UB-Cool/Wet and AB-Cool/Wet climate regimes characteristics of the monthly precipitation patterns include:

(a) Precipitation is lower in the Fall-Early Winter season at the GRG and YRS sites, and precipitation redistributes, increasing earlier in the season (i.e., September/October) and decreasing later in the season (i.e., November/December).

(b) The Winter-Early Spring season precipitation is lower at the GRG site, due to lower precipitation in January and February.

(c) In contrast, Winter-Early Spring season precipitation is higher at the YRS site, mainly due to higher precipitation in February.

During the AB-Warm/Dry climate regime, generally the opposite patterns in precipitation prevail.

Redistribution of precipitation between climate regimes is reflected in shifts in timing of the Sep-Dec 1/2- and Oct-Dec 1/-3-Precipitation Dates (see Tables 3.2 and 3.7). Overall, the Sep-Dec 1/2-Precipitation Date for the GRG site is earlier during the UB- and AB-Cool/Wet climate regimes, corresponding with increased precipitation in September/October and decreased precipitation in November/December during the cool/wet climate regimes. In contrast, the Sep-Dec 1/2-Precipitation Date is later during the AB-Warm/Dry climate regime, corresponding to the shift in precipitation to later in the season during the warm/dry climate regime (i.e., increased precipitation in

November/December and decreased precipitation in September/October). Over the 20th Century at the YRS site, the Sep-Dec 1/2-Precipitation Date steadily shifts later in the Fall-Early Winter season, which is consistent with significant increases in precipitation in November and lower precipitation in October.

Monthly precipitation also changes over the 20th Century at the GRG and YRS sites (see Tables 3.2 and 3.8). At the GRG site, the changes include:

(a) Higher precipitation in September, but significantly lower precipitation in October and in December.

(b) Higher precipitation in January and February, and significantly lower precipitation in March.

At the YRS site, the changes in precipitation entail:

(a) Increased precipitation in November, but decreased precipitation in October and December, similar to the GRG site; and

(b) Significantly lower precipitation in February.

So like streamflow, seasonal and monthly precipitation exhibit cyclic patterns that correspond with climate regimes, and exhibit long-term changes over the 20th Century.

3.5 Seasonal and Daily Temperature Changes Over the 20th Century

Median temperatures were compared between climate regimes and over the 20th Century at the GRG and YRS sites, and results are summarized Tables 3.3-3.6. In general, results show that temperatures exhibit cyclic patterns corresponding to changes in climate regimes, but also show long-term trends over the 20th Century. For instance, temperatures increase over the 20th Century at both sites, but the increases at each site are not synchronous. The asynchrony is consistent with other studies, although other studies do not distinguish where in the CRB temperatures increased during the two time periods (e.g., Gershunov and Cayan, 2003; Wang and Schimel, 2003; Chen and Grasby, 2009).

Overall, total heating degree-days increase significantly and total cooling degree-days decrease in the Fall-Early Winter and Winter Early Spring seasons over the 20th Century (see Table 3.4). In addition, the Fall-Early Winter total heating degree-days at the GRG site and total cooling degree-days at both sites also change cyclically with the climate regimes. However, in the Winter-Early Spring season at both sites, total heating degree-days increase and total cooling degree-days decrease fairly steadily between climate regimes, and thus over the 20th Century.

Like seasonal temperatures, daily temperature characteristics also exhibit some cyclic patterns between climate regimes and long-term changes over the 20th Century, but the changes are not entirely consistent with those for seasonal temperature characteristics (see Tables 3.3-3.6). For example, maximum daily temperatures (Tmax) for most months at the GRG site change in concert with climate regime type (e.g., increasing during the warm/dry climate regime), but minimum daily temperatures (Tmin) for September and October change inversely with climate regime type; increasing during the cool/wet climate regimes and decreasing during the warm/dry climate regime. The inverse changes in September and October Tmin accompanying climate regime type may be related to the positive relationship between Tmin and precipitation in September and October, and the fact that precipitation tends to increase in September/October during the cool/wet climate regimes. In addition to cyclic changes, Tmax and Tmin also increase significantly over the 20th Century at the GRG site.

Median daily temperatures (Tdaily) at the GRG site increase between the UB-Cool/Wet and AB-Warm/Dry climate regimes, as may be expected, but in the later half of the century, changes in Tdaily vary with the month. Over the 20th Century, Tdaily increases significantly in all months except November, which shows no discernible change.

As with the GRG site, September Tmin at the YRS site changes inversely with climate regime type, since September precipitation tends to be higher during the cool/wet climate regimes than during the warm/dry climate regime, and September Tmin and precipitation are positively correlated (see Tables 3.3 and 3.5). Over the 20th Century, median Tmin increases significantly in very month, except December, which exhibits no discernible change.

Changes in Tmax between climate regimes at the YRS site are akin to those for the GRG site, but over the 20th Century, changes in Tmax are in contrast to those for the GRG site. Tmax for most months exhibits cyclic changes in concert with climate regimes. Yet over the 20th Century, Tmax increases in September and October, but between December and March, Tmax either decreases or exhibits no discernible change over the 20th Century. Causes of depressed Tmax during the winter months at the YRS site may include the combined effects of winter temperature inversions plus sulfate aerosols derived from sulfur dioxide in emissions from area coal fired power plants and vehicles.

In summary, increasing temperatures over the 20th Century are accompanied by decreases in median annual precipitation and median ABY at both sites. The decreases in precipitation at the two sites occur during different times of the century, but the decrease in median ABY at both sites occurs between the UB-Cool/Wet and AB-Warm/Dry climate regimes. The decrease in median ABY at the YRS site is coincident with decreases in median annual precipitation, but is also coincident with changes in land use, land cover and water use, including construction of upstream storage reservoirs. Reservoirs constructed upstream of the GRG and YRS sites during the early part of the 20th Century often stored runoff for irrigation, but not for long-term storage. Thus, captured inflow was released during the growing season, thereby changing timing and distribution of flows compared to pre-dam flow conditions. But, water losses typically increase with storage and changes in timing, for example from reservoir evaporation, infiltration, and bank storage; channel and conveyance losses; and increased evapotranspiration resulting from land cover change and irrigation. Total water lost depends on factors including soil type, wind, climate regime type (i.e., cool/wet or warm dry regime), annual hydroclimatic conditions; water operations, anthropogenic climate change.

Moreover, diversions from the upper Gunnison River system, including transmountain diversions to the eastern side of Colorado that began in the early 1900's, may adversely affect groundwater recharge. The transmountain diversions are from the headwaters of Tomichi Creek, and although Tomichi Creek joins the Gunnison River below the gauge at the GRG site, headwater diversions may reduce basin recharge from snowmelt, which in turn may reduce flows at the GRG gauge (Liu et al., 2004). So decreases in median ABY in some basins in the Upper CRB during the 20th Century may be due partly to drier conditions during the AB-Warm/Dry climate regime, but may also be related to reduced groundwater recharge from diversions; and to increased water losses from reservoir evaporation, bank storage, and seepage; channel and conveyance losses, increased evapotranspiration, and other sources.

In general, temperatures increase over the 20th Century at the GRG and YRS sites, and increases occur most consistently in Tmin and Tdaily, paralleling observations by Wang and Schimel (2003). Other research also determined that temperature increased in the CRB over the century (e.g., Gershunov and Cayan, 2003; Wang and Schimel, 2003; Chen and Grasby, 2009), but the studies also identified two time periods during the century when temperatures increased. The first increase in temperature occurred during the 1940's, corresponding with the transition to the AB-Warm/Dry climate regime. The second increase occurred since the 1970's, which corresponds with the increase in temperature over the 20th Century (i.e., the difference in median temperatures between the UB- and AB-Cool/Wet climate regimes).

Long-term increases in temperature are consistent with anticipated effects of anthropogenic climate change, but the results also suggest influence of other anthropogenic external forcings. For example, September Tmax at the YRS and GRG sites exhibit either no change or nonsignificant trends over the 20th Century. September Tmax may be depressed by late season agricultural and urban irrigation (e.g., Pielke and Avissar, 1990; Stohlgren et al., 1998; Chase et al., 1999; Baron et al., 2000; Bounoua et al., 2000). No irrigation occurs during the winter in the upper Yampa River Basin, yet Tmax for December-March at the YRS site either decreases significantly or shows no discernable change over the 20th Century, which is in contrast to changes in wintertime Tmax at the GRG site. Depressed Tmax during the winter months at the YRS site may be related to combined effects of wintertime temperature inversions and sulfate aerosols originating from sulfur dioxide in emission from upwind coal-fired power plants (Ramanathan et al., 2001) and vehicles.

3.6 September-March Complementary T and P Patterns -- Introduction

Spearman's ρ rank correlation was used to associate temperature with precipitation and streamflow between September and March, and significant associations ($\alpha \leq 0.02$) gave rise to September-March complementary temperature and precipitation (T and P) patterns related to upcoming ABY. The September-March complementary T and P patterns are also unique to climate regime type, influenced by external forcings, and are specific to individual river basins. In general, the complementary T and P patterns for the UB-Cool/Wet and AB-Cool/Wet climate regimes are similar, and they differ from the complementary pattern for the AB-Warm/Dry climate regime. Since complementary T and P patterns for the cool/wet climate regimes evolve differently than those for the warm/dry climate regime, not all wetter years are alike, and not all drier years are alike. A wetter year evolves differently during a cool/wet climate regime than during a warm/dry climate regime, and likewise for drier years. Complementary T and P patterns also differ between the GRG and YRS sites because of factors, including differences in physiography of the two river basins, and external forcings affecting climate in each basin.

The complementary T and P patterns accompanying the three climate regimes for the YRS and GRG sites are illustrated in Figures 3.1-3.3 and 3.4-3.6, respectively. Plus (+) and minus (-) signs are located on the lines connecting the variables in rectangles or circles, and the signs represent significant positive or negative associations, respectively, between the variables. Values for Spearman's ρ, α and p of the associations comprising the complementary T and P patterns for the YRS and GRG sites are summarized in Tables 3.11 and 3.12, respectively. Shaded variables in Figures 3.1-3.6 are the variables used in the Enhanced WSP models developed from the complementary T and P patterns to predict ABY during the three climate regimes at the YRS and GRG sites.

Generally, the complementary T and P patterns show that the frequency of significant associations is lower in the early fall (e.g., September) when the patterns are setting up; the frequency is higher when the patterns are established (e.g., November through January), and the frequency decreases as the complementary T and P patterns dissipate between February and March. The evolution of complementary T and P patterns lags development of ENSO conditions in the Pacific by about three to four months, as described by Hidalgo and Dracup (2003). Most of the significant associations comprising the complementary T and P pattern occur during the Fall-Early Winter season (September-December), prior to most of the main snow accumulation season, December-March (DJFM).

During the UB- and AB-Cool/Wet climate regimes, Tmin is often a key component of the complementary T and P pattern, and September temperature and/or precipitation are early indicators of ABY. Since precipitation tends to increase in September/October during the cool/wet climate regimes, and correlates positively with Tmin, then September Tmin increases as precipitation increases. In comparison, Tmax is a key component of the complementary T and P pattern during the AB-Warm/Dry climate regime, and October temperatures are early indicators of ABY. October, rather than September conditions, are early indicators during the warm/dry climate regime, because precipitation decreases in September/October, and precipitation and Tmax are negatively associated. So October Tmax tends to increase as precipitation decreases.

3.7 Complementary T and P Patterns for the UB-Cool/Wet Climate Regime

The significant associations comprising the complementary T and P pattern for the UB-Cool/Wet climate regime at the YRS site are shown in Figure 3.1, and accompanying Spearman's ρ, α and p are summarized in Table 3.11. In general, the complementary temperature and precipitation conditions associated with higher ABY during the UB-Cool/Wet climate regime involve cooler Tmax but warmer Tmin during the Fall-Early Winter and Winter-Early Spring seasons, and precipitation that begins earlier in the fall. Precipitation arriving in November and January are important to overall precipitation and flow conditions. Alternatively, lower precipitation and ABY during the UB-Cool/Wet climate regime at the YRS site generally involve the opposite hydroclimatic conditions; warmer Tmax, cooler Tmin, and lower precipitation between the Fall-Early Winter and Winter-Early Spring seasons.

Higher ABY is associated with higher precipitation in September/October, which may increase antecedent soil moisture conditions, in turn, increase spring snowmelt runoff efficiency (Pagano et al., 2004). Hence, the NRCS uses fall precipitation and streamflow as proxies for antecedent soil moisture conditions in regression equations to predict snowmelt runoff (Pagano et al., 2004). While wetter antecedent conditions may foster more efficient snowmelt runoff, results of this research also suggest that higher precipitation in the early fall is also part of hydroclimatic conditions accompanying higher precipitation and ABY in the upcoming year during cool/wet climate cycles.

The number of statistically significant temperature associations with precipitation, flow, and other temperature characteristics during the Fall-Early Winter season at the GRG site is lower than at the YRS site as a consequence of a relatively short period of record for the UB-Cool/Wet climate regime (i.e., 18 years) and low accuracy of flow data, especially in the Fall-Early Winter season. However, data accuracy is good for the two later climate regimes, and consequently the number of statistically significant temperature associations is higher for the two later climate regimes. Similar to the YRS site, the complementary T and P pattern associated with higher ABY during the UB-Cool/Wet climate regime at the GRG site involves higher precipitation that begins earlier in the fall, and higher precipitation in January (see Figure 3.4 and Table 3.12). Temperatures may be mild overall, due to warmer Tmin associated with higher precipitation. Alternatively, the complementary T and P pattern associated with lower ABY entails conditions that are opposite of those associated with higher ABY; lower precipitation and cooler Tmin.

Even though the complementary T and P pattern for the UB-Cool/Wet climate regime at the GRG and YRS sites are similar, the patterns are also unique for each river basin. Differences in the complementary patterns include daily temperature variables associated with ABY and the main time period comprising the complementary T and P pattern. At the YRS site, Tmax and Tmin are both key components of the complementary T and P pattern associated with ABY, whereas Tmin and Tdaily are key components of the complementary T and P pattern at the GRG site. The complementary T and P for the GRG site entails hydroclimatic conditions mainly between September and January, and at the YRS site, the complementary pattern extends later in the Winter-Early Spring season, including temperature conditions for February and March.

The complementary T and P patterns may also suggest the relative time of day when precipitation tends to arrive in wetter or drier years during each climate regime. For example, Tmax typically occurs during the day, and Tmax is negatively associated with precipitation. Thus, when precipitation is higher during the day, Tmax may be cooler due to cloud cover. Alternatively, Tmin typically occurs at night, and Tmin is positively associated with precipitation. So when precipitation is higher at night, Tmin may tend to be warmer due to cloud cover and moist conditions.

3.8 Complementary T and P Patterns for the AB-Warm/Dry Climate Regime

The complementary T and P pattern associated with the relative magnitude of ABY for the AB-Warm/Dry climate regime at the YRS site is illustrated in Figure 3.2, and Spearman's ρ, α and p for the main associations of the complementary T and P patterns are summarized in Table 3.11. In general, higher ABY during the AB-Warm/Dry climate regime at the YRS site is associated with cooler temperature conditions overall, and higher precipitation that begins later in the Fall-Early Winter season. Cooler Tmax typically accompanies higher precipitation between October and January, and increased precipitation in January is also associated with higher precipitation for the Winter-Early Spring season. Alternatively, lower ABY at the YRS site is associated with generally warmer Tmax and lower precipitation between October and January. In contrast to the complementary T and P pattern for the UB-Cool/Wet climate regime, results suggest that temperature conditions of the Fall-Early Spring are more closely associated than temperature conditions of the Winter-Early Spring with ABY.

The complementary T and P pattern associated with ABY during the AB-Warm/Dry climate regime at the GRG site is similar to that for the YRS site, generally involving cooler temperatures and higher precipitation that begins later in the Fall-Early Winter season (see Figure 3.5). Although temperatures may be cooler overall, early indications of upcoming ABY include warmer Tmax and lower precipitation in September. Alternatively, prevailing temperature and precipitation conditions associated with lower ABY during the AB-Warm/Dry climate regime at the GRG site are generally the opposite of those associated with higher ABY.

Complementary patterns for the AB-Warm/Dry climate regime exhibit differences, in addition to similarities, between the YRS and GRG sites. For example, the complementary T and P pattern for the GRG site encompasses a longer time period (September-March) compared to that for the YRS site, which encompasses hydroclimatic conditions mainly for October-January. This is in contrast to the time periods over which the complementary patterns are defined for the UB-Cool/Wet climate regime; September-January for the GRG site, and September-March for the YRS site.

3.9 Complementary T and P Patterns for the AB-Cool/Wet Climate Regime

Figure 3.3 illustrates the complementary T and P patterns associated with upcoming precipitation and ABY during the AB-Cool/Wet climate regime for the YRS site, and Table 3.11 summarizes Spearman's ρ, α and p of the main associations of the complementary T and P pattern. The complementary T and P pattern associated with higher ABY during the AB-Cool/Wet climate regime is similar to that for the UB-Cool/Wet climate regime. Warmer Tmin in September is associated with higher precipitation in the Fall-Early Winter season, and September precipitation is a significant early indicator of upcoming precipitation and ABY, and is a component of the Enhanced WSP models. Cooler Tmax and warmer Tmin in the early months of the Fall-Early Winter (e.g., October and November) are associated with higher precipitation and ABY, similar to the UB-Cool/Wet climate regime. However, between December and March, Tmin is a significant component of the complementary T and P patterns, but not Tmax. This is in contrast to the complementary T and P pattern for the UB-Cool/Wet climate regime, but is a key component of the complementary pattern during the UB-Cool/Wet climate regime. The change from Tmax to Tmin as key components of the complementary patterns is consistent with changes in Tmax between the UB- and AB-Cool/Wet climate regimes, which suggest depressed Tmax during the winter months at the YRS site.

Lower ABY during the AB-Cool/Wet climate regime at the YRS site is associated with the opposite conditions of those for higher ABY. In general, conditions involve warmer Tmax, cooler Tmin and lower precipitation in the Fall-Early Winter and Winter-Early Spring seasons.

Unlike the YRS site, the complementary T and P pattern associated with upcoming ABY at the GRG site does not change substantially between the UB-Cool/Wet and AB-Cool/Wet climate regimes (see Figures 3.4 and 3.6, and Table 3.12). The complementary T and P pattern associated with higher ABY during the AB-Cool/Wet climate regime entails warmer Tmin, cooler Tmax and higher precipitation during both seasons. Precipitation begins earlier in the Fall-Early Winter season (e.g., September) and continues later in the Winter-Early Spring season (e.g., February). The complementary pattern associated with lower ABY entails essentially the opposite conditions accompanying higher ABY; warmer Tmax, cooler Tmin, lower precipitation during both seasons, and precipitation later in the Fall-Early Winter season.

3.10 Changes in Complementary T and P Patterns over the 20th Century

In addition to cyclical changes in complementary T and P patterns between climate regimes, the complementary patterns also exhibit long-term changes over the 20th Century. Although the long-term changes are consistent with the effects of some anthropogenic external forcings that are specific to each river basin, they may also involve other external forcings and climate variability.

Temperatures increase and amount and distribution of precipitation change over the 20th Century at the GRG site. Temperature increases are consistent with anticipated effects of anthropogenic climate change, but changes in precipitation may be influenced by factors including climate change, as well as other external forcings. Tmin is a significant variable in the complementary T and P patterns for the UB-Cool/Wet and AB-Cool/Wet climate regimes, but Tmax is also a significant component of the complementary T and P pattern during the AB-Cool/Wet climate regime. In that regard, the complementary T and P patterns for the AB-Coo/Wet and AB-Warm/Dry climate regimes are similar. Plus, the time period over which the complementary T and P pattern is defined increases from about September-January during the UB-Cool/Wet climate regime to September-March during the AB-Cool/Wet climate regime, which is also similar to the complementary T and P pattern for the AB-Warm/Dry climate regime. Thus, the complementary T and P patterns for the AB-Cool/Wet climate regime at the end of the 20th Century at the GRG site entails of characteristics of the complementary T and P patterns for the UB-Cool/Wet climate regime and the AB-Warm/Dry climate regime.

Temperatures generally increase over the 20th Century at the YRS site, similar to the GRG site. However in contrast to the GRG site, Tmax during the winter months does not increase, but instead, Tmax is depressed. Depressed Tmax during the winter months may be related to the combined effects of wintertime temperature inversions and the cooling effects of aerosols, such as from sulfur dioxide in vehicular and coal fired power plant emissions. As Tmax is depressed during the winter, Tmin emerges as significantly associated with precipitation and upcoming ABY at the end of the 20th Century at the YRS site. Plus, the time period over which the complementary T and P pattern is defined shortens over the 20th Century from September-March during the UB-Cool/Wet climate regime to September-January during the AB-Cool/Wet climate regime. Like the GRG site, the time period over which the complementary pattern is defined for the AB-Cool/Wet climate regime is similar to that for the AB-Warm/Dry climate regime. Thus, changes in complementary T and P patterns over the century at the YRS site reflect anticipated effects of anthropogenic climate change and the combined effects of sulfate aerosols and wintertime temperature inversions.

3.11 Complementary T and P Patterns for the Reconstructed Undepleted Flows

Spearman's ρ Rank Correlation identified significant associations between the CWCB reconstructed undepleted flows and the temperature and precipitation data for WY 1975-2001, the AB-Cool/Wet climate regime. The complementary T and P patterns are the same for the reconstructed undepleted and the gauge annual flow volumes, but not for the seasonal flow volumes of the Fall-Early Winter and Winter-Early Spring seasons. Thus, climate signals are evident in the CWCB reconstructed undepleted flows on annual scales, but are not consistently evident on seasonal scales.

3.12 Using Complementary T and P Patterns to Predict ABY

3.12.1 Introduction

The Enhanced WSP models, which are based on the complementary T and P patterns for each climate regime, were developed to predict ABY. The September-December (Sep-Dec) and September-March (Sep-Mar) Enhanced WSP model results for each climate regime are summarized in Table 3.13, and illustrated in Figures 3.7-3.10 and 13.11-3.14 for the YRS and GRG sites, respectively. Table 3.14 presents the Sep-Dec and Sep-Mar Enhanced WSP model equations for the YRS and GRG sites. Overall, the Sep-Dec and Sep-Mar Enhanced WSP models for the YRS and GRG sites accurately predict ABY during each climate regime, but proportionately more variance in ABY is explained by temperature and precipitation conditions between September and December. Although some temperature and precipitation conditions between January and March improve model fit, the improvements are relatively small and typically result from incorporating

January hydroclimatic conditions. Therefore, most of the predictive information of upcoming ABY is detectable in the fall, prior to substantial snow accumulation.

Like actual gauge flows, the Enhanced WSP models for the AB-Cool/Wet climate regime were also applied to the CWCB reconstructed undepleted flows for the same period of record, and the results are mixed. The Sep-Dec and Sep-Mar Enhanced WSP models predict reconstructed undepleted ABY about as accurately as actual gauge ABY for the YRS and GRG sites. In addition, the Enhanced WSP models tend to over-predict and under-predict reconstructed undepleted ABY in drier years and wetter years, respectively, similar to model predictions of actual gauge ABY at the GRG site. Thus, although climate signals accompanying the AB-Cool/Wet climate regime are evident on annual scales in the reconstructed undepleted flows, adjusting gauge flows for water management activities did not substantially improve prediction of ABY.

Coefficients of determination and accuracy of the Enhanced WSP models do not decrease over the 20th Century at either site in the Upper CRB, in fact, some Enhanced WSP models exhibit improvement over the century. This is in contrast to decreasing accuracy in coordinated water supply forecasts in the CRB over the 20th Century (Pagano et al., 2004; Jain et al., 2005). Results of the Sep-Dec and Sep-Mar linear regression models demonstrate that the methodology may be integrated into existing forecast methods to potentially improve water supply forecast accuracy and increase lead time.

3.12.2 Model Predictions of Actual Gauge and Undepleted Flows -- YRS Site

Characteristics of the Sep-Dec and the Sep-Mar Enhanced WSP model results for actual flows during the three climate regimes and for the reconstructed undepleted flows are summarized in Table 3.13 and illustrated in Figures 3.7-3.10 for the YRS site. The Sep-Dec Enhanced WSP models are comprised of hydroclimatic variables between September and December, and the Sep-Mar Enhanced WSP models usually included variables for September to January. This is because proportionately more of the variance in ABY is explained by the Sep-Dec models, and including January hydroclimatic conditions generally improved model fit more than including hydroclimatic conditions for February or March.

The Enhanced WSP model results show that the Sep-Dec and Sep-Mar Enhanced WSP models accurately predict ABY during the three climate regimes at the YRS site. The Sep-Dec Enhanced WSP models explain most of the variance in ABY, and are often nearly as or more accurate than the Sep-Mar Enhanced WSP models. Approximately 58%-76% of the variance in ABY is explained by the Sep-Dec Enhanced WSP models compared to 59%-77% of the variance in ABY explained by the Sep-Mar Enhanced WSP models (see Table 3.13). Accuracy of and the amount of variance explained by the Sep-Dec and Sep-Mar Enhanced WSP models varies over the 20th Century (see Table 3.13 and Figures 3.7-3.10). During the UB-Cool/Wet climate regime, the Sep-Mar Enhanced WSP model is more accurate than the Sep-Dec model at predicting ABY, indicating that January precipitation increases accuracy of the Enhanced WSP models during the UB-Cool/Wet climate regime.

In contrast, during the AB-Cool/Wet climate regime at the end of the century, the Sep-Dec Enhanced WSP model is at least as accurate as the Sep-Mar regression model (Figures 3.7 and 3.9, and Table 3.13). This may be due to improved accuracy of flow data, but may also be influenced by changes in climate over the 20th Century. For example, Fall-Early Winter precipitation increases but Winter-Early Spring precipitation decreases over the century.

The Sep-Dec and Sep-Mar Enhanced WSP models during the AB-Warm/Dry climate regime explain about the same amount of variance in ABY, 58% and 59%, respectively (see Table 3.13 and Figure 3.8). But both Enhanced WSP models during the AB-Warm/Dry climate regime explain less variance in and are less accurate at predicting ABY than the models for the UB-Cool/Wet and AB-Cool/Wet climate regimes.

Differences in variables comprising the Enhanced WSP models between climate regimes correspond with some changes in the complementary T and P patterns between climate regimes. For example, during the cool/wet climate regimes, the Fall-Early Winter precipitation shifts to earlier in the seasonal, increasing in September/October and decreasing in November/December. Alternatively during the warm/dry climate regime, precipitation increases in the fall but the distribution shifts later in the fall, decreasing in September/October and increasing November/December. Accordingly, September precipitation is a variable in the Enhanced WSP models for both cool/wet climate regimes, but not during the warm/dry climate regime. The Enhanced WSP models for the AB-Cool/Wet climate regime also reflect depressed Tmax primarily in months of winter and early spring. Where the Sep-Dec and Sep-Mar models for the UB-Cool/Wet climate regime include temperature and precipitation variables, the Enhanced WSP models for the AB-Cool/Wet climate regime are composed primarily of precipitation variables, potentially due to altered relationships among temperature, precipitation and ABY.

Enhanced WSP model results for the CWCB reconstructed undepleted flows for AB-Cool/Wet climate regime at the YRS site, summarized in Table 3.13 and illustrated in Figure 3.10, are similar to those for actual gauge flows. The Sep-Dec and Sep-Mar Enhanced WSP models explain about the same amount of variance in and are similarly accurate at predicting reconstructed undepleted ABY. Thus, the temperature signal for the AB-Cool/Wet climate regime is evident in the reconstructed undepleted flows on annual scales, but adjusting gauge flows for water management activities generally does not improve the accuracy of water supply predictions.

3.12.3 Model Predictions of Actual Gauge and Undepleted Flows -- GRG Site

The Enhanced WSP models and the results for the GRG site are summarized in Table 3.13, and illustrated in Figures 3.11-3.14, plus Table 3.14 summarizes the Sep-Dec and Sep-Mar Enhanced WSP model equations. Overall, Enhanced WSP model predictions of ABY are reasonably accurate, and significant predictive information about upcoming ABY is available in the fall. The results suggest that the Sep-Dec Enhanced WSP model for the GRG site may be more accurate during the warm/dry climate regime, but the Sep-Mar Enhanced WSP models may be more accurate during the cool/wet climate regimes at the GRG site.

The Sep-Dec and Sep-Mar Enhanced WSP models for the UB-Cool/Wet climate regime explain less variance in ABY than the models for the other climate regimes (see Table 3.13 and Figure 3.11). Even though r^2 is comparatively low for the Sep-Dec and Sep-Mar Enhanced WSP models for the UB-Cool/Wet climate regime, the predictions of ABY are reasonably accurate. Approximately 67%-78% of Sep-Dec and Sep-Mar Enhanced WSP model predictions of ABY are within 15-20% of actual ABY, which is similar to the accuracy of other models for the GRG and YRS sites.

Factors contributing to lower model r^2 include low accuracy of streamflow data during the UB-Cool/Wet climate regime at the GRG site, particularly in the fall, which adversely affects Enhanced WSP model fit. Although the streamflow record during that time is comprised of daily flow values, the daily values do not change for up to a month at a time, so the data are often monthly rather than daily time increments. Monthly streamflow data are too coarse to accurately reflect subtle changes in daily temperature and precipitation patterns associated with climate signals.

Figures 3.11-3.13 show that the Enhanced WSP models for all three climate regimes at the GRG site tend to over-predict in drier years and under-predict in wetter years, but the tendencies are less pronounced during the AB-Warm/Dry climate regime. In fact, accuracy of the Sep-Dec and Sep-Mar Enhanced WSP models for that time period are similar to those for the YRS site during that time (see Figures 3.12 and 3.8). The Sep-Dec Enhanced WSP model is more accurate than the Sep-Mar model for the GRG site. Approximately 72% and 76% of predictions of ABY by the Sep-Dec Enhanced WSP model are with 15% and 20%, respectively, of actual ABY. In comparison, 62% and 77% of the Sep-Mar Enhanced WSP model predictions are within 15% and 20%, respectively, of actual ABY.

Accuracy of the Sep-Mar Enhanced WSP model for the AB-Cool/Wet climate regime is similar to that for the two previous climate regimes, but accuracy of the Sep-Dec Enhanced WSP model is the lowest of the three climate regimes, even though the Sep-Dec Enhanced WSP model explains 67% of the variance in ABY (see Table 3.13 and Figure 3.13).

Hydroclimatic variability is known to be relatively high in the Gunnison River (Woodhouse, 2003), however the results indicate that variability is greater in streamflow than in the temperature and precipitation patterns that accompany the climate regimes. This may suggest that modifications to land use, land cover and water use in the Upper Gunnison River Basin over the 20th Century may have resulted in water losses in the system (e.g., evaporation, transpiration, and seepage) that are greater during drier conditions but are lower during wetter conditions. Accordingly, streamflow would be lower during drier conditions, but higher during wetter conditions, which is consistent with Enhanced WSP model tendencies to over-predict in drier conditions and under-predict in wetter conditions. This assertion is substantiated by results of applying the Enhanced WSP models to the CWCB reconstructed undepleted flows for the AB-Cool/Wet climate regime at the GRG site. Model fit and accuracy of the Sep-Dec and Sep-Mar Enhanced WSP models using the reconstructed undepleted flows are less than for actual gauge flows for the same time period (see Table 3.13 and Figures 3.13 and 3.14). The Sep-Mar Enhanced WSP model explains less variance in and is less accurate at predicting reconstructed undepleted ABY than actual gauge ABY. Plus, the Sep-Dec and Sep-Mar Enhanced WSP models tend to over-predict reconstructed undepleted ABY in drier years and under-predict in wetter years, similar to predictions of actual gauge ABY. Hence, adjusting gauge flows for water management activities does not improve model fit or accuracy for the GRG site, similar to results for the YRS site.

The tendencies of the Enhanced WSP models for the GRG site to over-predict in drier years and under-predict in wetter years, whether actual gauge or reconstructed undepleted flows are used, suggest that modifications to land use, land cover and water use in the basin have greater effects on streamflow variability than variations in climate, and understanding the effects on streamflow are important to accurate modeling and forecasting. Enhanced WSP model results also suggest that the magnitude of water losses may vary with hydroclimatic conditions not only on annual scales, but on climate regime scales, as well. Differences in water losses between wetter and drier hydroclimatic conditions may result from combinations of factors including: (a) increases in temperature over the 20th Century; (b) changes in land use, land cover and water use over the 20th Century; and (c) physiographic characteristics, such as lighter soils (CSU Cooperative Extension, 2000) and valley winds in the Upper Gunnison River Basin (Sato and Kondo, 1988).

In summary, the Sep-Dec and Sep-Mar Enhanced WSP models are reasonably accurate at predicting ABY for each of the three climate regimes at the GRG site, even though hydroclimatic variability in the Gunnison River basin is considered among the most variable in the CRB (Woodhouse, 2003). Also, in contrast to decreasing water supply forecasting accuracy over the 20th Century in the CRB (Pagano et al., 2004; Jain et al., 2005), accuracy of Enhanced WSP model predictions of ABY at both sites does not decrease over the century.

3.13 Summary and Conclusions

In summary, results of this research show that individual climate regimes are a useful basis upon which to characterize hydroclimatic variability. The underpinnings of hydroclimatic variability in the Upper CRB involve complementary temperature and precipitations patterns that accompany wetter or drier hydroclimatic conditions on climate regime and annual scales. Combined effects of relevant climate modes influencing hydroclimate in the CRB shape climate regimes which are characterized by complementary temperature and precipitation patterns (i.e., cool/wet or warm/dry) for each river basin. The complementary patterns for climate regimes of the same type (e.g., cool/wet) are similar, and they differ from complementary patterns for climate regimes of the opposite type (e.g., warm/dry). In addition, although complementary temperature and precipitation patterns accompanying climate regimes share similarities between basins, they are also different, which may be related to differences in river basin physiography and external forcings relevant to each basin.

Since natural and anthropogenic external forcings influence climate modes that shape climate regimes, the external forcings also influence the complementary temperature and precipitation patterns which characterize climate regimes. So these complementary patterns not only change cyclically with changes in climate regimes, but they also exhibit changes over the 20^{th} Century due to influences of external forcings. For example, temperatures generally increase over the century in both seasons at both sites, as demonstrated by higher total heating degrees and lower total cooling degree-days. The increases occur at two different time periods during the century, which is consistent with other research (e.g., Gershunov and Cayan, 2003; Wang and Schimel, 2003; Chen and Grasby, 2009). The first temperature increase occurred during the 1940's, which corresponds to the increase in temperature between the UB-Cool/Wet and AB-Warm/Dry climate regimes, and the second increase occurred since the 1970's (e.g., Gershunov and Cayan, 2003; Wang and Schimel, 2003; Chen and Grasby, 2009), which corresponds to the observed increase in temperature over the 20th Century (i.e., between the UB- and AB-Cool/Wet climate regimes).

In contrast to generally increasing temperatures in the CRB, Tmax between December and March at the YRS site either decreases or exhibits no significant change. Combined effects of wintertime temperature inversions and sulfate aerosols from sulfur dioxide in emissions from upwind coal fired power plants (Ramanathan et al., 2001) and vehicles may contribute to depressed Tmax at the YRS site.

While temperatures increase over the 20th Century, median annual precipitation decreases at the YRS and GRG sites, however the decreases in precipitation at each site occur at different times during the century. The decrease in median annual precipitation at the YRS site coincides with the transition to the AB-Warm/Dry climate regime. But instead of precipitation increasing again during the AB-Cool/Wet climate regime, lower median annual precipitation persists through the century. The AB-Cool/Wet climate regime is also when median annual precipitation decreases at the GRG site, which is contrary to expectations for a cool/wet climate regime. Decreases in precipitation at the GRG and YRS sites in the later part of the 20th Century may be related to anthropogenic climate change, as well as other factors, such as sulfate aerosols (Jacobson, et al., 2007; Unger et al, 2009).

Streamflow also changes over the 20th Century on seasonal and annual scales at the GRG and YRS sites. Median ABY at both sites decreases earlier in the century, between the UB-Cool/Wet and AB-Warm/Dry climate regimes, yet ABY does not increase again during the following cool/wet climate regime (i.e., AB-Cool/Wet climate regime). While decreases in ABY coincide with the warm/dry climate regime, persistently lower flows through the 20th Century may be caused by cumulative effects of land and water resource development and other external forcings in the upper Yampa and Gunnison river basins.

Persistently lower ABY coincides with shifts in timing of annual flow volumes. Between the AB-Warm/Dry and AB-Cool/Wet climate regimes, the WY 1/3-Flow Date shifted significantly earlier at the GRG site and shifted later at the YRS site. Since the WY 1/3-Flow Date showed no discernible change earlier in the 20th Century when median ABY decreased, this may suggest that the relationship between magnitude and timing of annual flow volumes may be relatively invariant between climate regimes, if other changes in the basin are occurring at sufficiently low magnitude and rate. However, anthropogenic external forcings may disrupt the relationship between magnitude and timing of annual flow volumes, causing timing of flow volumes to shift either earlier or later, depending on the anthropogenic external forcings affecting basin hydrology. Effects of anthropogenic external forcings may also be amplified or dampened by natural external forcings (e.g., solar variability or volcanic eruptions) or internal climate variability.

Accompanying each of the three climate regimes at the two sites during the 20th Century are unique complementary temperature and precipitation (T and P) patterns which evolve on annual scales between fall and early spring, and are associated with upcoming precipitation and ABY. The complementary T and P patterns establish by the fall and are: (a) detectable as early as September; (b) persistent through early spring (March); (c) associated with relative magnitudes of upcoming precipitation and ABY; (d) unique to climate regime type; (e) specific to each river basin; and (f) influenced of external forcings, including climate change, solar variability, air pollution (e.g., sulfate aerosols), and modifications to land use, land cover and water use. Complementary T and P patterns evolving between fall and early spring are consistent with Hidalgo and Dracup (2003) and Archer and Fowler (2008) who found that April-September streamflow for the upper CRB and the River Jhelum in Pakistan, respectively, is more correlated with total precipitation for October-January than with any other time period (e.g., October-March, December-March, January-March, or October-September). The Upper CRB and the River Jhelum are both snowmelt-dominated river systems and are influenced by ENSO at least during the winter. Hence, similar to climate regimes which are characterized by prevailing temperature and precipitation patterns (e.g., cool/wet), combined effects of major climate modes and other factors influencing annual hydroclimate in the CRB also entail complementary temperature and precipitation patterns between fall and early spring that are associated with upcoming wetter or drier conditions.

Complementary T and P patterns depict temperature and precipitation conditions between September and March accompanying extreme conditions (i.e., wetter or drier) during each climate regime, thus wet years evolve differently during a cool/wet climate regime than during a warm/dry climate regime, and likewise for dry years. The complementary T and P patterns also represent dynamic patterns in temperature and precipitation that evolve between September and March, and are associated with upcoming precipitation and ABY. Sep-Dec and Sep-Mar Enhanced WSP models, developed from characteristics of the complementary T and P patterns during Sep-Dec and Sep-Mar, respectively, accurately predict ABY for each climate regime at the two sites. While r^2 for the Sep-Mar Enhanced WSP models is often higher than for the Sep-

Dec models, the Sep-Dec Enhanced WSP models explain proportionately more of the variance in upcoming ABY. Thus, much of the predictive information about upcoming ABY is detectable in the fall, well before substantial snowpack development. While winter snowpack is the main source of water supply in the CRB, significant predictive information about the upcoming water supply is detectable as early as September, which may advance forecast lead time as much as six months; from April 1 to October 1 of the previous year.

Like actual gauge flows, the temperature and precipitation signals accompanying the AB-Cool/Wet climate regime are also evident on annual scales in the CWCB reconstructed undepleted flows for the YRS and GRG sites. However, the signals are not consistently evident on seasonal scales for Fall-Early Winter and Winter-Early Spring. Even though reconstructed undepleted flows are adjusted for water management activities, applying the Enhanced WSP models to reconstructed undepleted flows does not always improve predictions of ABY at either the YRS or GRG sites. Plus, Enhanced WSP model results for reconstructed undepleted ABY for the GRG site exhibit similar tendencies to over-predict in drier years and under-predict in wetter years as observed in results for actual gauge flows. This suggests that other factors not considered in development of reconstructed undepleted flows are influencing relationships between climate signals and streamflow. For example: (a) effects of changes in land use, land cover, as well as water use on basin water balance; (b) related water losses, such as those associated with diversions, conveyance, reservoir storage, and irrigation, may be more significant than expected; and (c) transbasin diversions, including headwater diversions, and subsequent effects on basin groundwater recharge. Those factors also vary with climate regimes and anthropogenic climate change, and subsequent combined effects on the inherent capacity of river basins to moderate effects of wetter or drier conditions may be analogous to effects of draining wetlands on intensifying drought or flood conditions (Galatowitsch and van der Valk, 1994; McAllister et al., 2000).

If magnitude and rates of change in a basin, for instance changes in climatic, water use, land use and land cover, are sufficiently low, then the relationship between hydroclimatic conditions and streamflow may be maintained. Begueria et al. (2003) and Dow (2007) found that streamflow "flashiness" and flood frequency decreased as changes in land use and land cover subsided. Amount and rate of change in the Upper Gunnison Basin during the AB-Cool/Wet climate regime may have been sufficiently low because Enhanced WSP model predictions of reconstructed undepleted ABY are about as accurate as model predictions of actual gauge ABY. In addition, Enhanced WSP model predictions of reconstructed undepleted ABY also tend to over-predict in drier years and under-predict in wetter years, similar to Enhanced WSP model predictions of actual gauge ABY. In addition to the factors potentially causing the Enhanced WSP models to over- and under-predict, prediction accuracy for reconstructed undepleted ABY may be affected by disaggregation methods used to generate daily reconstructed undepleted flows values from monthly values. In conclusion, adjusting actual gauge flow for water management activities did not substantively improve accuracy of predictions of streamflow volumes. In addition, because the period of record of the reconstructed undepleted flow datasets for the YRS and GRG sites is coincident primarily with the AB-Cool/Wet climate regime, the climate signal observed in the undepleted flow data is specific for that climate regime, but not for others.

This research corroborates other studies which demonstrated that site elevation is an important factor in detecting climate signals (e.g., Hidalgo and Dracup, 2003; Colle, et al., 2000; Reed et. al., 2001; Dracup, 2005; Wang et. al., 2005). Sites at higher elevations are often less developed, thereby minimizing the effects of land surface modifications (Chase et al., 1999) and water use changes, and are not as influenced by the PBL (Stull, 1988) which confound detection of climate signals.

Hydroclimate in the Gunnison River Basin is considered among the most variable in the CRB because the basin is uniquely situated relative to the boundaries of climate modes influencing hydroclimate in the Upper CRB (Woodhouse, 2003). In that case, the GRG site may represent a "worst case scenario" for detecting climate signals. The results suggest that hydroclimatic variability in the Upper Gunnison River Basin may be due more to combined effects of modifications to land use, land cover, and water use plus subsequent effects of climate change than solely to anthropogenic climate change . Since the methodology used in this research was successful in characterizing temperature and precipitation patterns on climate regime and annual scales that are related to wetter or drier conditions, and in indicating long-term change over the 20^{th} in the Gunnison River Basin, then the methods are likely to be successful in other tributaries of the CRB.

The results of this research suggest alternative strategies which may be integrated into existing water supply forecast procedures to improve forecast accuracy and advance lead time by as much as six months; from April 1 to October 1 of the previous year. Some alternative strategies include:

(a) Define the 30-year flow reference period used by the NRCS to determine long-term mean/median conditions to coincide with the current climate regime, a climate regime of the same type as the current regime, or a simulated climate regime of the same type as the current regime, plus relevant external forcings and climate variability.

(b) Extend the period of analysis from primarily December-March (DJFM) to September-March to incorporate the early indicators and evolution of the complementary T and P pattern associated with upcoming precipitation and ABY.

(c) Select regression variables of the complementary T and P patterns associated with ABY for the current climate regime and specific river basin.

(d) Reconstructed undepleted, or "natural," flow datasets may be improved by taking into consideration the appropriate climate regime and subsequent effects of climate change and other external forcings.

Results also demonstrate that hydroclimatic variability is more deterministic than previously thought, since the underpinnings of hydroclimatic variability in the CRB are complementary temperature and precipitation patterns associated with wetter or drier hydroclimatic conditions on climate regime and annual scales, and that external forcings influence the complementary T and P patterns. Ascertaining the underpinnings of hydroclimatic variability in the CRB may lead to long-range decadal climate forecasts (Pagano and Garen, 2005). Temperature relationships with precipitation and streamflow accompanying each climate regime of the 20th Century were established by this research, and based on that foundation, the physical mechanisms underlying the relationships may be determined.

Results of this research may have other applications including, in downscaling climate models, longer-term forecasting, river restoration and management; and improving water resources engineering methods that assume stationarity.

3.14 References

Archer, D.R, Fowler, H.J., 2008. Using meteorological data to forecast seasonal runoff on the River Jhelum, Pakistan. Journal of Hydrology 361, 10-23.

Baron, J.S., Rueth, H.M., Wolfe, A.M., Nydick, K.R., Allstott, E.J., Minear, J.T., Moraska, B., 2000. Ecosystem responses to nitrogen deposition in the Colorado Front Range. Ecosystem 3, 352-368.

Begueria, S., López-Moreno, J.I., Lorente, A., Seeger, M. Garcia-Ruiz, J.M., 2003. Assessing the effect of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. Ambio 32, 283-286.

Bounoua, L., Collatz, G.J., Los, S.O., Sellers, P.J., Dazlich, D.A., Tucker, C.J., Randall, D.A., 2000. Sensitivity of climate to changes in NDVI. Journal of Climate 12, 2277-2292.

Chase, T.N., Pielke, R.A., Sr., Kittel, T.G.G., Baron, J.S., Stohlgren, T.J., 1999. Potential impacts on Colorado Rocky Mountain weather due to land use change on the adjacent Great Plains. Journal of Geophysical Research 104, 16673-16690.

Chen, Z., Grasby, S.E., 2009. Impact of decadal and century-scale oscillations on hydroclimatic trend analyses. Journal of Hydrology 365, 122-133.

Colle, B.A., Mass, C.F., Westrick, K.J., 2000. MM5 Precipitation Verification over the Pacific Northwest during the 1997-99 Cool Seasons. Weather and Forecasting 15, 730-744.

Colorado State University (CSU) Cooperative Extension, 2000. Improving forage yields and quality in Colorado. Agronomy News 20, 1-14.

Dow, C.L., 2007. Assessing regional land-use/cover influences on New Jersey Pinelands streamflow through hydrograph analysis. Hydrological Processes 21, 185-197.

Dracup, J., 2005. Climate Change and Water Supply Reliability. Public Interest Energy Research Program (PIER), Publication Number CEC-500-2005-053. California Energy Commission. California Climate Change Center Series # 2005-014. Page 3. Online at: Online at: http://www.energy.ca.gov/pier/project_reports/CEC-500-2005-053.html.

Galatowitsch, S.M., van der Valk, A.J., 1994. Restoring Prairie Wetlands an Ecological Approach. Iowa State University Press, Ames, IA.

Gershunov, A., 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.

Hidalgo, H.G., Dracup, J.A., 2003. ENSO and PDO effects on hydroclimatic variables of the Upper Colorado River Basin. Journal of Hydrometeorology 4, 5-23.

Jacobson, M.Z., Kaufman, Y.J., Rudich, Y., 2007. Examining feedbacks of aerosols to urban climate with a model that treats 3-D clouds with aerosol inclusions. Journal of Geophysical Research 112, D24205, doi:10.1029/2007JD008922.

Jain, S., Hoerling, M., Eischeid, J., 2005. Decreasing reliability and increasing synchroneity of western North American streamflow. Journal of Climate 18, 613-618.

Liu, F., Williams, M.W., Caine, N., 2004. Source waters and flow paths in an alpine catchment, Colorado Front Range, United States. Water Resources Research 40, W09401, doi: 10.1029/2004WR003076.

McAllister, L.S., Peniston, B.E., Leibowitz, S.G., Abbruzzese, B., Hyman, J.B., 2000. A synoptic assessment for prioritizing wetland restoration efforts to optimize flood attenuation. Wetlands 20, 70-83.

Pagano, T.P., Garen, D., and Sorooshian, S., 2004. Evaluation of official western U.S. seasonal water supply outlooks, 1922-2002. Journal of Hydrometeorology 5, 896-909.

Pielke, R.A. and Avissar, R., 1990. Influence of landscape structure on local and regional climate. Landscape Ecology 4, 133-155.

Ramanathan, V., Crutzen, P.J., Kiehl, J.T., Rosenfeld, D., 2001. Aerosols, climate, and the hydrological cycle. Science 294, 2119-2124.

Reed, S., King, S., Koren, V., Smith, M., Zhang, Z., Wang, D., 2001. Parameterization Assistance for NWS Hydrology Models Using ArcView, Proceedings of the 21 Annual ESRI International User Conference, San Diego, CA, July 9-13, 2001.

Sato, T., Kondo, J., 1988. A simple model of drainage flow in a valley. Boundary-Layer Meteorology 45, 355-369.

Stohlgren, T.J., Chase, T.N., Pielke, R.A., Sr, Kittel, T.G.F., and Baron, J.S., 1998. Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas. Global Change Biology 4, 495-504.

Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers. Dordrecht, The Netherlands. Pps. 1-2.

Unger, N., Shindell, D.T., Wang, J.S., 2009. Climate forcing by the on-road transportation and power generation sectors. Atmospheric Environment 43, 3077-3085.

Wang, G., and Schimel, D., 2003. Climate change, climate modes, and climate impacts. Annual Review of Environmental Resources, 28: 1-28.

Wang, T., Ren, H., Ma, K., 2005. Climatic signals in tree ring of *Picea schrenkiana* along an altitudinal gradient in the central Tianshan Mountains, northwestern China. Trees 19, 735-741.

Woodhouse, C.A., 2003. A 431-yr reconstruction of western Colorado snowpack from tree rings. Journal of Climate 16, 1551-1560.

Table 3.1 Comparisons of Median Values of Gauge Flows between Climate Regimes and Comparison of Median Values between Reconstructed Undepleted Flows and Gauge Flows for Each Climate Regime at the GRG and YRS Sites

	GRG Site—Comparison of Gauge Flows between Climate Cycles			GRG Site—Comparison of Gauge and Reconstructed Undepleted Flows		
	UC/W[1] to AW/D[2]	AW/D to AC/W[3]	UC/W to AC/W	RU[8]-AC/W to UC/W	RU-AC/W to AW/D	RU-AC/W to AC/W
ABY	S -[4]	nd[5]	S -	S -	S +	S +
WY 1/3-Q[6] Date	nd	S -	n -[7]	S -	S +	S +
Sep-Dec Q Vol	S +[4]	S -	nd	S -	S -	S -
Oct-Dec Q Vol	S -	S +	nd	S -	S -	S -
Jan-Mar Q Vol	S -	S +	nd	S -	S +	S -
Oct-Dec 1/3 Q Date	nd	S +	S +	nd	S +	S +
	YRS Site—Comparison of Gauge Flows between Climate Cycles			**YRS Site—Comparison of Gauge and Reconstructed Undepleted Flows**		
	UC/W[1] to AW/D[2]	**AW/D to AC/W[3]**	**UC/W to AC/W**	**RU[8]-AC/W to UC/W**	**RU-AC/W to AW/D**	**RU-AC/W to AC/W**
ABY	n -	nd	n -	nd	S +	S +
WY 1/3 Q Date	nd	n +[6]	nd	nd	S +	S +
Sep-Dec Q Vol	n -	nd	S -	S -	nd	nd
Oct-Dec Q Vol	nd	n -	S -	S -	n -	nd
Jan-Mar Q Vol	S -	n -	S -	S -	n +	n +
Oct-Dec 1/3 Q Date	nd	nd	nd	S -	n -	S -
Jan-Mar 1/3 Q Date	S -	nd	S -	nd	S +	S +

1. UC/W = Unaltered Basin-Cool/Wet climate cycle.
2. AW/D = Altered Basin-Warm/Dry climate cycle.
3. AC/W = Altered Basin-Cool/Wet climate cycle.
4. S +, S - = Significant increase decrease.
5. nd = no discernible change.
6. Q = Flow.
7. n +, n - = not significant positive or negative trend.
8. RU = Reconstructed Undepleted flows.

Table 3.2 Comparison of Median Values for Precipitation between Climate Regimes at the GRG and YRS Sites

GRG Site—Comparison of Precipitation Variables between Climate Regimes				YRS Site—Comparison of Precipitation Variables between Climate Regimes			
	UC/W[1] to AW/D[2]	AW/D to AC/W[3]	UC/W to AC/W		UC/W to AW/D	AW/D to AC/W	UC/W to AC/W
Annual Precipitation				**Annual Precipitation**			
	nd[4]	S -[5]	n -[6]		S -	nd	S -
Seasonal Precipitation				**Seasonal Precipitation**			
Sep-Dec	nd	nd	nd	**Sep-Dec**	S +	S -	nd
Oct-Dec	n +[6]	n -	n -	**Oct-Dec**	S +	n -	n +
Jan-Mar	S +[5]	S -	nd	**Jan-Mar**	n -	nd	n -
Seasonal Precipitation Dates				**Seasonal Precipitation Dates**			
S-D[7] 1/2-Precip[8] Date	S +	S -	nd	**S-D 1/2 Precip Date**	S +	S +	S +
O-D[7] 1/3-Precip Date	nd	n -	nd	**O-D 1/3 Precip Date**	S +	nd	S +
Total Monthly Precipitation				**Total Monthly Precipitation**			
Sep	nd	n +	n +	**Sep**	S -	S +	nd
Oct	n -	nd	S -	**Oct**	S -	nd	n -
Nov	S +	n -	nd	**Nov**	S +	n +	S +
Dec	nd	S -	S -	**Dec**	n +	S -	n -
Jan	n +	nd	n +	**Jan**	nd	nd	nd
Feb	S +	n -	n +	**Feb**	n -	n -	S -
Mar	nd	S -	S -	**Mar**	nd	nd	nd

1. UC/W = Unaltered Basin-Cool/Wet climate cycle.
2. AW/D = Altered Basin-Warm/Dry climate cycle.
3. AC/W = Altered Basin-Cool/Wet climate cycle.
4. nd = no discernible change.
5. S +, S - = Significant increase, significant decrease.
6. n +,n - = Not significant positive or negative trend.
7. S-D, O-D = Sep-Dec, Oct-Dec.
8. Precip = precipitation.

Table 3.3 **Comparison of Median Values for Temperature between Climate Regimes at the GRG and YRS Sites**

	GRG Site				YRS Site		
	UC/W[1] to AW/D[2]	AW/D to AC/W[3]	UC/W to AC/W		UC/W to AW/D	AW/D to AC/W	UC/W to AC/W
Heating Degree-Days[4]				**Heating Degree-Days**			
Sep-Dec	nd[5]	nd	S +[6]	**Sep-Dec**	n +	S +	S +
Oct-Dec	S +	n -[7]	n +[7]	**Oct-Dec**	n +	nd	n +
Jan-Mar	nd	S +	S +	**Jan-Mar**	n +	S +	S +
Cooling Degree-Days[5]				**Cooling Degree-Days**			
Oct-Dec	S -[6]	n +	S -	**Oct-Dec**	S -	n +	n -
Jan-Mar	S -	nd	S -	**Jan-Mar**	S -	S -	S -
Median Max Daily Temp[8]				**Median Max Daily Temp**			
Sep	S +	S -	nd	**Sep**	nd	nd	n +
Oct	S +	S -	n +	**Oct**	S +	S -	S +
Nov	n -	n -	S -	**Nov**	nd	nd	n -
Dec	S +	n -	S +	**Dec**	n +	n -	nd
Jan	S +	n -	S +	**Jan**	n +	n -	nd
Feb	S +	n -	S +	**Feb**	S +	S -	S -
Mar	n +	S +	S +	**Mar**	n -	nd	nd
Median Min Daily Temp				**Median Min Daily Temp**			
Sep	S -	S +	nd	**Sep**	n -	S +	S +
Oct	n -[7]	S +	S +	**Oct**	S +	nd	S +
Nov	nd	S +	n +	**Nov**	nd	S +	S +
Dec	S +	nd	S +	**Dec**	n +	nd	nd
Jan	S +	n +	S +	**Jan**	S +	nd	S +
Feb	S +	nd	S +	**Feb**	n +	n +	S +
Mar	n +	S +	S +	**Mar**	S +	S +	S +
Median Daily Temp				**Median Daily Temp**			
Sep	n -	S +	n +	**Sep**	n -	S +	S +
Oct	S +	S -	S +	**Oct**	S +	nd	S +
Nov	nd	nd	nd	**Nov**	nd	nd	n +
Dec	S +	nd	S +	**Dec**	nd	nd	nd
Jan	S +	nd	S +	**Jan**	nd	n +	S +
Feb	S +	nd	S +	**Feb**	nd	S +	S +
Mar	S +	S +	S +	**Mar**	nd	S +	S +

Table 3.4 Results of Kruskal-Wallis Nonparametric Comparison of Median Seasonal and Maximum Daily Temperatures between Climate Regimes at the YRS and GRG Sites

Variable	Climate Regimes Compared	Critical Value	YRS Site K Value	GRG Site K Value
Sep-Dec Total HDD	UB-C/W[1] and AB-W/D[2]	3.84146	1.63	0.38
	UB-C/W and AB-C/W[3]	3.84146	5.14	4.24
	AB-W/D and AB-C/W	3.84146	5.26	0.46
Oct-Dec Total HDD	UB-C/W and AB-W/D	3.84146	2.48	8.41
	UB-C/W and AB-C/W	3.84146	3.10	1.56
	AB-W/D and AB-C/W	3.84146	0.88	1.27
Oct-Dec Total CDD	UB-C/W and AB-W/D	3.84146	4.03	8.31
	UB-C/W and AB-C/W	3.84146	3.47	4.28
	AB-W/D and AB-C/W	3.84146	1.46	1.88
Jan-Mar Total HDD	UB-C/W and AB-W/D	3.84146	2.09	0.86
	UB-C/W and AB-C/W	3.84146	29.05	5.36
	AB-W/D and AB-C/W	3.84146	8.83	8.48
Jan-Mar Total CDD	UB-C/W and AB-W/D	3.84146	5.25	5.30
	UB-C/W and AB-C/W	3.84146	14.53	8.55
	AB-W/D and AB-C/W	3.84146	10.18	0.51
Sep Max Daily Temp	UB-C/W and AB-W/D	3.84146	0.43	11.81
	UB-C/W and AB-C/W	3.84146	1.93	0.56
	AB-W/D and AB-C/W	3.84146	0.91	9.15
Oct Max Daily Temp	UB-C/W and AB-W/D	3.84146	4.88	15.26
	UB-C/W and AB-C/W	3.84146	4.12	1.33
	AB-W/D and AB-C/W	3.84146	5.21	7.96
Nov Max Daily Temp	UB-C/W and AB-W/D	3.84146	0.75	1.47
	UB-C/W and AB-C/W	3.84146	0.00	8.51
	AB-W/D and AB-C/W	3.84146	1.43	2.46
Dec Max Daily Temp	UB-C/W and AB-W/D	3.84146	2.52	13.78
	UB-C/W and AB-C/W	3.84146	0.05	10.56
	AB-W/D and AB-C/W	3.84146	3.18	2.68

[1]UB-C/W = Unaltered Basin-Cool/Wet climate regime
[2]AB-W/D = Altered Basin-Warm/Dry climate regime
[3]AB-C/W = Altered Basin-Cool/Wet climate regime

Table 3.5 Results of Kruskall-Wallis Nonparametric Comparison of Median Values of Maximum and Minimum Daily Temperatures between Climate Regimes at the YRS and GRG Sites

Variable	Climate Regimes Compared	Critical Value	YRS Site K Value	GRG Site K Value
Jan Max Daily Temp	UB-C/W[1] and AB-W/D[2]	3.84146	1.70	11.70
	UB-C/W and AB-C/W[3]	3.84146	0.20	13.38
	AB-W/D and AB-C/W	3.84146	1.71	1.06
Feb Max Daily Temp	UB-C/W and AB-W/D	3.84146	9.05	10.16
	UB-C/W and AB-C/W	3.84146	10.93	10.16
	AB-W/D and AB-C/W	3.84146	10.48	2.48
Mar Max Daily Temp	UB-C/W and AB-W/D	3.84146	2.24	2.47
	UB-C/W and AB-C/W	3.84146	0.49	18.73
	AB-W/D and AB-C/W	3.84146	0.54	16.72
Sep Min Daily Temp	UB-C/W and AB-W/D	3.84146	3.55	4.28
	UB-C/W and AB-C/W	3.84146	19.35	0.50
	AB-W/D and AB-C/W	3.84146	27.87	10.17
Oct Min Daily Temp	UB-C/W and AB-W/D	3.84146	6.74	2.29
	UB-C/W and AB-C/W	3.84146	4.01	5.03
	AB-W/D and AB-C/W	3.84146	0.19	8.80
Nov Min Daily Temp	UB-C/W and AB-W/D	3.84146	0.31	0.98
	UB-C/W and AB-C/W	3.84146	15.26	2.74
	AB-W/D and AB-C/W	3.84146	42.84	4.18
Dec Min Daily Temp	UB-C/W and AB-W/D	3.84146	1.69	5.27
	UB-C/W and AB-C/W	3.84146	0.69	4.92
	AB-W/D and AB-C/W	3.84146	0.31	0.05
Jan Min Daily Temp	UB-C/W and AB-W/D	3.84146	4.10	7.16
	UB-C/W and AB-C/W	3.84146	8.41	7.67
	AB-W/D and AB-C/W	3.84146	0.19	3.57
Feb Min Daily Temp	UB-C/W and AB-W/D	3.84146	2.31	5.88
	UB-C/W and AB-C/W	3.84146	8.73	6.76
	AB-W/D and AB-C/W	3.84146	3.57	0.97
Mar Min Daily Temp	UB-C/W and AB-W/D	3.84146	3.92	3.31
	UB-C/W and AB-C/W	3.84146	27.80	12.49
	AB-W/D and AB-C/W	3.84146	59.93	21.42

[1]UB-C/W = Unaltered Basin-Cool/Wet climate regime
[2]AB-W/D = Altered Basin-Warm/Dry climate regime
[3]AB-C/W = Altered Basin-Cool/Wet climate regime

Table 3.6 Results of Kruskall-Wallis Nonparametric Comparison of Median Values of Daily Temperatures between Climate Regimes at the YRS and GRG Sites

Variable	Climate Regimes Compared	Critical Value	YRS Site K Value	GRG Site K Value
Sep Monthly Temp	UB-C/W[1] and AB-W/D[2]	3.84146	2.37	2.47
	UB-C/W and AB-C/W[3]	3.84146	6.52	1.18
	AB-W/D and AB-C/W	3.84146	8.82	4.30
Oct Monthly Temp	UB-C/W and AB-W/D	3.84146	12.48	20.51
	UB-C/W and AB-C/W	3.84146	9.81	9.39
	AB-W/D and AB-C/W	3.84146	0.77	4.60
Nov Monthly Temp	UB-C/W and AB-W/D	3.84146	0.43	0.06
	UB-C/W and AB-C/W	3.84146	0.88	0.24
	AB-W/D and AB-C/W	3.84146	1.36	1.23
Dec Monthly Temp	UB-C/W and AB-W/D	3.84146	0.92	7.59
	UB-C/W and AB-C/W	3.84146	0.28	4.76
	AB-W/D and AB-C/W	3.84146	0.18	0.79
Jan Monthly Temp	UB-C/W and AB-W/D	3.84146	0.19	5.17
	UB-C/W and AB-C/W	3.84146	4.21	5.63
	AB-W/D and AB-C/W	3.84146	1.71	0.00
Feb Monthly Temp	UB-C/W and AB-W/D	3.84146	0.30	10.81
	UB-C/W and AB-C/W	3.84146	32.37	6.07
	AB-W/D and AB-C/W	3.84146	32.97	0.38
Mar Monthly Temp	UB-C/W and AB-W/D	3.84146	0.78	7.93
	UB-C/W and AB-C/W	3.84146	15.07	13.52
	AB-W/D and AB-C/W	3.84146	12.59	12.81

[1]UB-C/W = Unaltered Basin-Cool/Wet climate regime
[2]AB-W/D = Altered Basin-Warm/Dry climate regime
[3]AB-C/W = Altered Basin-Cool/Wet climate regime

Table 3.7 Results of Kruskall-Wallis Nonparametric Comparison of Median Values of Seasonal Precipitation between Climate Regimes at the YRS and GRG Sites

Variable	Climate Regimes Compared	Critical Value	YRS Site K Value	GRG Site K Value
Annual Precipitation	UB-C/W[1] and AB-W/D[2]	3.84146	4.81	0.00
	UB-C/W and AB-C/W[3]	3.84146	0.61	4.32
	AB-W/D and AB-C/W	3.84146	4.21	3.00
Sep-Dec Total Precipitation	UB-C/W and AB-W/D	3.84146	4.29	0.37
	UB-C/W and AB-C/W	3.84146	1.41	0.00
	AB-W/D and AB-C/W	3.84146	3.89	0.66
Oct-Dec Total Precipitation	UB-C/W and AB-W/D	3.84146	5.76	1.22
	UB-C/W and AB-C/W	3.84146	1.18	2.69
	AB-W/D and AB-C/W	3.84146	1.88	1.97
Jan-Mar Total Precipitation	UB-C/W and AB-W/D	3.84146	3.59	4.92
	UB-C/W and AB-C/W	3.84146	3.70	0.46
	AB-W/D and AB-C/W	3.84146	0.06	6.43
Sep-Dec 1/2-Precip Date	UB-C/W and AB-W/D	3.84146	8.10	6.58
	UB-C/W and AB-C/W	3.84146	5.49	0.42
	AB-W/D and AB-C/W	3.84146	20.37	9.82
Oct-Dec 1/3-Precip Date	UB-C/W and AB-W/D	3.84146	7.70	0.21
	UB-C/W and AB-C/W	3.84146	9.77	1.23
	AB-W/D and AB-C/W	3.84146	0.49	3.05

[1]UB-C/W = Unaltered Basin-Cool/Wet climate regime
[2]AB-W/D = Altered Basin-Warm/Dry climate regime
[3]AB-C/W = Altered Basin-Cool/Wet climate regime

Table 3.8 Results of Kruskall-Wallis Nonparametric Comparison of Median Values of Monthly Precipitation between Climate Regimes at the YRS and GRG Sites

Variable	Climate Regimes Compared	Critical Value	YRS Site K Value (Chi Square)	GRG Site K Value (Chi Square)
Sep Total Precipitation	UB-C/W[1] and AB-W/D[2]	3.84146	16.07	0.05
	UB-C/W and AB-C/W[3]	3.84146	1.71	3.07
	AB-W/D and AB-C/W	3.84146	8.70	2.26
Oct Total Precipitation	UB-C/W and AB-W/D	3.84146	5.09	1.02
	UB-C/W and AB-C/W	3.84146	2.75	13.31
	AB-W/D and AB-C/W	3.84146	0.31	0.25
Nov Total Precipitation	UB-C/W and AB-W/D	3.84146	3.86	4.99
	UB-C/W and AB-C/W	3.84146	9.50	0.22
	AB-W/D and AB-C/W	3.84146	1.37	3.09
Dec Total Precipitation	UB-C/W and AB-W/D	3.84146	2.43	0.98
	UB-C/W and AB-C/W	3.84146	1.15	4.40
	AB-W/D and AB-C/W	3.84146	5.50	9.95
Jan Total Precipitation	UB-C/W and AB-W/D	3.84146	0.31	2.34
	UB-C/W and AB-C/W	3.84146	0.01	1.97
	AB-W/D and AB-C/W	3.84146	0.16	0.36
Feb Total Precipitation	UB-C/W and AB-W/D	3.84146	1.27	8.76
	UB-C/W and AB-C/W	3.84146	4.29	2.90
	AB-W/D and AB-C/W	3.84146	1.21	2.45
Mar Total Precipitation	UB-C/W and AB-W/D	3.84146	0.10	0.01
	UB-C/W and AB-C/W	3.84146	0.03	4.42
	AB-W/D and AB-C/W	3.84146	0.03	5.60

[1]UB-C/W = Unaltered Basin-Cool/Wet climate regime
[2]AB-W/D = Altered Basin-Warm/Dry climate regime
[3]AB-C/W = Altered Basin-Cool/Wet climate regime

Table 3.9 Results of Kruskall-Wallis Nonparametric Comparison of Median Values of Seasonal and Annual Flow between Climate Regimes at the YRS and GRG Sites

Variable	Climate Regimes Compared	Critical Value	YRS Site K Value (Chi Square)	GRG Site K Value (Chi Square)
ABY	UB-C/W[1] and AB-W/D[2]	3.84146	1.20	15.65
	UB-C/W and AB-C/W[3]	3.84146	2.64	13.42
	AB-W/D and AB-C/W	3.84146	0.02	0.19
WY 1/3-Q Date	UB-C/W and AB-W/D	3.84146	0.08	0.85
	UB-C/W and AB-C/W	3.84146	0.60	3.38
	AB-W/D and AB-C/W	3.84146	1.23	6.70
Sep-Dec Q Volume	UB-C/W and AB-W/D	3.84146	3.78	7.28
	UB-C/W and AB-C/W	3.84146	4.24	0.23
	AB-W/D and AB-C/W	3.84146	0.47	7.64
Oct-Dec Q Volume	UB-C/W and AB-W/D	3.84146	1.85	8.33
	UB-C/W and AB-C/W	3.84146	5.19	1.92
	AB-W/D and AB-C/W	3.84146	2.64	7.76
Oct-Dec 1/3-Q Date	UB-C/W and AB-W/D	3.84146	0.33	3.73
	UB-C/W and AB-C/W	3.84146	0.42	10.27
	AB-W/D and AB-C/W	3.84146	0.74	16.09
Jan-Mar 1/3-Q Date	UB-C/W and AB-W/D	3.84146	25.50	4.84
	UB-C/W and AB-C/W	3.84146	29.61	6.0
	AB-W/D and AB-C/W	3.84146	0.75	5.06

[1]UB-C/W = Unaltered Basin-Cool/Wet climate regime
[2]AB-W/D = Altered Basin-Warm/Dry climate regime
[3]AB-C/W = Altered Basin-Cool/Wet climate regime

Table 3.10 Results of Kruskall-Wallis Nonparametric Comparison of Median Actual Flows for Each Climate Regime with Median Undepleted Flows at the YRS and GRG Sites

Variable	Climate Regimes Compared	Critical Value	YRS Site K Value (Chi Square)	GRG Site K Value (Chi Square)
Actual and Undepleted ABY	UB-C/W[1] and Undepleted AB-C/W[2]	3.84146	0.39	4.54
	AB-W/D[3] and Undepleted AB-C/W	3.84146	4.24	10.42
	AB-C/W and Undepleted AB-C/W	3.84146	4.66	4.02
Actual and Undepleted WY 1/3-Q Date	UB-C/W and Undepleted AB-C/W	3.84146	9.95	0.42
	AB-W/D and Undepleted AB-C/W	3.84146	7.07	12.69
	AB-C/W and Undepleted AB-C/W	3.84146	3.53	18.71
Actual and Undepleted Sep-Dec Q Volume	UB-C/W and Undepleted AB-C/W	3.84146	4.24	14.76
	AB-W/D and Undepleted AB-C/W	3.84146	0.19	52.22
	AB-C/W and Undepleted AB-C/W	3.84146	0.78	39.64
Actual and Undepleted Oct-Dec Q Volume	UB-C/W and Undepleted AB-C/W	3.84146	5.74	16.86
	AB-W/D and Undepleted AB-C/W	3.84146	2.33	18.16
	AB-C/W and Undepleted AB-C/W	3.84146	0.05	41.38
Actual and Undepleted Oct-Dec 1/3-Q	UB-C/W and Undepleted AB-C/W	3.84146	5.15	0.06
	AB-W/D and Undepleted AB-C/W	3.84146	2.75	9.24
	AB-C/W and Undepleted AB-C/W	3.84146	8.53	13.86
Actual and Undepleted Jan-Mar 1/3-Q	UB-C/W and Undepleted AB-C/W	3.84146	0.00	6.38
	AB-W/D and Undepleted AB-C/W	3.84146	9.33	22.43
	AB-C/W and Undepleted AB-C/W	3.84146	7.38	16.89

[1]UB-C/W = Unaltered Basin-Cool/Wet climate regime
[2]AB-W/D = Altered Basin-Warm/Dry climate regime
[3]AB-C/W = Altered Basin-Cool/Wet climate regime

Table 3.11	Associations Comprising the Complementary T and P Patterns for the YRS Site		
UB-Cool/Wet Climate Regime			
Y vs X	**ρ**	**α**	**p**
Oct Mdn[1] Max T vs ABY	- 0.48	0.01	0.003
Oct Mdn Max T vs Oct Prec	- 0.49	0.01	0.002
Nov Mdn Max T vs ABY	- 0.57	0.0001	< 0.001
Nov Mdn Max T vs Nov Prec	- 0.51	0.01	0.002
Dec Mdn Max T vs ABY	- 0.58	0.001	< 0.001
Dec Mdn Max T vs Dec Mdn Min T	0.89	0.001	< 0.001
Feb Mdn Max T vs ABY	- 0.53	0.01	0.002
Mar Mn[2] Max T vs ABY	- 0.43	0.02	0.0104
Mar Mdn Max T vs Mar Mdn Min T	0.66	0.001	< 0.001
Sep Mdn Min T vs Sep Prec	0.66	0.001	< 0.001
Sep Mdn Min T vs Mar Mdn Min T	0.74	0.001	< 0.001
Nov Mdn Min T vs Dec Mdn Min T	0.50	0.01	0.002
Dec Mdn Min T vs Jan Mdn Min T	0.53	0.01	0.002
Dec Mdn Min T vs Jan Prec	0.51	0.01	0.003
Jan Mdn Min T vs Jan Prec	0.61	0.001	< 0.001
AB-Warm/Dry Climate Regime			
Y vs X	**ρ**	**α**	**p**
Oct Mn Max Daily T vs ABY	- 0.42	0.02	0.011
Oct Mn Max Daily T vs Oct Prec	- 0.79	0.001	< 0.001
Nov Mn Max Daily T vs ABY	- 0.59	0.001	< 0.001
Nov Mn Max Daily T vs Nov Prec	- 0.50	0.01	0.002
Nov Mn Max Daily T vs Dec Mn Max T	0.44	0.02	0.0104
Dec Mn Max T vs Dec Prec	- 0.57	0.001	< 0.001
Dec Mdn Max Daily T vs Jan Mdn Max Daily T	0.50	0.01	0.002
Jan Mdn Max Daily T vs Jan Mdn Min Daily T	0.68	0.001	< 0.001
Jan Mdn Min Daily T vs Jan Prec	0.65	0.001	< 0.001
AB-Cool/Wet Climate Regime			
Y vs X	**ρ**	**α**	**p**
Oct Mdn Max Daily T vs ABY	- 0.45	0.02	0.011
Oct Mdn Max Daily T vs Oct Prec	- 0.61	0.001	< 0.001
Sep Mdn Min T vs Oct Prec	0.52	0.01	0.002
Sep Mdn Min T vs Sep Prec	0.60	0.001	< 0.001
Nov Mn Max Daily T vs Nov Prec	- 0.47	0.02	0.0103
Nov Mdn Max Daily T vs Nov Mdn Min Daily T	0.51	0.01	0.003
Nov Mdn Min Daily T vs Dec Mdn Min Daily T	0.54	0.01	0.002
Dec Mdn Min Daily T vs ABY	0.48	0.01	0.003
Dec Mdn Min Daily T vs Dec Prec	0.50	0.01	0.003

[1] Mdn = Median
[2] Mn = Mean

Table 3.12 Associations Comprising Complementary T and P Patterns for the GRG Site

Y vs X	ρ	α	p
UB-Cool/Wet Climate Regime			
Sep Mdn[1] Daily T vs ABY	0.54	0.02	0.011
Sep Prec vs Oct Mn[2] Max Daily T	- 0.55	0.01	0.003
Oct Mn[2] Max Daily T vs Oct-Mar Prec	0.57	0.02	0.011
Oct Mdn Min Daily T vs Oct Prec	0.84	0.001	< 0.001
Oct Mdn Min Daily T vs Jan Mdn Min Daily T	- 0.61	0.01	0.003
Nov Mn Min Daily T vs Oct-Mar Prec	0.59	0.01	0.003
Nov Mn Min Daily T vs Jan-Mar Prec	0.61	0.01	0.003
Nov Mdn Min Daily T vs Jan Mdn Min Daily T	0.58	0.02	0.0103
Nov Mdn Min Daily T vs Jan Mdn Daily T	0.65	0.01	0.002
Jan Mdn Min Daily T vs Jan Prec	0.68	0.01	0.002
Jan Mdn Min Daily T vs ABY	0.63	0.01	0.001
Jan Mn Daily T vs Jan-Mar Prec	0.61	0.01	0.003
Jan Mn Daily T vs ABY	0.71	0.001	< 0.001
AB-Warm/Dry Climate Regime			
Y vs X	**ρ**	**α**	**p**
Sep Mdn Max Daily T vs Jan-Mar Prec	0.61	0.001	< 0.001
Oct Mdn Daily T vs ABY	- 0.46	0.02	0.0103
Nov Mdn Max Daily T vs ABY	- 0.66	0.001	< 0.001
Nov Mdn Max Daily T vs Mar Mdn Max Daily T	0.51	0.01	0.002
Dec Mdn Max Daily T vs Mar Mdn Max Daily T	0.54	0.01	0.002
Mar Mdn Max Daily T vs Jan-Mar Prec	- 0.47	0.02	0.003
Mar Mdn Max Daily T vs Oct-Mar Prec	- 0.60	0.001	< 0.001
Jan Prec vs Mar Mn Max Daily T	- 0.45	0.02	0.011
Feb Prec vs Mar Mn Max Daily T	- 0.43	0.02	0.011
AB-Cool/Wet Climate Regime			
Y vs X	**ρ**	**α**	**p**
Sep Mdn Min Daily T vs ABY	0.43	0.02	0.011
Sep Mdn Min Daily T vs Sep Prec	0.59	0.001	< 0.001
Sep Mdn Min T vs Oct Prec	0.58	0.001	< 0.001
Sep Prec vs Feb Mdn Min T	0.51	0.01	0.003
Oct Mdn Min Daily T vs ABY	0.67	0.001	< 0.001
Oct Mdn Min Daily T vs Oct Prec	0.66	0.001	< 0.001
Oct Mdn Min Daily T vs Nov Mdn Min Daily T	0.54	0.01	0.002
Nov Mdn Min Daily T vs ABY	0.46	0.02	0.0104
Nov Mdn Min Daily T vs Sep-Dec Prec	0.86	0.001	< 0.001
Dec Mdn Max Daily T vs Feb Mdn Max Daily T	0.57	0.001	< 0.001
Dec Mdn Max Daily T vs Mar Mdn Max Daily T	0.60	0.001	< 0.001
Feb Mdn Max Daily T vs Mar Mdn Max Daily T	0.58	0.001	< 0.001
Feb Mdn Max Daily T vs Feb Mdn Min T	0.90	0.001	< 0.001
Mar Mn Max Daily T vs ABY	– 0.48	0.01	0.003

Table 3.13	YRS and GRG Sites Percent of Predicted Annual Basin Yield that is within 15% and 20% of Actual ABY During the Three Climate Regimes of the 20th Century							
Site & Climate Regime	**Sep-Mar** Model Variables	**r^2** Sep-Mar Model	**% of Predicted within 15% of Actual ABY**[1]	**% of Predicted within 20% of Actual ABY**	**Sep-Dec** Model Variables	**r^2** Sep-Dec Model	**% of Predicted within 15% of Actual ABY**	**% of Predicted within 20% of Actual ABY**
YRS Site								
UB-[6] *Cool/Wet*	- Sep Prec[2] - Nov Prec - Dec Tmax[3] - Jan Prec	0.76	72	86	- Sep Prec - Oct Tmax - Nov Prec - Nov Tmax	0.69	66	79
AB-[7] *Warm/Dry*	- Oct Tmax - Nov Tmax - Dec Prec - Jan Prec	0.59	61	81	- Oct Tmax - Nov Tmax - Nov Tmin[4] - Dec Prec	0.58	58	74
AB- Cool/Wet	- Sep Prec - Oct Prec - Dec Prec - Jan Prec	0.77	70	78	- Sep Prec - Oct Prec - Oct Tmin - Dec Prec	0.76	74	78
Undepleted Q AB- Cool/Wet	- Sep Prec - Oct Prec - Dec Prec - Jan Prec	0.75	76	76	- Sep Prec - Oct Prec - Oct Tmin - Dec Prec	0.70	75	75
GRG Site								
UB- Cool/Wet	- Sep Median Tdaily[5] - Oct Prec - Jan Tmin - Jan Prec	0.58	72	78	- Sep Tdaily - Oct Tmin - Nov Prec - Dec Tmin	0.43	0.67	0.72
AB- Warm/Dry	- Oct Median Tdaily - Nov Tmax - Dec Tmax - Jan Prec	0.67	62	72	- Oct Median Tdaily - Nov Tmax - Nov Tmin - Dec Tmax	0.66	72	76
AB- Cool/Wet	- Oct Tmin - Nov Prec - Dec Tmax - Feb Prec	0.66	64	77	- Oct Tmin - Nov Prec - Dec Tmax - Dec Tmin	0.67	48	61
Undepleted Q AB- Cool/Wet	- Oct Tmin - Nov Prec - Dec Tmax - Feb Prec	0.58	43	74	- Oct Tmin - Nov Prec - Dec Tmax - Dec Tmin	0.69	54	67

[1]ABY = Annual Basin Yield
[2]Prec = Precipitation
[3]Tmax = Maximum daily temperature.
[4]Tmin = Minimum daily temperature.
[5]Median Tdaily = Median daily temperature.
[6]UB = Unaltered Basin conditions
[7]AB = Altered Basin conditions

Table 3.14

GRG and YRS Sites
Enhanced WSP Models for Actual Gauge ABY for the
UB-Cool/Wet, AB-Warm/Dry and AB-Cool/Wet Climate Regimes, and
for the Reconstructed Undepleted ABY for the AB-Cool/Wet Climate Regime

Site and Climate Regime	Sep-Dec Enhanced WSP Model	Sep-Mar Enhanced WSP Model
YRS Site		
UB-Cool/Wet	**ABY** = 732,453 – 23,688*_Sep Prec_ – 5,953*_Oct Tmax_ - 1,930*_Nov Tmax_ + 62,202*_Nov Prec_	**ABY** = 512,027 - 18,884*_Sep Prec_ + 39,911*_Nov Prec_ - 8,587*_Dec Tmax_ + 28,566*_Jan Prec_
AB-Warm/Dry	**ABY** = 861,573 – 4,948*_Oct Tmax_ – 4,911*_Nov Tmax_ – 4,926*_Nov Tmin_ + _22,141_*_Dec Prec_	**ABY** = 804,794 – 4,629*_Oct Tmax_ – 6,428*_Nov Tmax_ + 17,283*_Dec Prec_ + 17,881*_Jan Prec_
AB-Cool/Wet	**ABY** = 188,362 + 21,010*_Sep Prec_ + 57,015*_Oct Prec_ – 2,896*_Oct Tmin_ + 39,318*_Dec Prec_	**ABY** = 100,164 + 21,923*_Sep Prec_ + 51,451*_Oct Prec_ + 38,641*_Dec Prec_ + 10,607*_Jan Prec_
Reconstructed Undepleted Flows for the AB-Cool/Wet	**ABY** = 272,439 + 17,874*_Sep Prec_ + 65,018*_Oct Prec_ - 4,689*_Oct Tmin_ + 35,370*_Dec Prec_	**ABY** = 149,078 + 13,134*_Sep Prec_ + 48,748*_Oct Prec_ + 40,076*_Dec Prec_ +13,873*_Jan Prec_
GRG Site		
UB-Cool/Wet	**ABY** = 88,767 + 20,600*_Sep Tdaily_ – 25,384*_Oct Tmin_ + 1,597*_Nov Prec_ – 2,459*_Dec Tmin_	**ABY** = -145,045 + 16,521*_Sep Tdaily_ – 49,038*_Oct Prec_ + 54,572*_Jan Prec_ + 7,005*_Jan Tmin_
AB-Warm/Dry	**ABY** = 2,268,634 – 21,272*_Oct Tdaily_ – 12,997*_Nov Tmax_ – 9,838*_Nov Tmin_ – 5,403*_Dec Tmax_	**ABY** = 2,117,210 - 22,413*_Oct Tdaily_ – 12,288*_Nov Tmax_ - 4,478*_Dec Tmax_ + 41,557*_Jan Prec_
AB-Cool/Wet	**ABY** = 1,146,194 + 14,220*_Oct Tmin_ + 109,431*_Nov Prec_ + 27,317*_Dec Tmin_ - 30,025*_Dec Tmax_	**ABY** = - 136,226 + 28,850*Oct Tmin + 132,351*Nov Prec - 4,561*Dec Tmax + 245,889*Feb Prec
Reconstructed Undepleted Flows for the AB-Cool/Wet	**ABY** = 1,123,785 + 17,703*_Oct Tmin_ + 102,962*_Nov Prec_ - 29,792*_Dec Tmax_ + 26,091*_Dec Tmax)_	**ABY** = - 1,959 + 30,032*_Oct Tmin_ + 130,372*_Nov Prec_ - 6,595*_Dec Tmax)_ + 161,692*_Feb Prec_

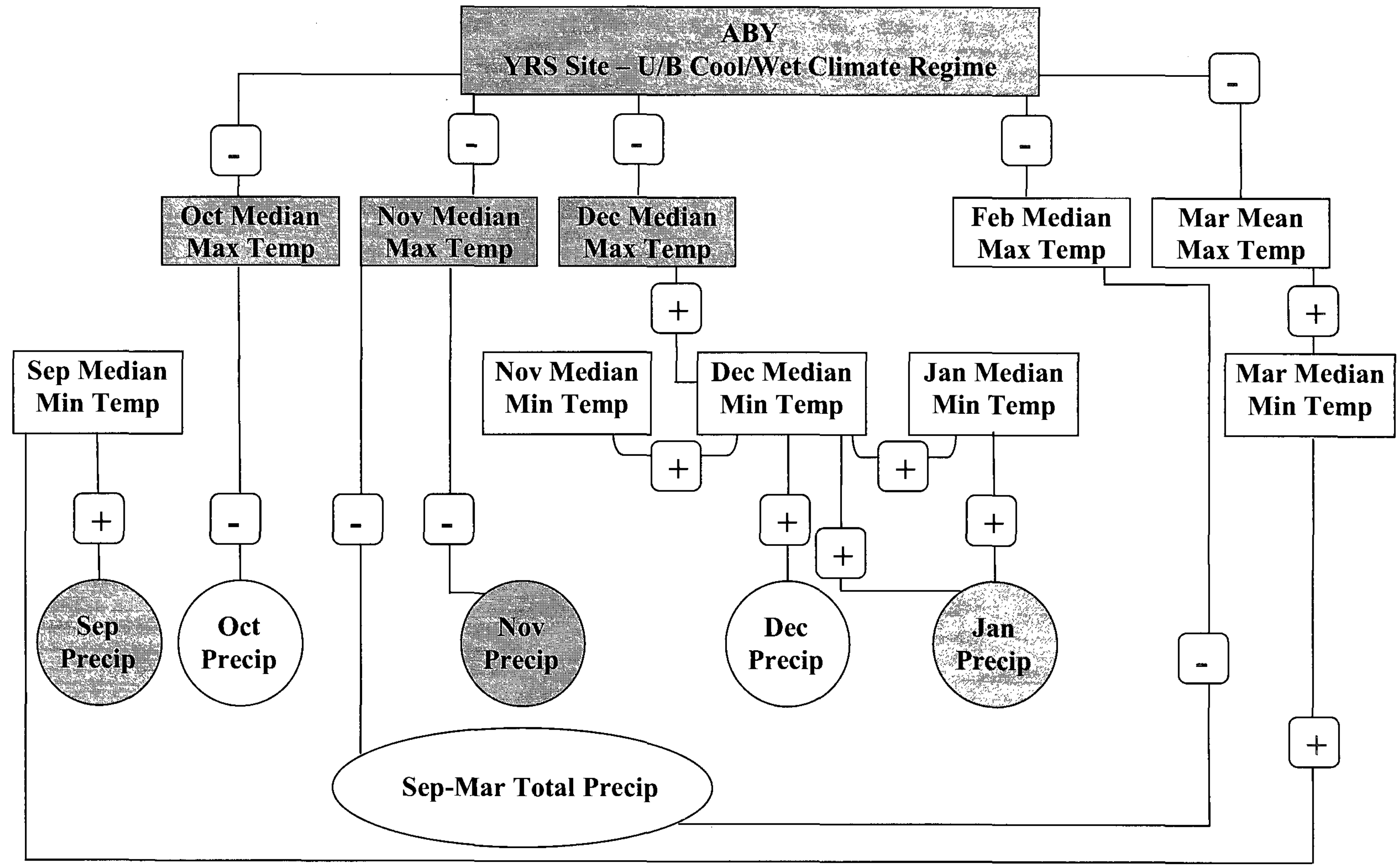


Figure 3.1 Lines represent significant associations ($\alpha \leq 0.02$) between variables and plus ("+") and minus ("-") signs on the lines indicate the sign of the association between the two variables connected by the line. Shaded circles and rectangles are variables of the complementary T and P pattern used in demonstration regression models to predict ABY. Precipitation shifts earlier in the fall during the cool/wet climate regime. In contrast to the GRG, Tmax is a significant indicator of ABY, along with precipitation in the fall and in Jan.

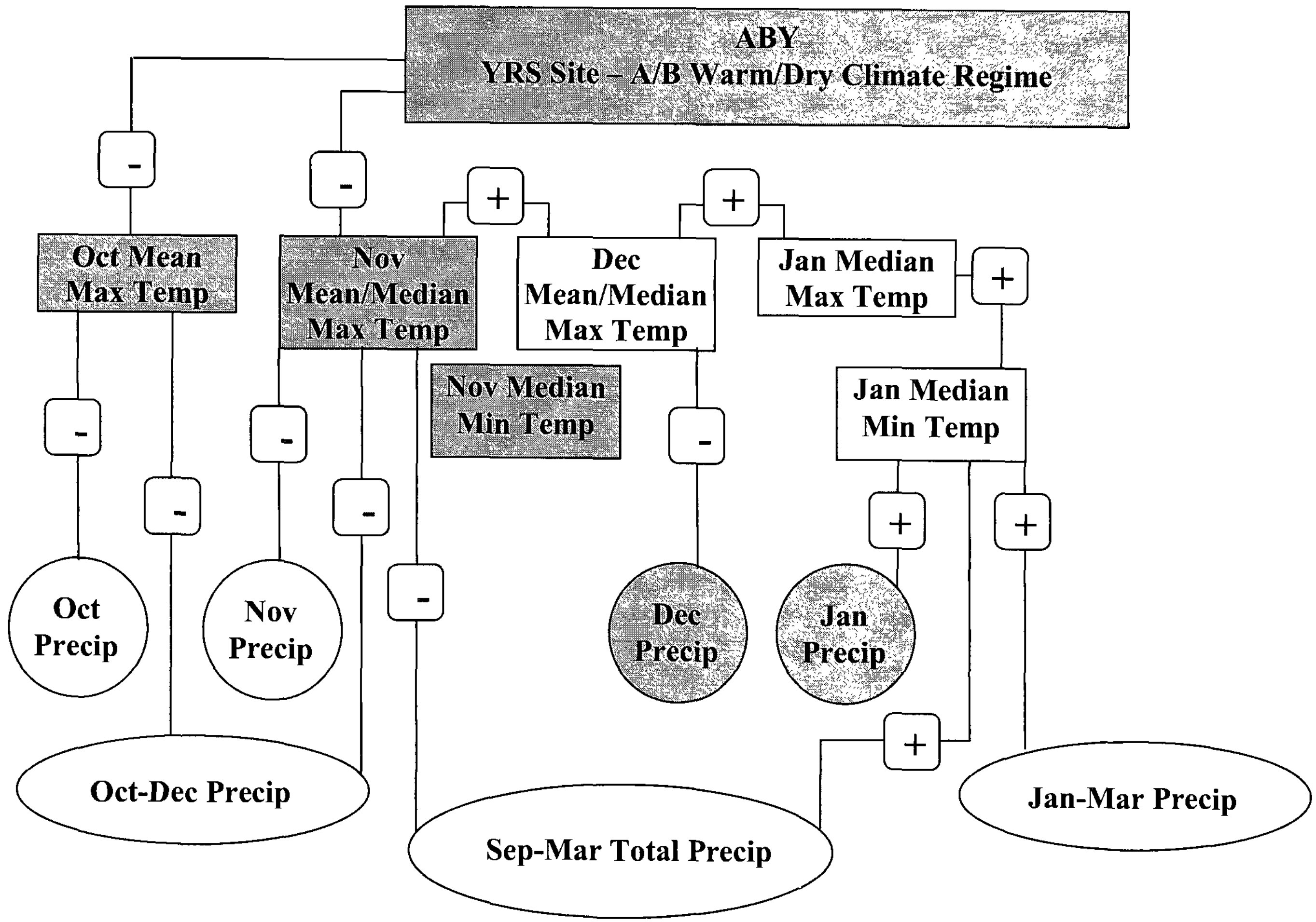


Figure 3.2 Lines represent significant associations ($\alpha \leq 0.02$) between variables and plus ("+") and minus ("-") signs on the lines indicate the sign of the association between the two variables connected by the line. Shaded circles and rectangles are variables of the complementary T and P pattern used in demonstration regression models to predict ABY. Precipitation shifts later in the fall during the warm/dry climate cycle, and as a result, precipitation in the winter months and fall temperature conditions are significant indicator of ABY.

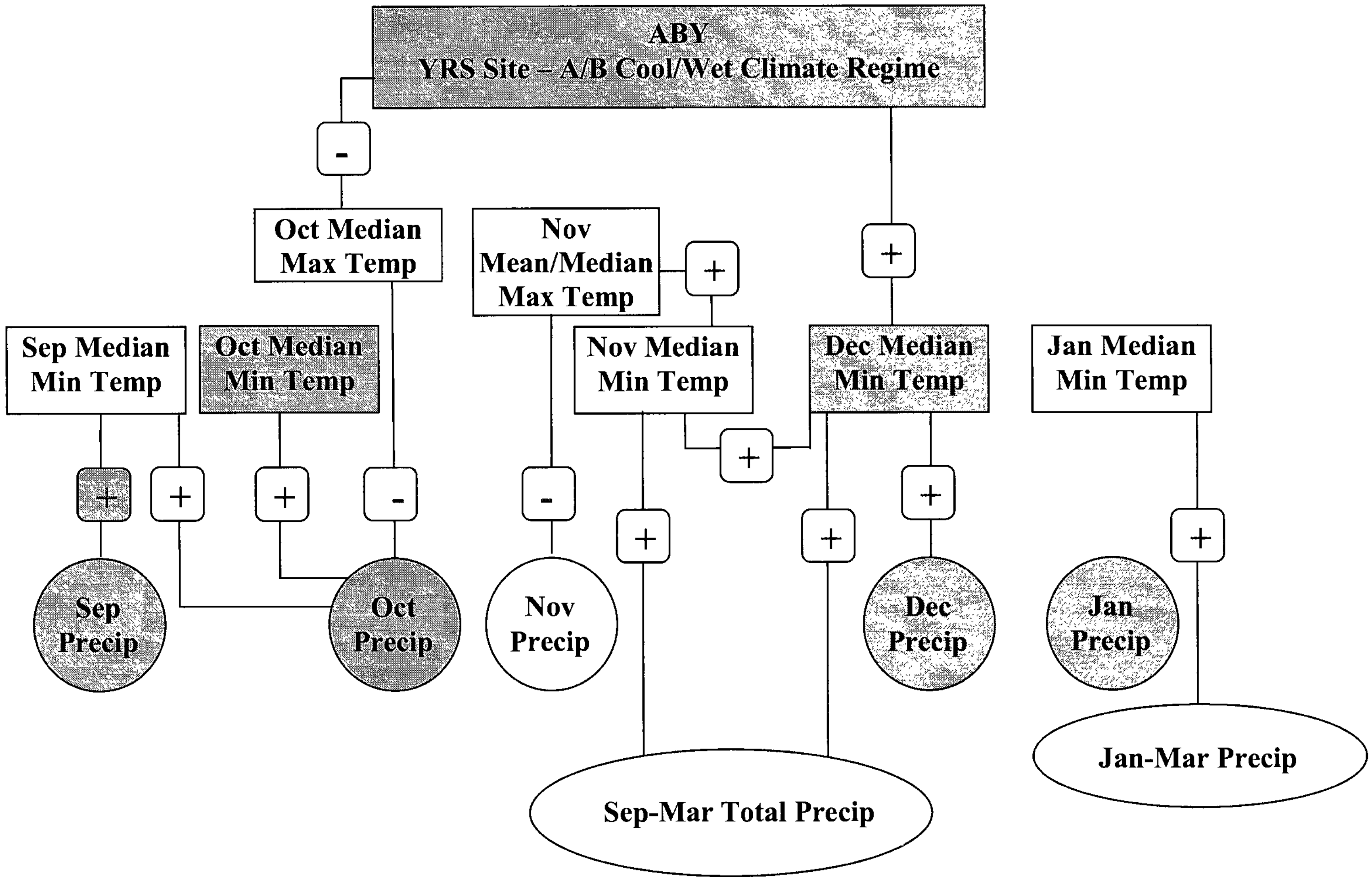


Figure 3.3 Lines represent significant associations ($\alpha \leq 0.02$) between variables and plus ("+") and minus ("-") signs on the lines indicate the sign of the association between the two variables connected by the line. Shaded circles and rectangles are variables of the complementary T and P pattern used in demonstration regression models to predict ABY. During the cool/wet climate cycle, precipitation begins early in the Fall but continues late in the season and January, and temperature and precipitation during that time are significant indicators of ABY.

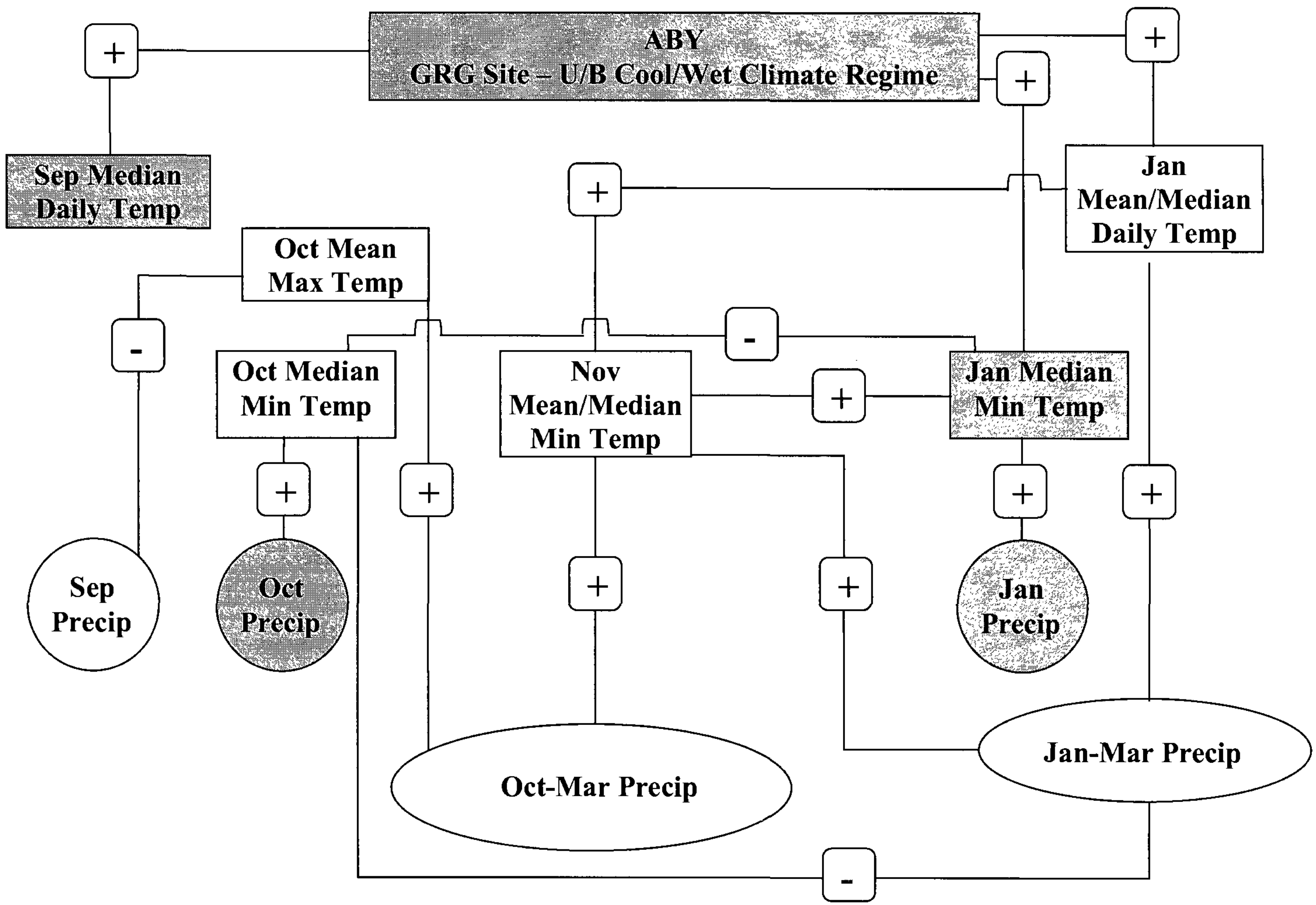


Figure 3.4 Lines represent significant associations ($\alpha \leq 0.02$) between variables in circles and rectangles, and plus ("+") and minus ("-") signs on the lines indicate the sign of the association between the two connected variables. Shaded circles and rectangles are variables of the complementary T and P pattern used in demonstration regression models to predict ABY. Precipitation increases in Sep/Oct during cool/wet climate regimes, and consequently, temperature and precipitation conditions of early fall are significant indicators of ABY.

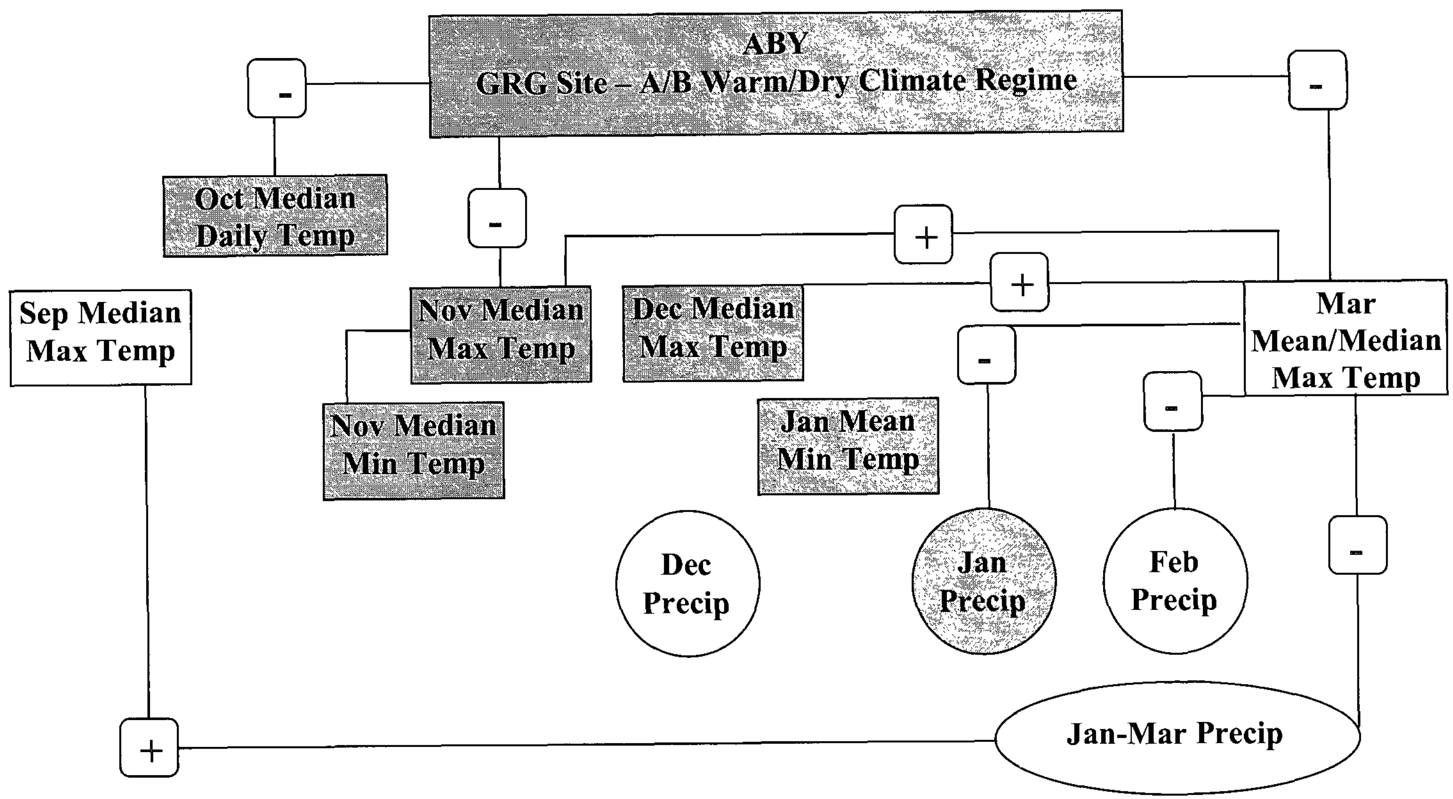


Figure 3.5 Lines represent significant associations ($\alpha \leq 0.02$) between variables in circles and rectangles, and plus ("+") and minus ("-") signs on the lines indicate the sign of the association between the two variables connected by the line. Shaded circles and rectangles are variables of the complementary T and P pattern used in demonstration regression models to predict ABY. Precipitation increases and shifts later in the fall during the warm/dry climate regime, thus precipitation associated with ABY is generally concentrated in the winter months.

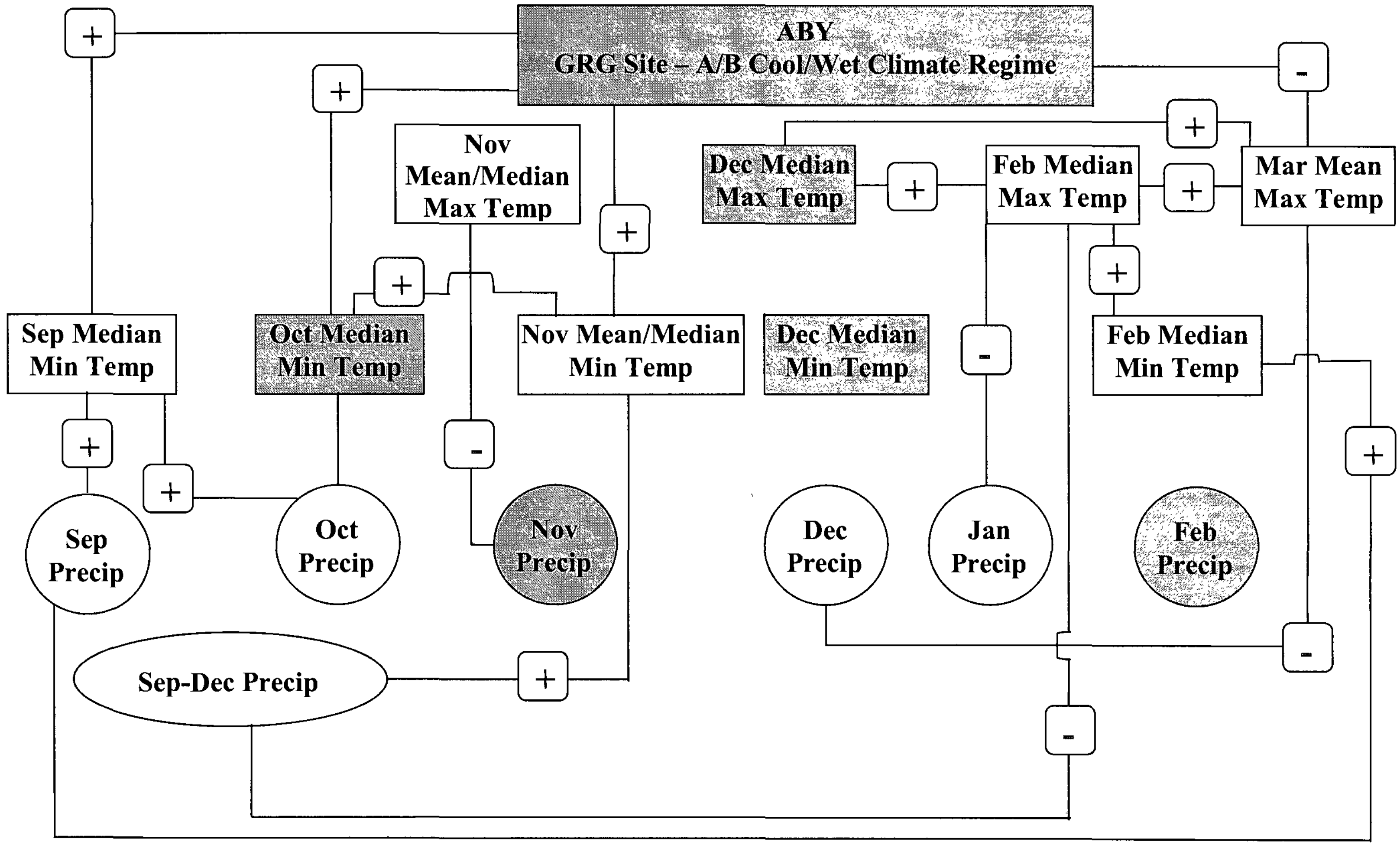


Figure 3.6. Lines represent significant associations ($\alpha \leq 0.02$) between variables in circles and triangles. Plus ("+") and minus ("-") signs on the lines indicate the sign of the association between the two variables connected by the line. Shaded circles and rectangles are variables of the complementary T and P pattern used in demonstration regression models to predict ABY. Precipitation in the fall shifts earlier in the season (Sep/Oct) during the cool/wet climate regime, plus Feb precipitation increases over the 20th Century, so these conditions are significant indicators of ABY.

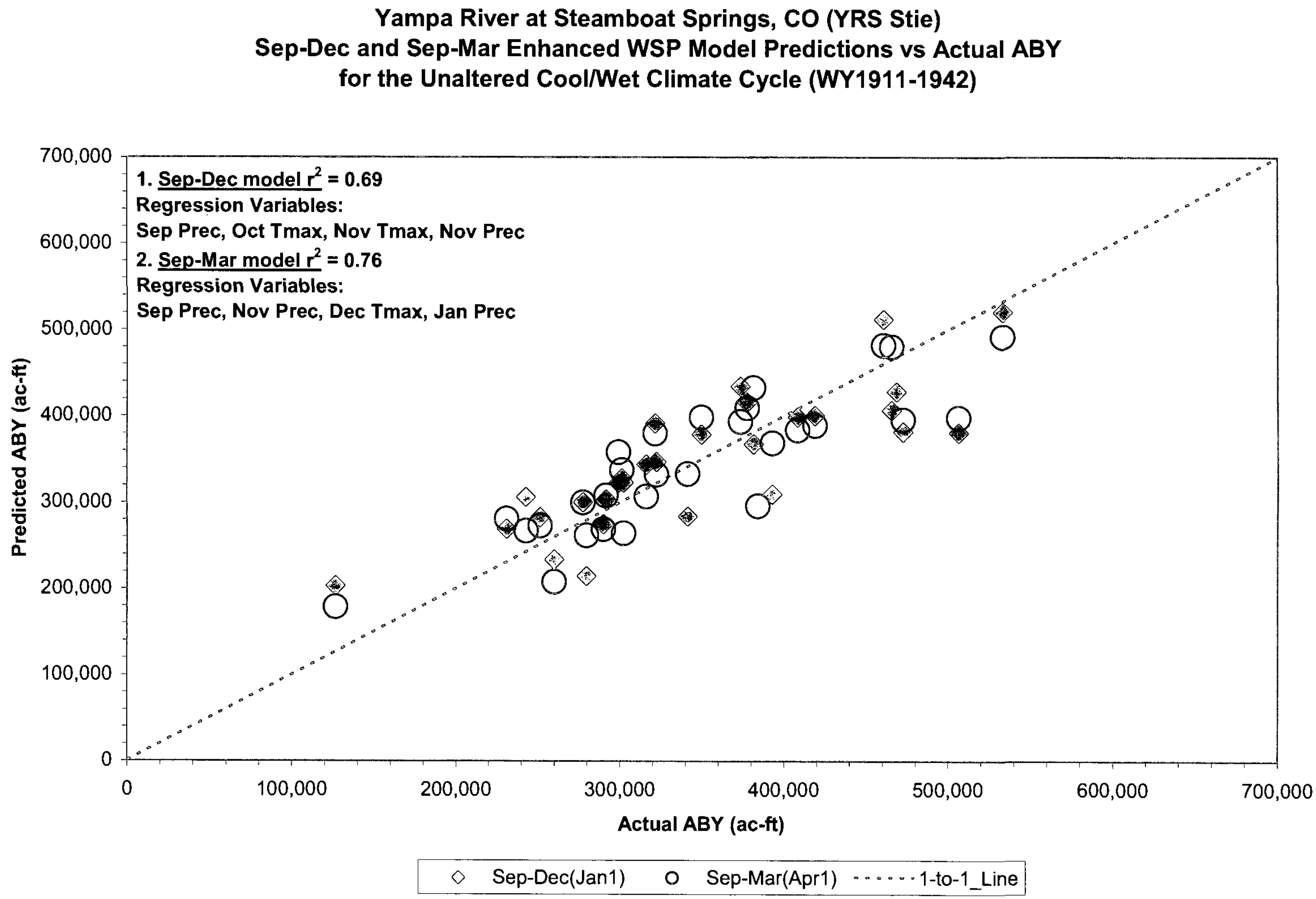


Figure 3.7. Sep-Dec and Sep-Mar Enhanced WSP models for the Unaltered Basin-Cool/Wet climate regime are reasonably accurate at predicting ABY, and explain 69%-76% of the variance in ABY. Most of the predictive information is available in the fall, and Sep precipitation is an early indicator of ABY in both Enhanced WSP models. Enhanced WSP models are in Table 3.14.

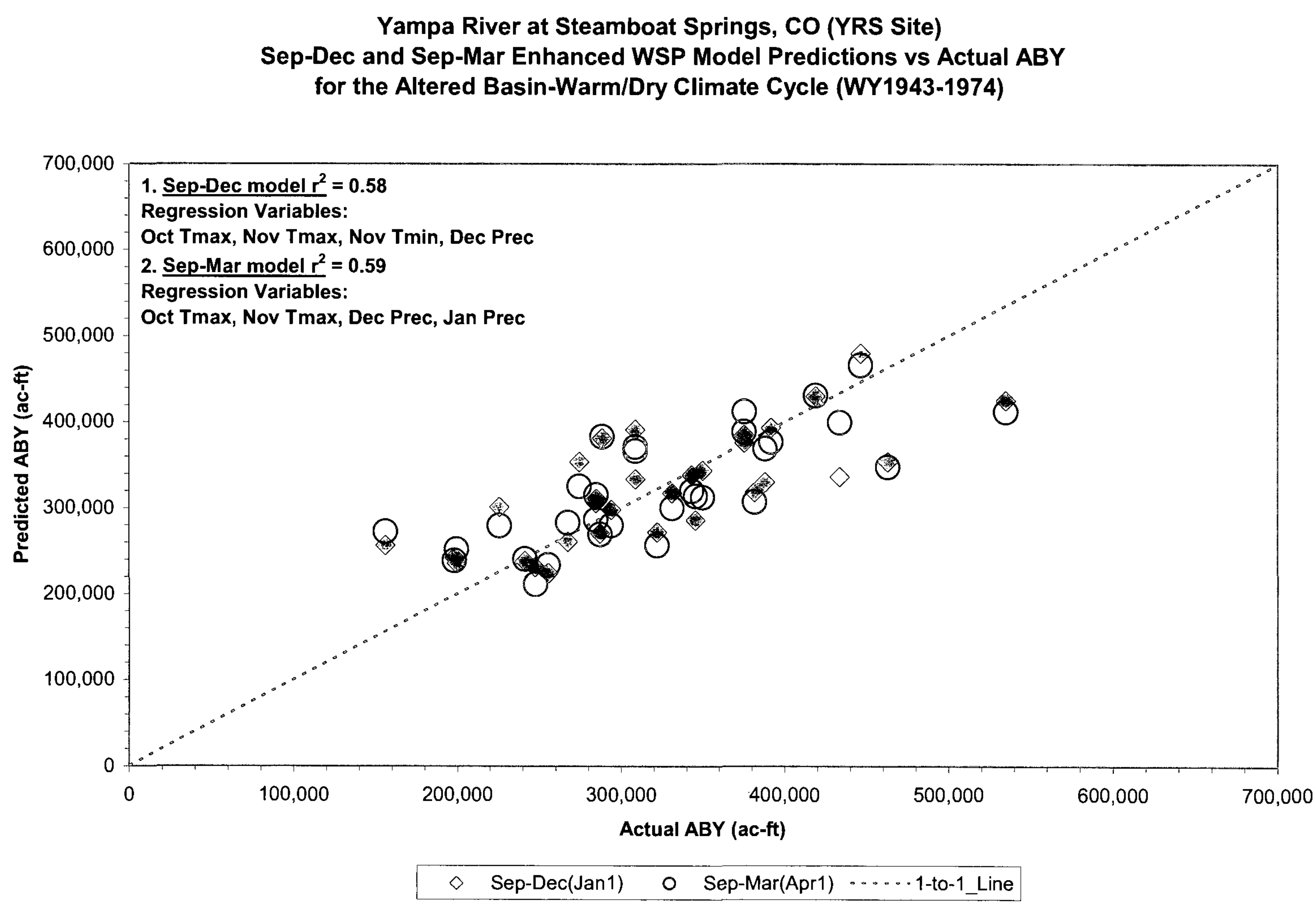


Figure 3.8 Sep-Dec and Sep-Mar Enhanced WSP models for the Altered Basin-Warm/Dry climate regime are reasonably accurate at predicting ABY, but the models do not explain as much variance in ABY as the Enhanced WSP models for the Unaltered Basin-Cool/Wet climate regime. October Tmax, rather than Sep prec, is an early indicator of ABY in both Enhanced WSP models. Enhanced WSP models are in Table 3.14.

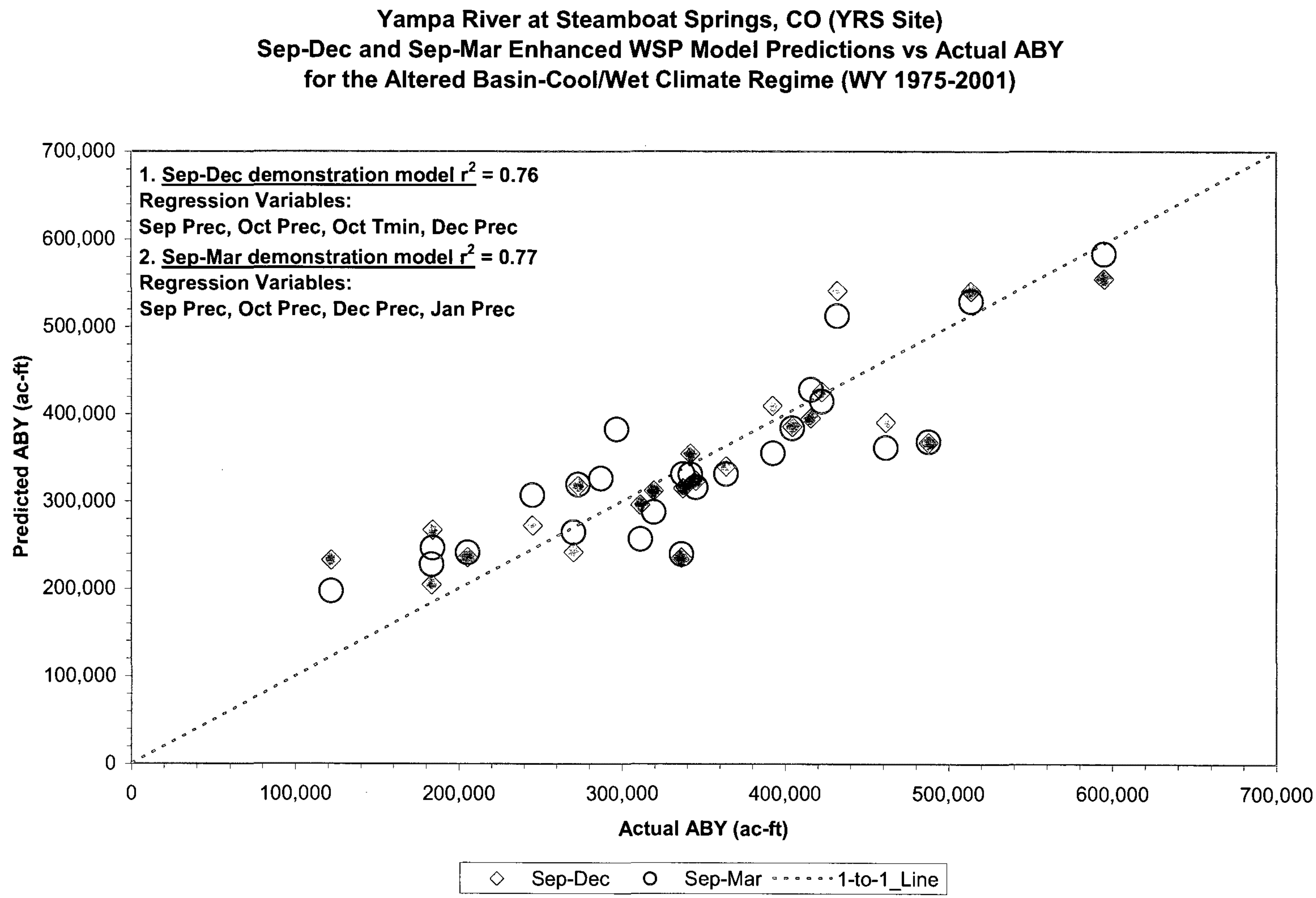


Figure 3.9 Sep-Dec and Sep-Mar Enhanced WSP models for the Altered Basin-Cool/Wet climate regime are reasonable accurate at predicting ABY, and the Enhanced WSP models explain 76%-77% of the variance in ABY. Sep prec is an early indicator of ABY in both Enhanced WSP models, like the Unaltered Basin-Cool/Wet climate regime. Enhanced WSP models are in Table 3.14.

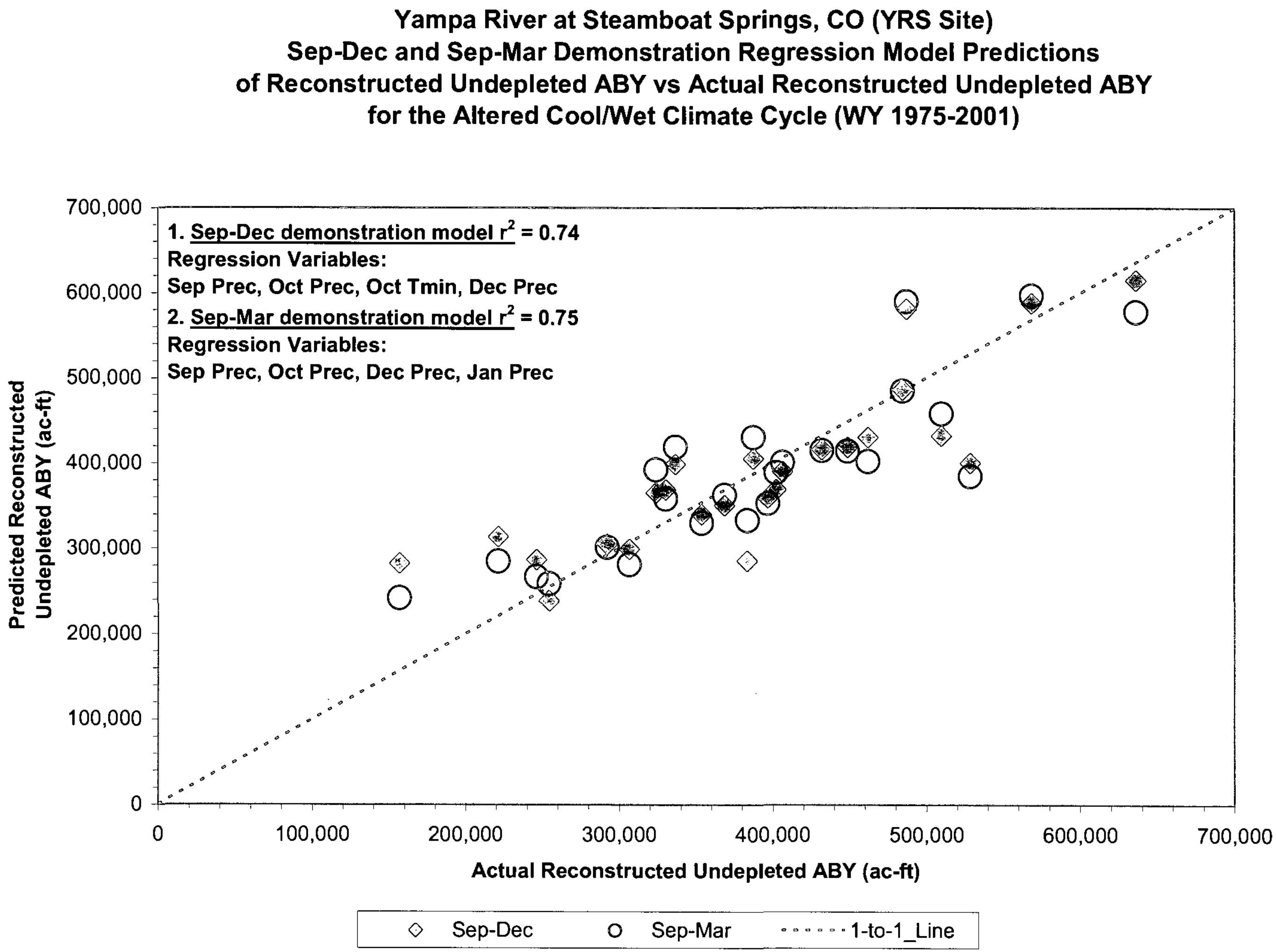


Figure 3.10 Results of the Sep-Dec and Sep-Mar Enhanced WSP models are similar to results for actual gauge ABY for the Altered Basin-Cool/Wet climate regime. This suggests that adjusting flows for water management and estimated return flow does not improve predictions of ABY. Enhanced WSP models are in Table 3.14.

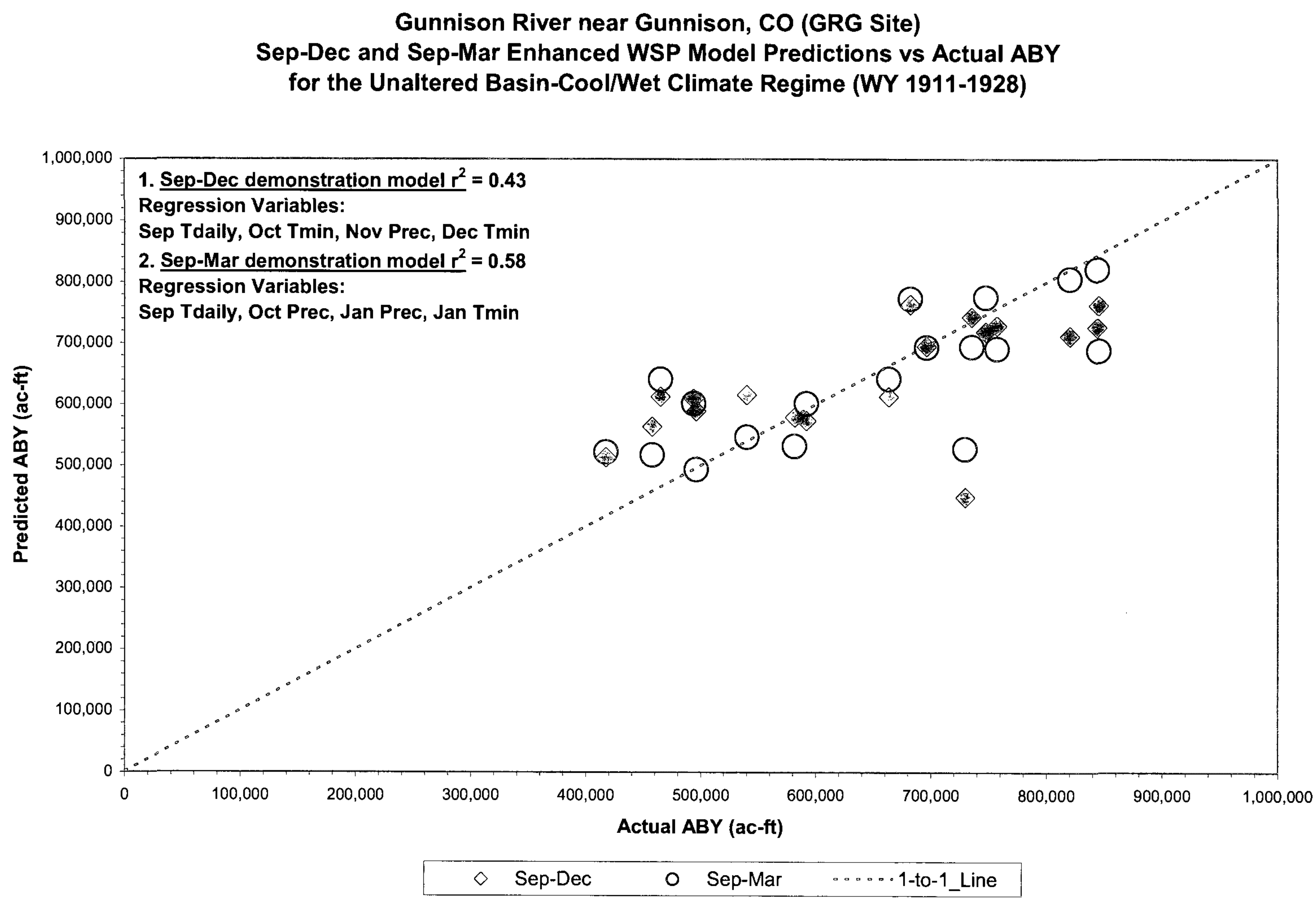


Figure 3.11 Sep-Dec and Sep-Mar Enhanced WSP models for the Unaltered Basin-Cool/Wet climate regime for the GRG site are reasonably accurate, although model r^2 is comparatively low. Both the Enhanced WSP tend to over-predict in drier years and under-predict in wetter years. Enhanced WSP models are in Table 3.14.

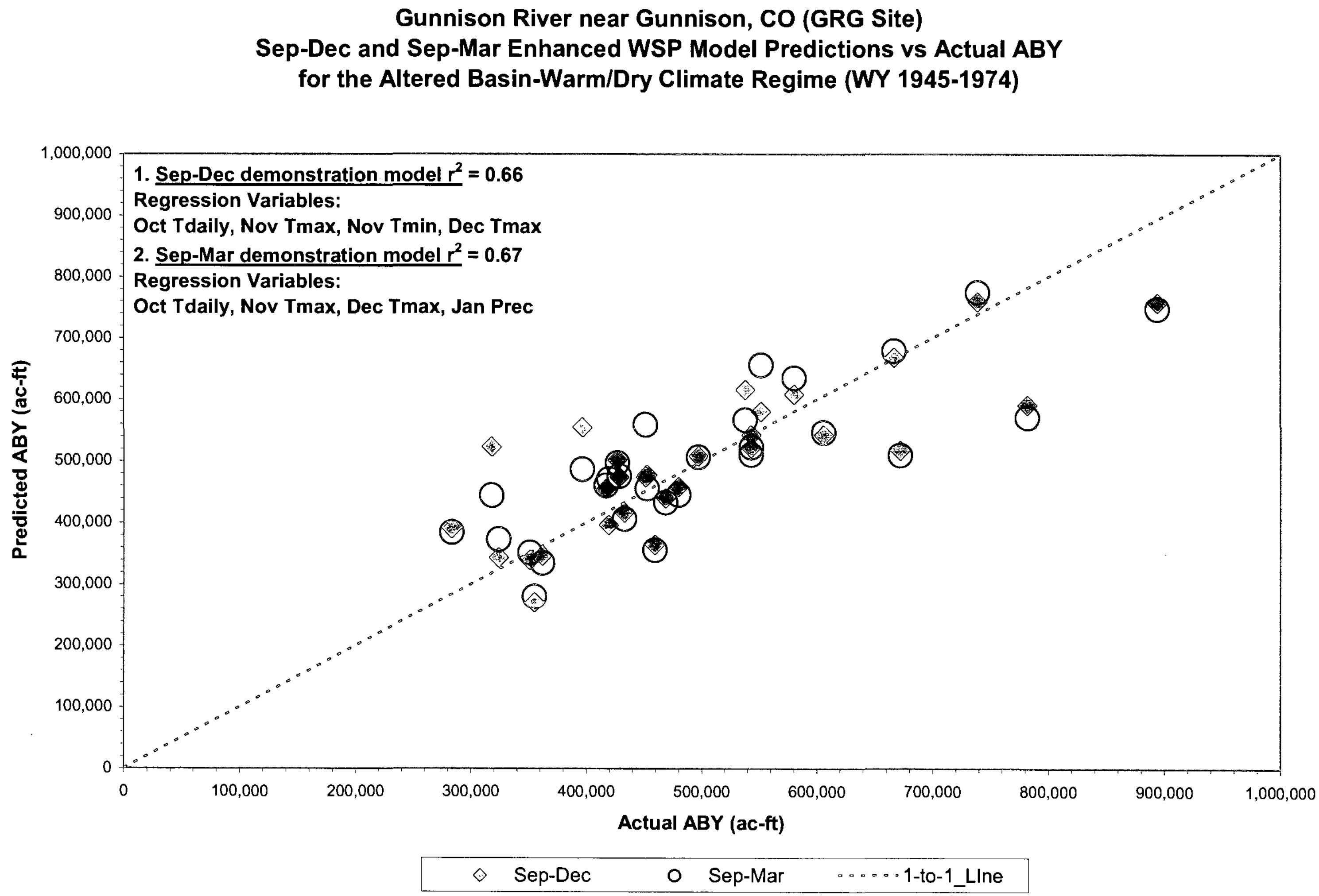


Figure 3.12 Compared to results for the Unaltered Basin-Cool/Wet climate regime, the Sep-Dec and Sep-Mar Enhanced WSP models for the Altered Basin-Warm/Dry climate regime explain more variance in ABY, and also tend to over-predict in drier years and under-predict in wetter years, although the tendencies are not as pronounced. Enhanced WSP models are in Table 3.14.

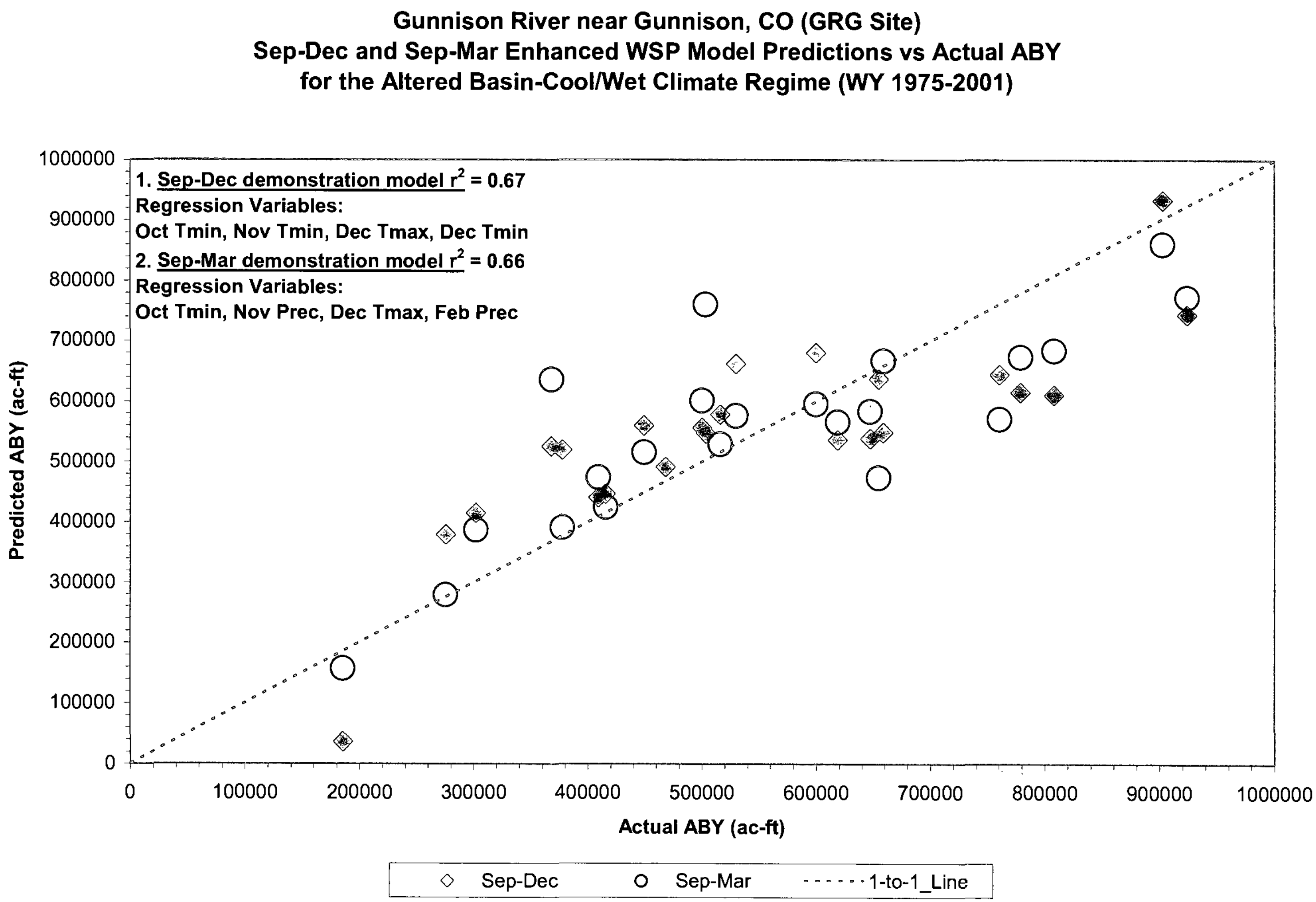


Figure 3.13 Sep-Dec and Sep-Mar Enhanced WSP models during the Altered Basin-Cool/Wet climate regime are also reasonably accurate and explain 66%-67% of the variance in ABY. Similar to the previous two climate regimes, the Enhanced WSP models also tend to over-predict in drier years and under-predict in wetter years. Enhanced WSP models are in Table 3.14.

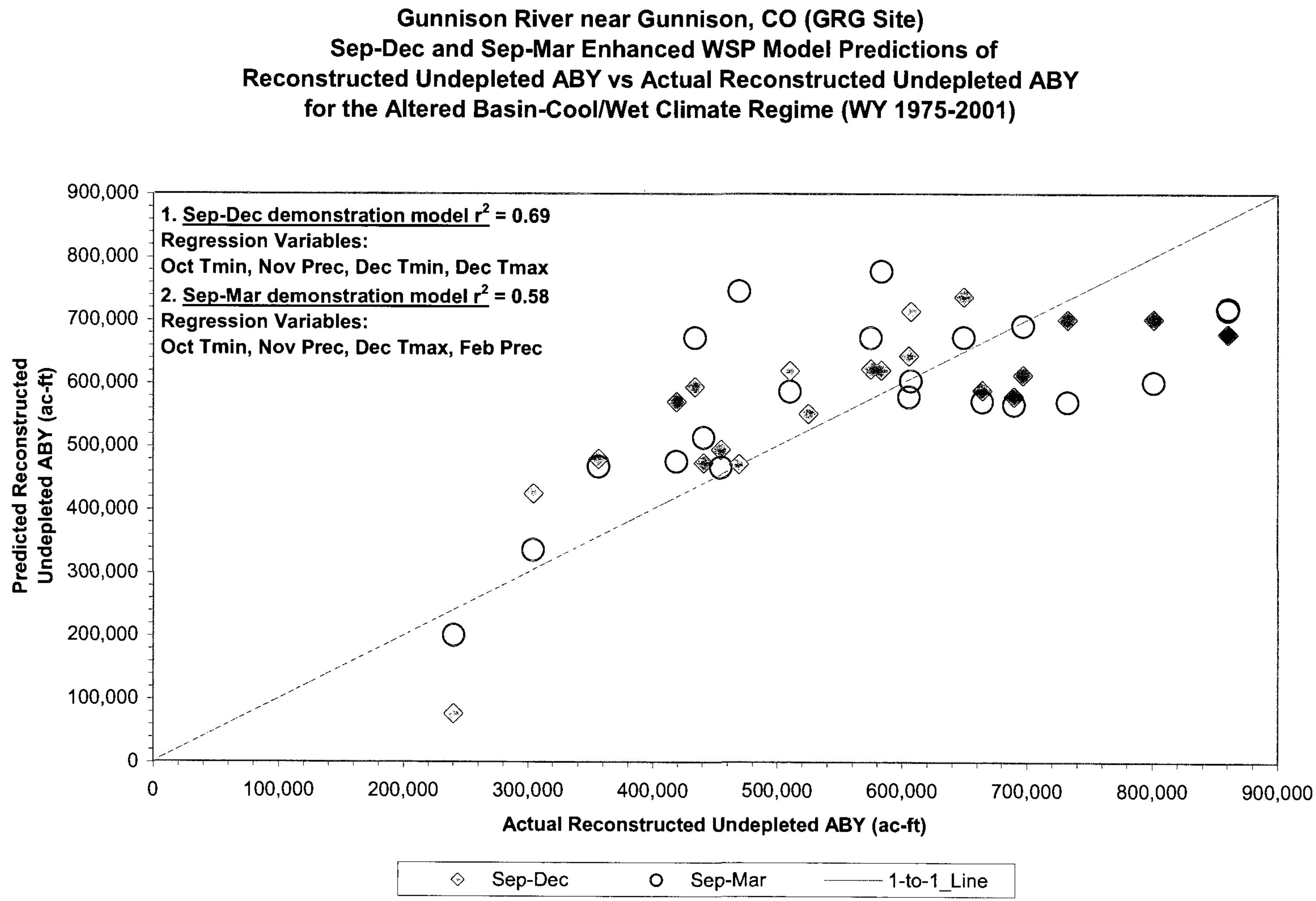


Figure 3.14 Similar to results for actual gauge ABY for the AB-Cool/Wet climate regime, the Sep-Dec and Sep-Mar Enhanced WSP models tend to over- and under-predict Reconstructed Undepleted ABY for the same climate regime. Adjusting flows for water management activities does not improve predictions of ABY, suggesting that additional factors are affecting relationships among streamflow and hydroclimate.

CHAPTER 4: APPLICATIONS

4.1 Introduction

Multiple linear regression models (i.e., the Enhanced WSP models) developed from characteristics of the complementary T and P patterns to predict ABY for each climate regime demonstrate that the unique Sep-Mar complementary temperature and precipitation patterns may be used to accurately predict ABY during each climate regime for two tributary basins in the Upper CRB. The results also show that significant predictive information related to upcoming precipitation and ABY is typically evident in the fall and detectable as early as September, instead of December-March. Thus, well before substantial snow accumulation, significant indications of upcoming ABY are available up to six months prior to the most reliable water supply forecast on April 1. However, rather than forecasting ABY, the NWS forecasts are for April-July flow volumes, which is most of the snowmelt runoff. For that reason, the objective of this study is to apply the same methodology and develop Sep-Dec and Sep-Mar Enhanced WSP models to predict April-July flow volumes for the AB-Cool/Wet climate regime (WY 1975-2001), and to compare model predictions to actual NWS forecasts for January 1 and April 1 to determine: (a) whether the methodology accurately predicts Apr-Jul flow volumes; and (b) how the accuracy of the Enhanced WSP models and NWS forecasts compare. The Enhanced WSP models were developed only for the AB-Cool/Wet climate regime because NWS Apr 1 forecasts are available for the YRS and GRG sites since WY 1991, and Jan 1 forecasts for the two sites are available since WY 2004.

4.2 Methods

This study uses the September-December complementary T and P patterns for the AB-Cool/Wet climate regime at the YRS and GRG sites to develop two demonstration multiple linear regression, or Enhanced WSP, models to predict Apr-Jul flow volumes for the AB-Cool/Wet climate regimes at the YRS and GRG sites. Temperature and precipitation characteristics for September-December comprise the Sep-Dec Enhanced WSP model, and likewise, temperature and precipitation characteristics for September-March comprise the Sep-Mar Enhanced WSP models.

Sep-Dec and Sep-Mar Enhanced WSP model predictions of Apr-Jul flow volumes are compared to the NWS coordinated water supply forecasts for January 1 and April 1, respectively. Accuracy of the EW Enhanced WSP model predictions were assessed by comparing the percentages of Enhanced WSP model predictions that are within 15% and 20% of actual Apr-Jul flow volumes, and accuracy of NWS forecasts were assessed in the same way. January 1 (Jan 1) NWS forecasts for the GRG and YRS sites are available since WY 2004, and the April 1 (Apr 1) NWS forecasts are available since 1991 at the YRS and GRG sites.

In addition to the AB-Cool/Wet climate regime of the 20th Century, Sep-Dec and Sep-Mar Enhanced WSP models were also developed for the warm/dry climate regime that began near the turn of the 21st Century, the Altered Basin (AB)-Warm/Dry-21 climate regime. The period of record is fairly short, and the complementary temperature and precipitation patterns associated with the AB-Warm/Dry-21 climate regime may continue to evolve throughout the warm/dry climate regime as the climate regime changes, for example due to PDO changing phase. The objectives of developing the

Enhanced WSP models for the AB-Warm/Dry-21 climate regime differ from those for the three climate regimes of the 20th Century. Enhanced WSP models for the AB-Warm/Dry-21 climate regime were developed to determine whether complementary temperature and precipitation patterns accompanying the AB-Warm/Dry-21 climate regime established relatively early in the climate regime, and to estimate the accuracy of the Enhanced WSP models in predicting Apr-Jul flow volume for WY 2002-2009 at the GRG and YRS sites.

The Sep-Dec and Sep-Mar Enhanced WSP model predictions for the entire AB-Cool/Wet climate regime, WY 1975-2001, are compared to actual Apr-Jul flows to determine model accuracy. Since NWS Apr 1 forecasts are available for WY 1991-2001 at the GRG and YRS sites, Sep-Mar (Apr 1) Enhanced WSP model predictions are compared to NWS Apr 1 forecasts during that time. Similarly, NWS Jan 1 forecasts are available for WY 2004-2009 at the YRS and GRG sites, so Sep-Dec Enhanced WSP model predictions for WY 2002-2009 are compared to NWS Jan 1 forecasts.

The same methodology applied to the actual gauge flows is also applied to the CWCB reconstructed undepleted flows to determine: (a) if the climate signals are evident in the undepleted flows, and to determine whether using reconstructed undepleted flow data improves accuracy of predictions.

4.3 Results

4.3.1 Model Predictions and Actual Apr-Jul Flow Volumes for WY 1975-2001

Table 4.1 summarizes percents of Enhanced WSP model predictions of Apr-Jul flow volumes that are within 15% and 20% of actual Apr-Jul flow volumes for WY

1975-2001 at the YRS and GRG sites. Also, Enhanced WSP model predictions versus actual Apr-Jul flow volumes are illustrated in Figures 4-1 and 4.5, and the Enhanced WSP model equations are presented in Table 4.4. Like the Enhanced WSP models to predict ABY, four temperature and precipitation variables comprise the Enhanced WSP models to predict Apr-Jul flow volumes. Although the Sep-Dec models for cool/wet climate regimes at the YRS and GRG sites typically include temperature or precipitation conditions for nearly every month between September and December, the Sep-Mar Enhanced WSP models typically include temperature and precipitation conditions primarily for September to December, plus January or February, as shown in Table 4.1.

The Enhanced WSP models explain 69%-72% and 55%-76% of the variance in Apr-Jul flow volumes at the YRS and GRG sites, respectively. Like the Enhanced WSP models for ABY, model accuracy is higher for the YRS site than the GRG site, and the Sep-Dec Enhanced WSP models for the YRS and GRG sites explain proportionately more variance in Apr-Jul flow volumes than the Sep-Mar Enhanced WSP models.

Approximately 65% and 70% of Enhanced WSP model predictions of the Sep-Dec and Sep-Mar Enhanced WSP models, respectively, are within 15% of actual Apr-Jul flow volumes at the YRS site, and approximately 74% of model predictions of both models are within 20% of actual flow volumes. Figure 4.1 shows that the Sep-Dec Enhanced WSP model is fairly accurate in predicting Apr-Jul flow volumes during the AB-Cool/Wet climate regime at the YRS site, thus the time period, September-December, leading up to the primary snow accumulation period, or December-March, provides significant indications of upcoming snowmelt runoff. The Sep-Mar Enhanced

WSP model tends to be more accurate when conditions are drier during the AB-Cool/Wet climate regime.

Accuracy of the Sep-Dec and Sep-Mar Enhanced WSP models is lower for the GRG site than for the YRS site, and the models tend to over-predict in drier conditions and under-predict in wetter conditions (see Figure 4.5). Approximately 29%-50% and 38%-59% of Enhanced WSP model predictions are within 15% and 20%, respectively, of actual Apr-Jul flow volumes. The results are consistent with those for ABY, although the models are more accurate at predicting ABY than Apr-Jul flow volumes. The tendency of the Enhanced WSP models for the GRG site to over- and under-predict during drier and wetter conditions, respectively, suggests that water losses (e.g., evaporation, transpiration, and channel losses) in the upper Gunnison River Basin may vary with changes in climate regimes, and the variations in water losses may be exacerbated by external forcings, including anthropogenic climate change, solar variability, water management and use activities, and land cover and land use changes. Consequently, the Enhanced WSP models do not completely capture the relationship between streamflow variability (i.e., natural and variability induced by external forcings) and temperature and precipitation. Also, because predictions of ABY tend to be more accurate than those of Apr-Jul flow volumes, water losses may be relatively more variable between April and July compared to the entire year.

4.3.2 Model Predictions and NWS Forecasts of Apr-Jul Flow Volumes for WY 1991-2001

Accuracy of Enhanced WSP model predictions and NWS forecasts of Apr-Jul flow volumes for WY 1991-2001 (late AB-Coo/Wet climate regime) for the YRS and GRG sites are summarized in Table 4.2. Approximately 78% and 100% of Jan 1 (Sep-Dec) and Apr 1 (Sep-Mar) Enhanced WSP model predictions, respectively, for the YRS site are within 15% of actual Apr-Jul flow volumes, compared to 36% of NWS Apr 1 forecasts that are within 15% of actual flow volumes. NWS Jan 1 forecasts are not available for this time period. When model predictions and NWS forecasts are assessed within 20% of actual Apr-Jul flow volumes, accuracy increases for Jan 1 Enhanced WSP model predictions and NWS Apr 1 forecasts. About 89% of Jan 1 and 100% of Apr 1 Enhanced WSP model predictions are within 20% of actual Apr-Jul flow volumes, and 91% of NWS Apr 1 forecasts are within 20% of actual flow volumes at the YRS site. Figure 4.2 shows that in general, Jan 1 and Apr 1 Enhanced WSP model predictions (solid diamonds and circles, respectively) tend to be more accurate than NWS Apr 1 forecasts (open circles) during moderate conditions, and NWS Apr 1 forecasts tend to be more accurate during extreme conditions at the YRS site.

Like the entire WY 1975-2001 period of record, accuracy of the WY 1991-2001 Enhanced WSP models is lower for the GRG site than for the YRS site. Approximately 22% and 50% of Jan 1 and Apr 1 Enhanced WSP model predictions, respectively, are within 15% of actual Apr-Jul flow volumes, compared to 64% of NWS Apr 1 forecasts that are within 15% of actual flow volumes (see Table 4.2). Accuracy of the Apr 1 Enhanced WSP model predictions and NWS Apr 1 forecasts are about equal when assessed within 20% of actual Apr-Jul flow volumes. Figure 4.6 shows that the Enhanced WSP models for WY 1991-2001 at the GRG site tend to over-predict in drier years and under-predict in wetter years, and overall, the Apr 1 Enhanced WSP model is more accurate than the Jan 1 model. The NWS Apr 1 forecasts tend to be more accurate than Enhanced WSP model predictions during drier conditions, but may tend to under-predict during wetter conditions, similar to the Enhanced WSP models.

4.3.3 Enhanced WSP Model Predictions and NWS Jan 1 and Apr 1 Forecasts for WY 2002-2009

The objective of developing Enhanced WSP models for the WY 2002-2009, the early part of the ongoing AB-Warm/Dry-21 climate regime, was to determine whether complementary temperature and precipitation patterns that evolve between September and March and are associated with upcoming water supply established early in the AB-Warm/Dry-21 climate regime, and to estimate the accuracy of the Enhanced WSP models. The Jan 1 and Apr 1 Enhanced WSP models are comprised of two regression variables, as opposed to four variables used in the Enhanced WSP models for WY 1975-2001, the AB-Cool/Wet climate regime of the 20th Century. Despite the relatively short period of record of the ongoing AB-Warm/Dry-21 climate regime, the Jan 1 and Apr 1 Enhanced WSP models are reasonably accurate at predicting Apr-Jul flow volumes, and typically outperform NWS forecasts for the YRS and GRG sites (see Table 4.2). Plus, the Jan 1 Enhanced WSP models are equally or more accurate than the Apr 1 models for the YRS and GRG sites.

Approximately 71% and 57% of Jan 1 and Apr 1 Enhanced WSP model predictions, respectively, are within 15% of actual Apr-Jul flow volumes, compared to 33% and 50% of NWS Jan 1 and Apr 1 forecasts, respectively, that are with 15% of actual flow volumes at the YRS site. When model predictions and forecasts are assessed within 20% of actual Apr-Jul flow volumes, the NWS forecast outperform Enhanced WSP model predictions. Approximately 71% of Jan 1 and Apr 1 Enhanced WSP model predictions are within 20% of actual Apr-Jul flow volumes, compared to 88% of NWS Apr 1 forecasts that are within 20% of actual flow volumes. Jan 1 and Apr 1 Enhanced WSP model predictions (solid figures in Figure 4.3) are reasonably accurate for the YRS site, but the Jan 1 Enhanced WSP model tends to be more accurate than the Apr 1 model, plus the Enhanced WSP models typically outperform NWS forecasts.

Enhanced WSP model predictions and NWS forecasts for the GRG site are less accurate than those for the YRS site during WY 2002-2009, although accuracy improves when predictions and forecasts are assessed within 20% of actual Apr-Jul flow volumes. Some of the flow records are affected by ice between September and March during WY 2002-2009, which may be an additional factor affecting Enhanced WSP model accuracy. Nonetheless, the Jan 1 and Apr 1 Enhanced WSP models explain 88% and 70% of variance in Apr-Jul flow volumes. Approximately 38% of Jan 1 and Apr 1 Enhanced WSP model predictions are within 15% of actual Apr-Jul flow volumes, but 75% and 50% of Jan 1 and Apr 1 Enhanced WSP model predictions, respectively, are within 20% of actual flow volumes at the GRG site. In comparison, 20% and 14% of NWS Jan 1 and Apr 1 forecasts, respectively, are with 15% of actual Apr-Jul flow volumes, and 20% and 29% of Jan 1 and Apr 1 forecasts are within 20% of actual flow volumes. Figure 4.7

shows that, overall, the Jan 1 and Apr 1 Enhanced WSP models accurately predict Apr-Jul flow volumes, and the models outperform NWS forecasts. Similar to results for the YRS site, the Jan 1 Enhanced WSP model is equally or more accurate than the Apr 1 Enhanced WSP model. The WY 2002-2009 Enhanced WSP models do not exhibit strong tendencies to over- and under-predict during drier and wetter conditions, respectively, as observed in results for WY 1991-2001. In contrast, the NWS Jan 1 and Apr 1 forecasts tend to over-predict in drier conditions, similar to Enhanced WSP models for WY 1991-2001.

Overall, the Jan 1 and Apr 1 regression models are reasonably accurate at predicting Apr-Jul flow volumes for WY 1975-2001 and WY 2002-2009 at the YRS and GRG sites, and the Enhanced WSP model results are generally more accurate for the YRS site than for the GRG site. Typically, Jan 1 Enhanced WSP models for WY 1991-2001 and WY 2002-2009 outperform NWS Jan 1forecasts for both sites, and the Apr 1 Enhanced WSP model predictions are equally or more accurate than NWS Apr 1 forecasts.

4.3.4 Enhanced WSP Model Predictions of Reconstructed Undepleted Flows

The same Enhanced WSP models applied to actual gauge data were also applied to the reconstructed undepleted flow data for the YRS and GRG sites to predict Apr-Jul reconstructed undepleted flow volumes for WY 1975-2001 to determine: (a) if the climate signal for the AB-Cool/Wet climate regime is also evident in the reconstructed undepleted flows; and (b) whether adjusting actual gauge flows for water management and other activities improves Enhanced WSP model predictions. Characteristics of the

Sep-Dec (Jan 1) and Sep-Mar (Apr 1) Enhanced WSP models and accuracy of predictions are summarized in Table 4.3, and the Enhanced WSP model equations are shown in Table 4.4. Sep-Dec and Sep-Mar model predictions of reconstructed undepleted Apr-Jul flow volumes are plotted against actual reconstructed undepleted Apr-Jul flow volumes in Figures 4.4 and 4.8 for the YRS and GRG sites, respectively.

Overall, the reconstructed undepleted flow Enhanced WSP models accurately predict undepleted Apr-Jul flow volumes for the YRS and GRG sites, and Enhanced WSP model predictions of undepleted flow volumes are typically about as accurate as Enhanced WSP model predictions of actual gauge flows for WY 1975-2001. In one case for the GRG site, Enhanced WSP model predictions of reconstructed undepleted Apr-Jul flow volumes are more accurate than those for actual gauge flows. Approximately 46% of Jan 1 and 74% of Apr 1 Enhanced WSP model predictions of reconstructed undepleted Apr-Jul flow volumes are within 20% of actual reconstructed undepleted Apr-Jul flow volumes, compared to 38% and 59% of Jan 1 and Apr 1 model predictions of gauge Apr-Jul flow volumes, respectively, that are within 20% of actual volumes. Figure 4.8 illustrates that the Enhanced WSP models also tend to over-predict reconstructed undepleted Apr-Jul flow volumes during drier conditions and under-predict during wetter conditions, as exhibited by Enhanced WSP model predictions of gauge Apr-Jul flow volumes.

Since the accuracy of Enhanced WSP models in predicting reconstructed undepleted Apr-Jul flow volumes is similar to that for gauge flows, and the Enhanced WSP models also tend to over- and under-predict both reconstructed undepleted and actual Apr-Jul flow volumes, then adjusting gauge flows for water management activities and other factors does not substantially improve water supply forecasts. This may be due to not accounting or incorrectly accounting for all effects of anthropogenic activities (e.g., modifications to land use, land cover, and water use), and how the effects vary with climate regimes and climate change in developing reconstructed undepleted flow data.

The NWS coordinated forecasts are based on "natural flows," which are akin to CWCB reconstructed undepleted flows except the computation of natural flows entails additional adjustments to the gauge flows, and the data are at monthly time increments, rather than daily. Results of this study suggest that computation of reconstructed undepleted or natural flows may not correctly account for water losses and gains within the two basins and how they vary with climate regimes, anthropogenic climate change and other factors. Accuracy of water supply forecasts decreased over the 20th Century in the CRB (Pagano et al., 2004; Jain et al., 2005), which may be associated in part with how accurately water losses and gains associated with modifications in land use, land cover and water use are represented in computing natural flow data sets, and how the losses and gains vary with climate regimes and climate change.

4.4 Summary and Conclusions

Overall, results of this study show that the Sep-Dec and Sep-Mar Enhanced WSP models accurately predict Apr-Jul flow volumes during the AB-Cool/Wet climate regime for the YRS and GRG sites, and Enhanced WSP model predictions compare favorably to NWS Jan and Apr 1 forecasts. Sep-Dec (Jan 1) Enhanced WSP model predictions are generally more accurate than NWS Jan 1 forecasts, demonstrating that temperature and precipitation conditions leading up to the main snow accumulation season are evolving complementary conditions in temperature and precipitation that are associated with the relative magnitude of the upcoming snowpack and Apr-Jul flow volumes.

The Enhanced WSP model results for actual gauge flow volumes at the YRS and GRG sites are generally as or more accurate than Enhanced WSP model predictions of reconstructed undepleted flow volumes. Hence, adjusting actual gauge flows for water management activities and other factors does not substantively improve Enhanced WSP model predictions of Apr-Jul flow volumes. Reasons that may explain in part why the accuracy of the Enhanced WSP model predictions of reconstructed undepleted Apr-Jul flow volumes is often lower than model predictions of actual gauge flow volumes may involve accurately estimating water losses related to anthropogenic activities and how the losses vary with climate regimes and anthropogenic climate change.

The influence of changes in land and water resources on water losses in the basin and subsequent effects on temperature and precipitation relationships with variations in streamflow may be most evident in the upper Gunnison River Basin. Enhanced WSP model predictions for the YRS site are more accurate than those for the GRG site, and NWS forecasts are also generally lower for the GRG site than for the YRS site. When model predictions and NWS Apr 1 forecasts are compared within 15% of actual Apr-Jul flow volumes, NWS Apr 1 forecasts outperform Sep-Mar (Apr 1) Enhanced WSP model predictions. But accuracy of Enhanced WSP model predictions and forecasts are essentially equal when compared within 20% of actual flow volumes.

Accuracy of the Enhanced WSP models tends to be higher for the YRS site than the GRG site, and accuracy also tends to be higher for predicting ABY than Apr-Jul flows at the GRG site. The differences in Enhanced WSP model accuracy between the two sites may be related to differences in physiography, as well as differences in the type and rate of changes in land use, land cover, and water use and management between the upper Yampa and Gunnison river basins. Combined effects of physiographic characteristics and type and rates of change in land and water resources in the upper Yampa River Basin may have been such that the relationship between variations in streamflow and hydroclimatic conditions has remained fairly steady. Accordingly, Enhanced WSP model accuracy is reasonably high. In contrast, physiographic characteristics of the upper Gunnison River Basin, including permeable soils (CSU Cooperative Extension, 2000) and characteristic valley drainage winds (Sato and Kondo, 1988), may predispose hydrologic processes in the upper Gunnison Basin to be more susceptible to effects of changes in climate, land use, land cover, and water use. Diversions from headwater areas of the upper Gunnison Basin to the east slope of Colorado, timber harvesting and clearing for ski areas and other development, as well as water management activities and associated water losses affect total water losses in the system. Water losses associated with water management activities include evaporation and seepage from reservoir storage, losses related to change in timing of releases, transmission losses, and water losses application of water for urban and agricultural irrigation. The magnitude of water losses also varies with changes in climate, including changes in climate regimes and anthropogenic climate change, so losses may be greater in drier conditions and lower in wetter conditions. Correspondingly, the Enhanced WSP models tend to over-predict in drier years and under-predict in wetter years.

In addition, the Enhanced WSP models for the GRG site may predict ABY more accurately than Apr-Jul flow volumes because of upstream reservoir storage and diversions that occurs between April and July, thereby affecting Apr-Jul flow volumes, but reservoir releases are made and return flows to the river occur throughout the growing season, so total annual flow volumes are more representative of hydroclimatic conditions. Results of this research suggest that the relatively high hydroclimatic variability in the upper Gunnison River Basin (Woodhouse, 2003) and lower forecast accuracy may then be due more to combined effects of modifications to land and water resources in the basin and changes in climate (i.e., changes in climate regime and anthropogenic climate change) than to climatic variability alone.

Application of the Sep-Dec and Sep-Mar Enhanced WSP models to predict Apr-Jul flow volumes for YRS and GRG sites during WY 2002-2009, the earlier part of the ongoing AB-Warm/Dry-21 climate regime, shows that complementary T and P patterns accompanying the climate regime and associated with upcoming Apr-Jul flow volumes establish early in the climate regime. However, while the complementary T and P patterns may establish early, they may also continue to evolve as climate modes change phase or due to solar variability during the climate regime. The Enhanced WSP models explain 70%-85% of variance in Apr-Jul flow volumes at the two sites, and the Sep-Dec Enhanced WSP models explain more variance in Apr-Jul flows than the Sep-Mar Enhanced WSP models at both sites. Hydroclimatic conditions between September and December during warm/dry climate regimes or during the early stage of warm/dry climate regimes may be more indicative of upcoming precipitation and Apr-Jul flow volumes than hydroclimatic conditions between January and March.

In general, the Jan 1 and Apr 1 Enhanced WSP models are also equally or more accurate than NWS Jan 1 and Apr 1 forecasts. Lower accuracy of NWS forecasts during

WY 2002-2009 may be related to the 30-year reference period used to estimate long-term mean/median values for NWS forecast procedures. The 30-year reference period is typically the last 30 years, which in this case, entails more than half of the previous cool/wet climate regime. Since the complementary T and P patterns are different for the AB-Cool/Wet and AB-Warm/Dry-21 climate regimes, then estimating mean/median values for periods of record encompassing more than one climate regime or for climate regimes other than the current one is not likely to result in mean/median values that are representative of hydroclimatic patterns accompanying the current climate regime, which may adversely affect forecast accuracy.

In conclusion, the methodology may be incorporated into existing water supply forecast methods to improve forecast accuracy and increase lead time. Earlier and reasonably accurate forecasts, for example as early as October 1, may assist water managers, farmers, and municipalities in planning and using water more efficiently and effectively.

4.5 References

Archer, D., and Fowler, H., 2008. Using meteorological data to forecast seasonal runoff on the River Jhelum, Pakistan. Journal of Hydrology 361, 10-23.

Balling, R.C., Jr., and Goodrich, G.B., 2007. Analysis of drought determinants for the Colorado River Basin. Climate Change 82, 179-194.

Bounoua, L., Collatz, G.J., Los, S.O., Sellers, P.J., Dazlich, D.A., Tucker, C.J., Randall, D.A., 2000. Sensitivity of Climate to Changes in NDVI. Journal of Climate 12, 2277-2292.

Bounoua, L., Defries, R., Collatz, G.J., Sellers, P., Khan, H., 2002. Effects of Land Cover Conversion on Surface Climate. Climate Change 52, 29-64.

Cayan, D.R., Peterson, D.H., 1989. The influence of North Pacific atmospheric circulation on streamflow in the West. In: Aspects of Climate Variability in the Pacific and the Western Americas, D.H. Peterson (Ed.), Geophysical Mongraphs, No. 55, American Geophysical Union, 375-397.

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

Cayan, D.R., 1996. Interannual climate variability and snowpack in the Western United States. Journal of Climate 9, 928-948.

Chase, T.N., Pielke, R.A., Sr., Kittel, T.G.G., Baron, J.S., Stohlgren, T.J., 1999. Potential impacts on Colorado Rocky Mountain weather due to land use change on the adjacent Great Plains. Journal of Geophysical Research 104, 16673-16690.

Colorado State University (CSU) Cooperative Extension, 2000. Improving forage yields and quality in Colorado. Agronomy News 20, 1-14.

Feddema, J.J., Oleson, K.W., Bonan, G.B., Mearns, L.O., Buja, L.E., Meehl, G.A., Washington, W.M., 2005. The Importance of Land-Cover Change in Simulating Future Climates. Science 310, 1674-1678.

Grantz, K., Rajagopalan, B., Clark, M., Zogona, E., 2005. A technique for incorporating large-scale climate information in basin-scale ensemble streamflow forecasts. Water Resources Research 41, W10410, doi:10.1029/2004WR003467.

Hereford, R., Webb, R.H., and Graham, S., 2002. Precipitation History of the Colorado Plateau Region, 1900-2000. U.S. Geological Survey Fact Sheet 119-02, 1-4.

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

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jain, S., Hoerling, M., and Eischeid, J., 2005. Decreasing reliability and increasing synchroneity of Western North American streamflow. Journal of Climate 18, 613-618.

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.

Marland, G., R.A. Pielke Sr., M. Apps, R. Avissar, R.A. Betts, K.J. Davis, P.C. Frumhoff, S.T. Jackson, L. Joyce, P. Kauppi, J. Katzenberger, K.G. MacDicken, R. Neilson, J.O. Niles, D.D.S.

Meehl, G.A., Arblaster, J.M., 2009. A lagged warm event-like response to peaks in solar forcing in the Pacific Region. Journal of Climate 22, 3647-3660.

Pagano, T.P., Garen, D., and Sorooshian, S., 2004. Evaluation of Official Western U.S. Seasonal Water Supply Outlooks, 1922-2002. Journal of Hydrometeorology 5, 896-909.

Pielke, R.A., Avissar, R., 1990. Influence of landscape structure on local and regional climate. Landscape Ecology 4, 133-155.

Quiring, S.M. and Goodrich, G.G., 2008. Nature and causes of the 2002 to 2004 drought in the southwestern United States compared with the historic 1953 to 1957 drought. Climate Research 36, 41-52.

Sato, T., Kondo, J., 1988. A simple model of drainage flow in a valley. Boundary-Layer Meteorology 45, 355-369.

Soukup, T.L., Aziz, O.A., Tootle, G.A., Piechota, T.C., Wulff, S.S., 2009. Long lead-time streamflow forecasting of the North Platte River incorporating oceanic-atmospheric climate variability. Journal of Hydrology 368, 131-142.

Stohlgren, T.J., Chase, T.N., Pielke, R.A., Sr, Kittel, T.G.F., Baron, J.S., 2003. Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas. Global Change Biology 4, 495-504.

Stull, R.B., 1988. An Introduction to Boundary Layer Meteorology. Kluwer Academic Publishers. Dordrecht, The Netherlands. Pps. 1-2.

Woodhouse, C.A., 2003. A 431-yr reconstruction of western Colorado snowpack from tree rings. Journal of Climate 16, 1551-1560.

Table 4.1	GRG and YRS Sites Percent of Enhanced WSP Model Predictions of Apr-Jul Flow Volumes that are within 15% and 20% of Actual Apr-Jul Flow Volumes for WY 1975-2001							
Site & Period of Record	**Sep-Mar Regression Variables**	**r^2**	**% of Apr 1 Predictions w/i 15% of Actual Apr-Jul Q Vol**	**% of Apr 1 Predictions w/i 20% of Actual Apr-Jul Q Vol**	**Sep-Dec Regression Variables**	**r^2**	**% of Jan 1 Predictions w/i 15% of Actual Apr-Jul Q Vol**	**% of Jan 1 Predictions w/i 20% of Actual Apr-Jul Q Vol**
YRS								
1975-2001	- Sep Prec - Oct Prec - Dec Prec - Jan Prec	0.72	70%	74%	- Sep Prec - Oct Prec - Dec Tmin - Dec Prec	0.69	65%	74%
GRG								
1975-2001	- Oct Tmin - Nov Tmin - Dec Tmax - Feb Prec	0.76	50%	59%	- Oct Tmin - Nov Tmin - Nov Prec - Dec Tmax	0.55	29%	38%

Table 4.2 GRG and YRS Sites
Percent of Enhanced WSP Model Predictions and NWS Forecasts[1] of Apr-Jul Flow Volumes that are within 15% and 20% of Actual Apr-Jul Flow Volume for WY 1991-2001 and WY 2002-2009

Site & Period of Record	Sep-Mar Regression Variables	r^2	% of Apr 1 Predictions w/i 15% of Actual Apr-Jul Q Vol	% of Apr 1 NWS Forecast w/i 15% of Actual Apr-Jul Q Vol	Sep-Dec Regression Variables	r^2	% of Jan 1 Predictions w/i 15% of Actual Apr-Jul Q Vol	% of Jan 1 NWS Forecast[2] w/i 15% of Actual Apr-Jul Q Vol
YRS								
1991-2001	- Sep Prec - Oct Prec - Dec Prec - Jan Prec	0.72	100%	36%	- Sep Prec - Oct Prec - Dec Tmin - Dec Prec	0.69	78%	na
2002-2008	- Sep Tmin - Jan Prec	0.70	57%	50%	- Sep Tmin - Dec Prec	0.68	71%	33%[3]
GRG			Apr 1 Prediction	Apr 1 Forecast			Jan 1 Prediction	Jan 1 Forecast
1991-2001	- Oct Tmin - Nov Tmin - Dec Tmax - Feb Prec	0.76	50%	64%	- Oct Tmin - Nov Tmin - Nov Prec - Dec Tmax	0.55	22%	na
2002-2008	- Nov Prec - Jan Prec	0.76	38%	14%	- Nov Prec - Dec Tmax	0.85	38%	20%[3]

Site & Period of Record	Sep-Mar Regression Variables	r^2	% of Apr 1 Predictions w/i 20% of Actual Apr-Jul Q Vol	% of Apr 1 NWS Forecast w/i 20% of Actual Apr-Jul Q Vol	Sep-Dec Regression Variables	r^2	% of Jan 1 Predictions w/i 20% of Actual Apr-Jul Q Vol	% of Jan 1 NWS Forecast[2] w/i 20% of Actual Apr-Jul Q Vol
YRS Site								
1991-2001	- Sep Prec - Oct Prec - Dec Prec - Jan Prec	0.72	100%	91%	- Sep Prec - Oct Prec - Dec Tmin - Dec Prec	0.69	89%	na
2002-2008	- Sep Tmin - Jan Prec	0.70	71%	88%	- Sep Tmin - Dec Prec	0.68	71%	50%[3]
GRG Site								
1991-2001	- Oct Tmin - Nov Tmin - Dec Tmax - Feb Prec	0.76	63%	64%	- Oct Tmin - Nov Tmin - Nov Prec - Dec Tmax	0.55	22%	na
2002-2008	- Nov Prec - Jan Prec	0.76	50%	29%	- Nov Prec - Dec Tmax	0.85	75%	20%[3]

[1] NWS Coord Forecast = National Weather Service coordinates water supply forecasts with the Natural Resources Conservation Service (NRCS) and other entities.
[2] NWS Coord Forecasts are the "e50," or 50% probability of exceedance forecast.
[3] NWS Jan 1 forecasts available since 2004 for the GRG and YRS sites.

Table 4.3 — GRG and YRS Sites

Percent of Enhanced WSP Model Predictions of Reconstructed Undepleted Apr-Jul Flows that are within 15% and 20% of Actual Undepleted Apr-Jul Flow Volumes for WY 1975-2001

Site & Period of Record	Sep-Mar Regression Variables	r^2	% of Apr 1 Predictions of Undepleted Apr-Jul Flow Vol w/i 15% of Actual Undepleted Apr-Jul Q Vol	Sep-Dec Regression Variables	r^2	% of Jan 1 Predictions of Undepleted Apr-Jul Flow Vol w/i 15% of Actual Undepleted Apr-Jul Q Vol
YRS Site			Apr 1 Prediction			Jan 1 Prediction
1975-2001	- Sep Prec - Oct Prec - Dec Prec - Jan Prec	0.73	75%	- Sep Prec - Oct Prec - Oct Tmin - Dec Prec	0.68	67%
GRG Site			Apr 1 Prediction			Jan 1 Prediction
1975-2001	- Oct Tmin - Nov Tmin - Dec Tmax - Feb Prec	0.42	58%	- Oct Tmin - Nov Tmin - Nov Prec - Dec Tmax	0.59	42%

Percent of Enhanced WSP Model Predictions of Reconstructed Undepleted Apr-Jul Flows that are within 20% of Actual Undepleted Apr-Jul Flow Volumes for WY 1975-2001

Site & Period of Record	Sep-Mar Regression Variables	r^2	% of Apr 1 Predictions of Undepleted Apr-Jul Flow Vol w/i 15% of Actual Undepleted Apr-Jul Q Vol	Sep-Dec Regression Variables	r^2	% of Jan 1 Predictions of Undepleted Apr-Jul Flow Vol w/i 15% of Actual Undepleted Apr-Jul Q Vol
YRS Site			Apr 1 Prediction			Jan 1 Prediction
1975-2001	- Sep Prec - Oct Prec - Dec Prec - Jan Prec	0.73	79%	- Sep Prec - Oct Prec - Oct Tmin - Dec Prec	0.68	75%
GRG Site			Apr 1 Prediction			Jan 1 Prediction
1975-2001	- Oct Tmin - Nov Tmin - Dec Tmax - Feb Prec	0.60	74%	- Oct Tmin - Nov Tmin - Nov Prec - Dec Tmax	0.59	46%

Table 4.4

GRG and YRS Sites

Enhanced WSP Models for Actual Gauge Flows for WY 1975-2001, WY 2002-2009 and Reconstructed Undepleted Flows for WY 1991-2001 for the YRS and GRG Sites

Site and Period of Record	Sep-Dec Enhanced WSP Models	Sep-Mar Enhanced WSP Models
YRS Site		
WY 1975-2001	**Apr-Jul Q Vol** = 229 336 + 8 190*Sep Prec + 56 133*Oct Pre + (-5 822*Oct Tmin) + 32 286*Dec Prec	**Apr-Jul Q Vol** = 64 835 + 10 427*Sep Prec + 45 427*Oct Prec + 31 970*Dec Prec + 15 581*Jan Prec
WY 2002-2009	**Apr-Jul Q Vol** =-700 646 + 24 163*Sep Tmin + 39 022*Dec Prec	**Apr-Jul Q Vol** = - 742 712 + 24 949*Sep Tmin + 46 530*Jan Prec
Reconstructed Undepleted Flows WY 1975-2001	**Apr-Jul Q Vol** = 248 342 + 9 630*Sep Prec + 55 847*Oct Prec + (-4 928*Oct Tmin) + 33 402*Dec Prec	**Apr-Jul Q Vol** = 100 400 + 11 350*Sep Prec + 45 992*Oct Prec + 32 937*Dec Prec + 17 194*Jan Prec
GRG Site		
WY 1975-2001	**Apr-Jul Q Vol** = 48 750 + 17 575*Oct Tmin + 93 712*Nov Prec + 12 357*Nov Tmin + (-8 253*Dec Tmax)	**Apr-Jul Q Vol** = - 75 750 + 13 467*Oct Tmin + 20 095*Nov Tmin + (-7 335*Dec Tmax) + 253 630*Feb Prec
WY 2002-2009	**Apr-Jul Q Vol** = 717 927 + (-176 577*Nov Prec) + (-10 167*Dec Tmax)	**Apr-Jul Q Vol** = 376 272 + (-150 938*Nov Prec) + 61 695*Jan Prec
Reconstructed Undepleted Flows WY 1975-2001	**Apr-Jul Q Vol** = 114 197 + 20 464*Oct Tmin + 89 006*Nov Prec + 12 893*Nov Tmin + (-9 295*Dec Tmax)	**Apr-Jul Q Vol** = -16 296 + 25 463*Oct Tmin + 97 819*Nov Prec + (-6 684*Dec Tmax) + 140 364*Feb Prec

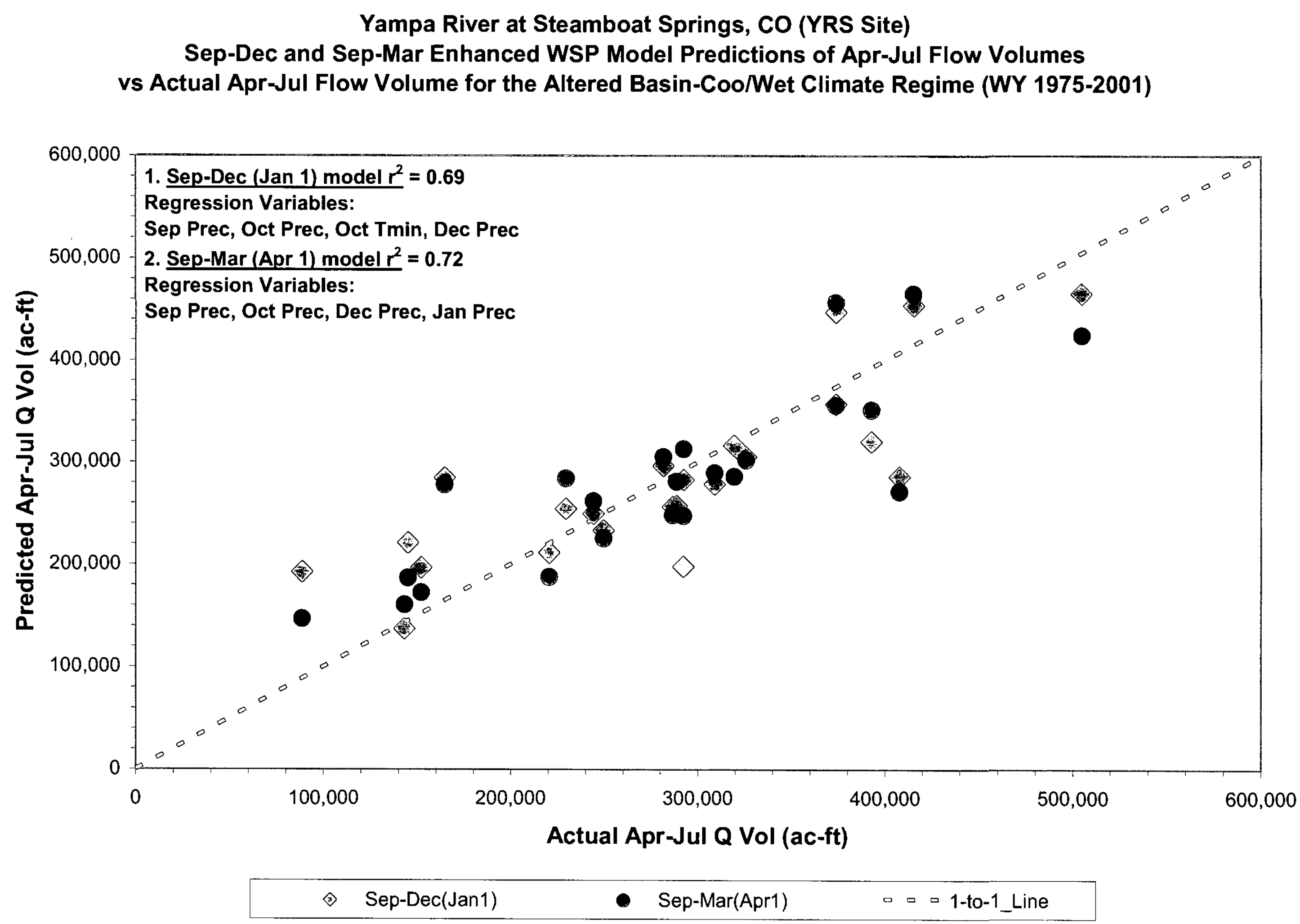


Figure 4.1 The Sep-Dec (diamonds) and Sep-Mar (circles) Enhanced WSP model predictions of Apr-Jul flow volumes are plotted against actual Apr-Jul flow volumes for WY 1975-2001 for the YRS site. The red line illustrates a one-to-one, or "perfect," model. Results for the Sep-Dec and Sep-Mar Enhanced WSP models explain similar amounts of variance in Apr-Jul flow volumes (69% and 72%, respectively), and they are reasonably accurate at predicting Apr-Jul flows. Enhanced WSP model equations are in Table 4.4.

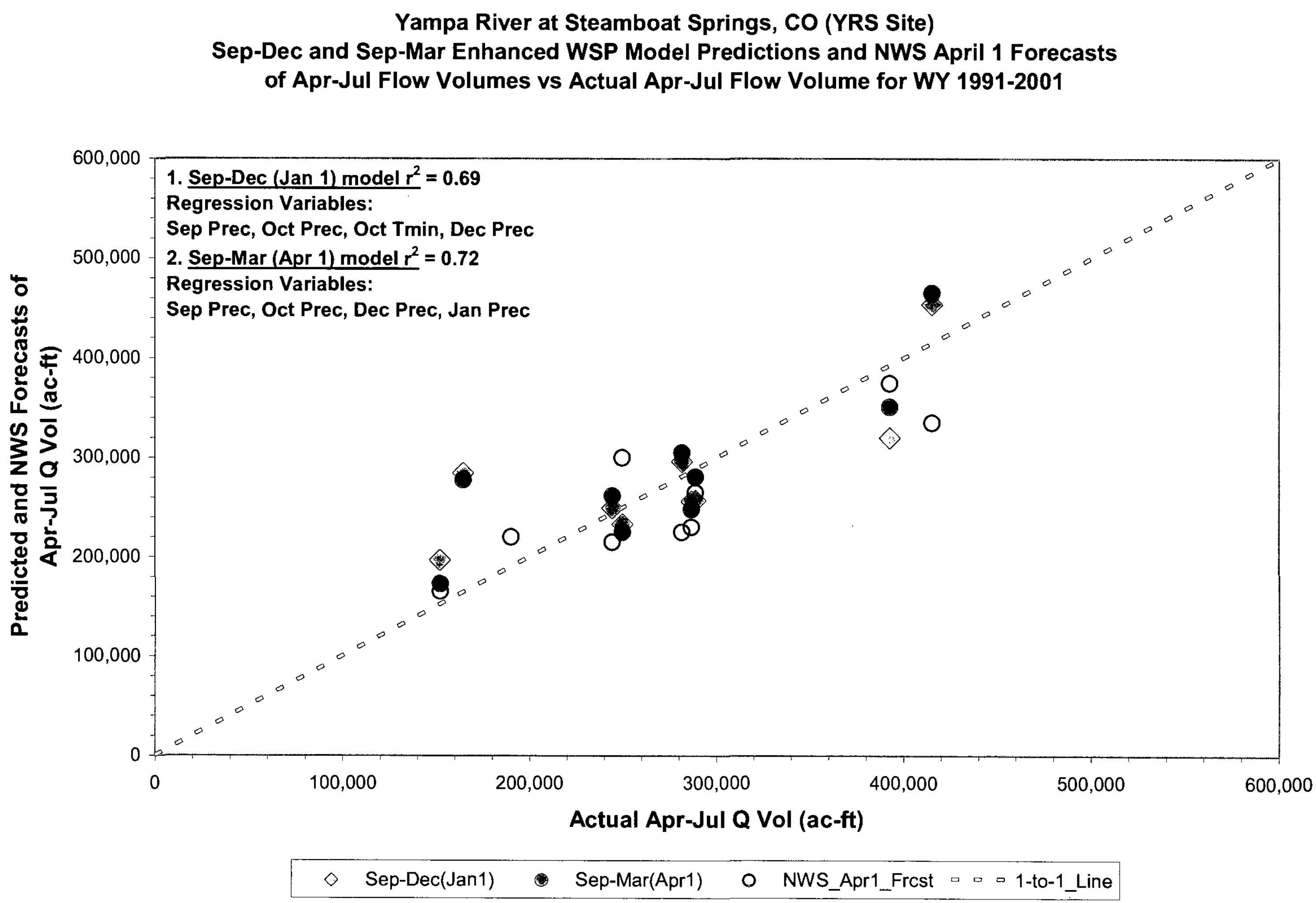


Figure 4.2 The Sep-Dec (Jan 1; diamonds) and Sep-Mar (Apr 1; circles) Enhanced WSP model predictions, and NWS Apr 1 forecasts (triangles) of Apr-Jul flow volumes plotted against actual Apr-Jul flow volumes for WY 1991-2001, the period of time when NWS Apr 1 forecasts are available for the YRS site. The Jan 1 and Apr1 Enhanced WSP model predictions tend to be more accurate than NWS forecasts during moderate conditions (center of the plot), but NWS Jan 1 forecasts tend to be more accurate during drier conditions (left side of the plot). Model equations are in Table 4.4.

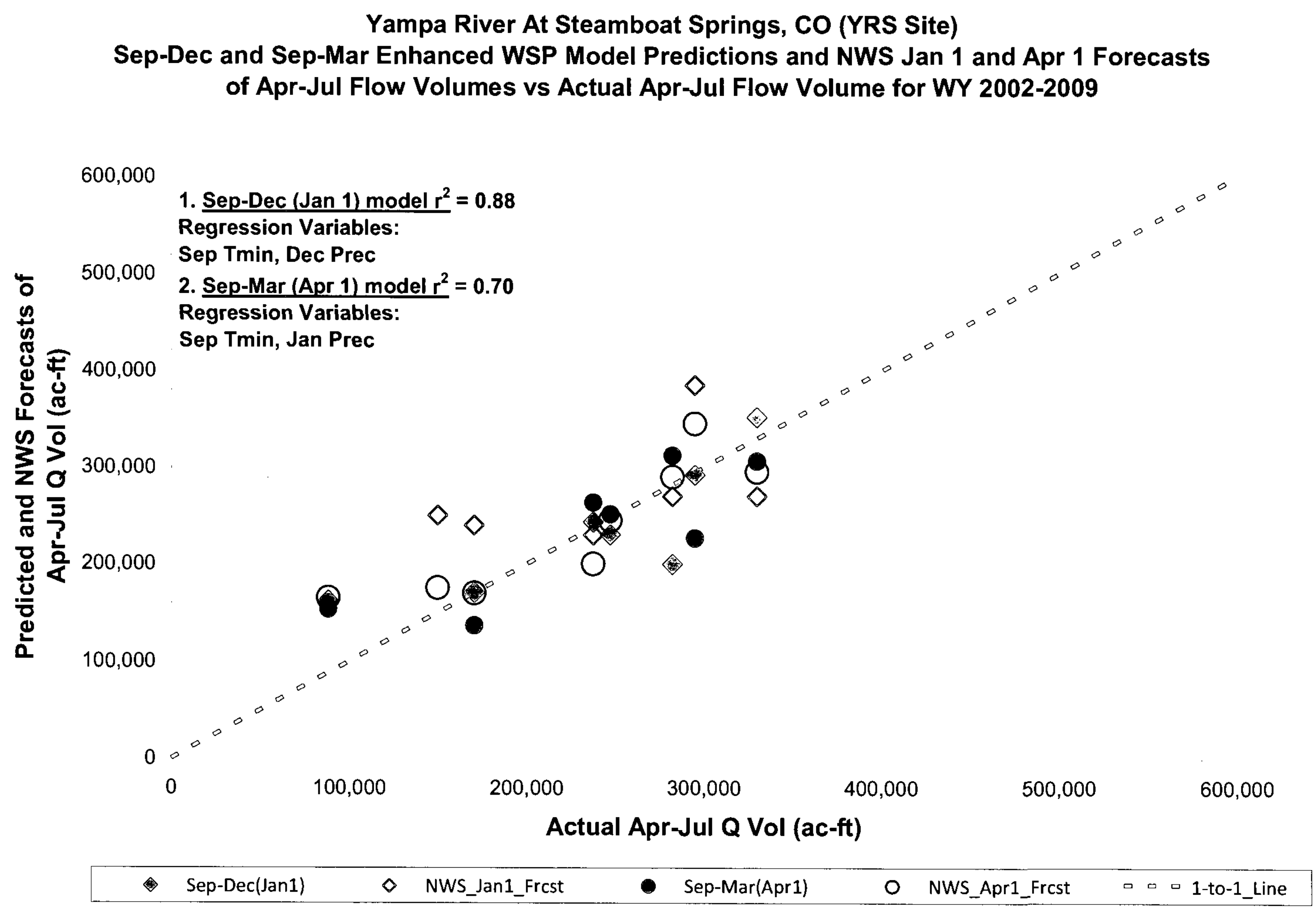


Figure 4.3 The Sep-Dec (Jan 1; diamonds) and Sep-Mar (Apr 1; circles) Enhanced WSP model predictions and NWS Jan 1 forecasts (open diamonds) and Apr 1 forecasts (open diamonds) of Apr-Jul flow volumes are plotted against actual Apr-Jul flow volumes for WY 2002-2009, when NWS Apr 1 and Jan1 forecasts are both available for the YRS site. The Jan 1 and Apr 1 Enhanced WSP models tend to be more accurate than NWS Jan 1 and Apr 1 forecasts. The Jan 1 Enhanced WSP model also explains more variance in Apr-Jul flow volumes than the Apr 1 model. Enhanced WSP model equations are in Table 4.4.

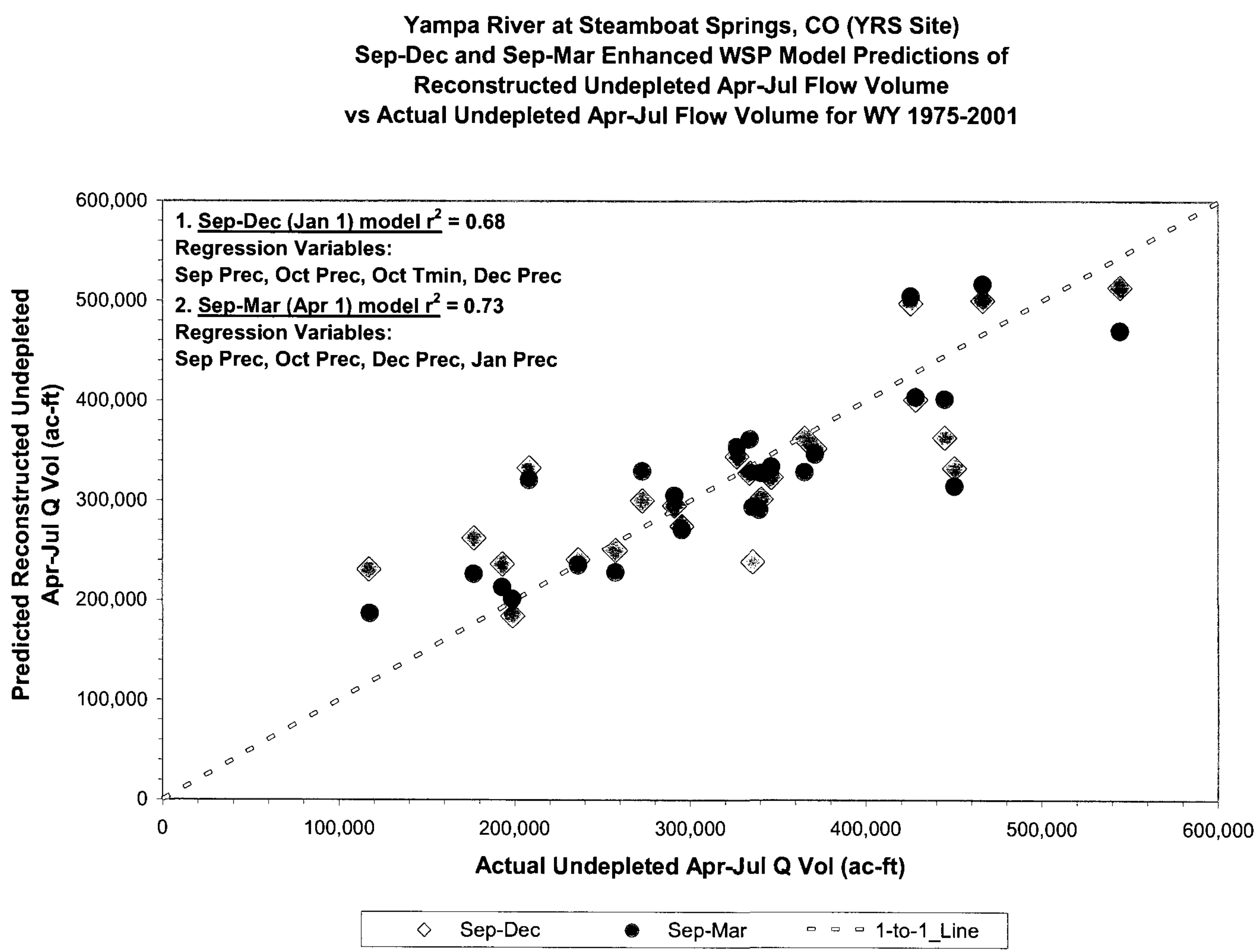


Figure 4.4 Sep-Dec (diamonds) and Sep-Mar (circles) Enhanced WSP model predictions of reconstructed undepleted Apr-Jul flow volume during the WY 1991-2001 at the YRS site are reasonably accurate, suggesting that the climate signal for the Alter Basin-Cool/Wet climate regime is evident in the reconstructed undepleted flows. Since the results for reconstructed undepleted flows and actual gauge flows (Figure 4.1) are similar, adjusting gauge flows for water management activities does not significantly improve predictions at the YRS site.

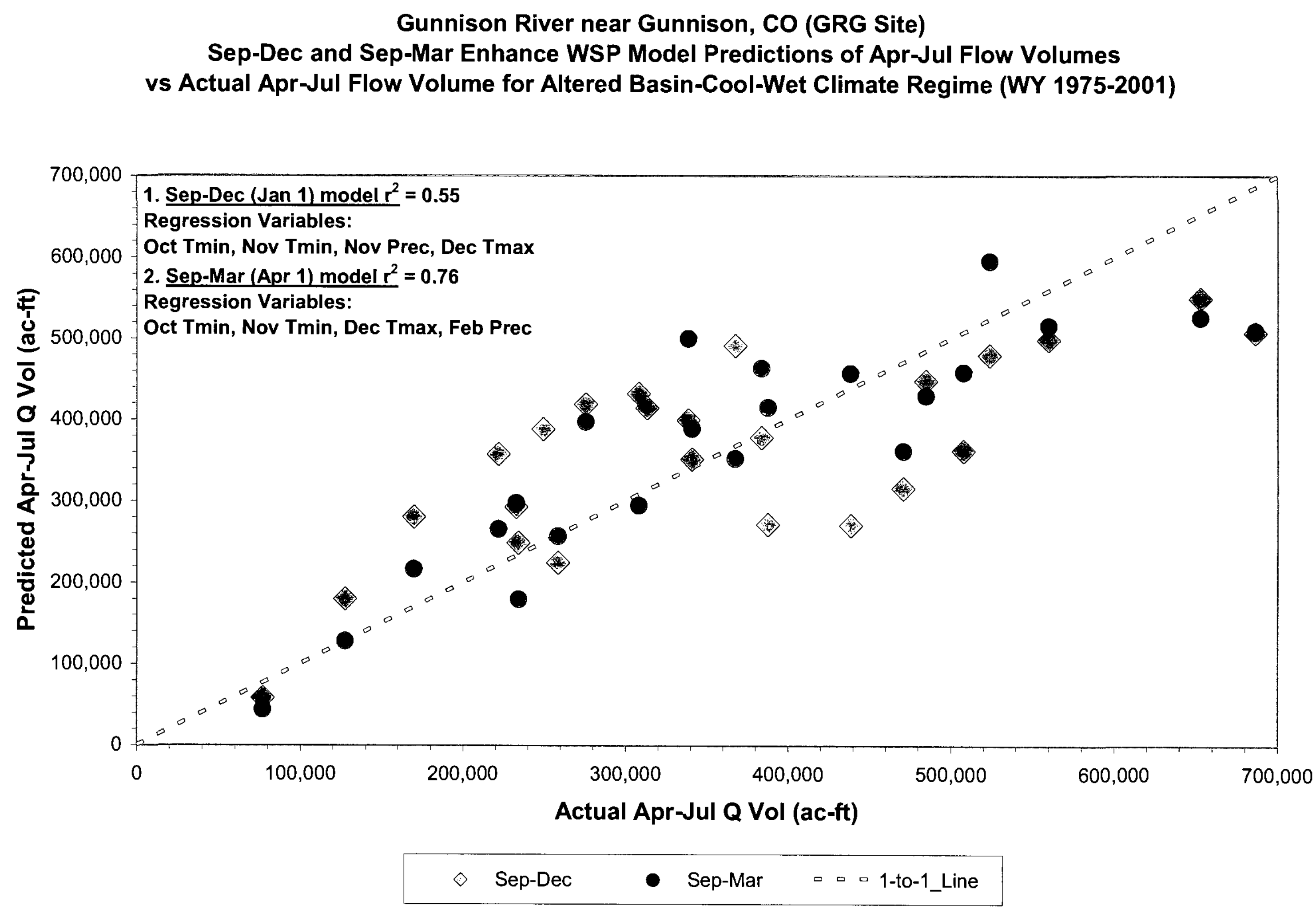


Figure 4.5 The Sep-Dec (solid diamond) and Sep-Mar (solid circles) model predictions of Apr-Jul flow volumes for WY 1975-2001 are plotted against actual Apr-Jul flow volumes. The Sep-Mar Enhanced WSP model explains more variance in Apr-Jul flow volumes and is more accurate than the Sep-Dec model. Both Enhanced WSP models tend to over-predict in drier conditions and under-predict in wetter conditions, although the tendencies are not as strong for the Sep-Mar model. Enhanced WSP model equations are in Table 4.4.

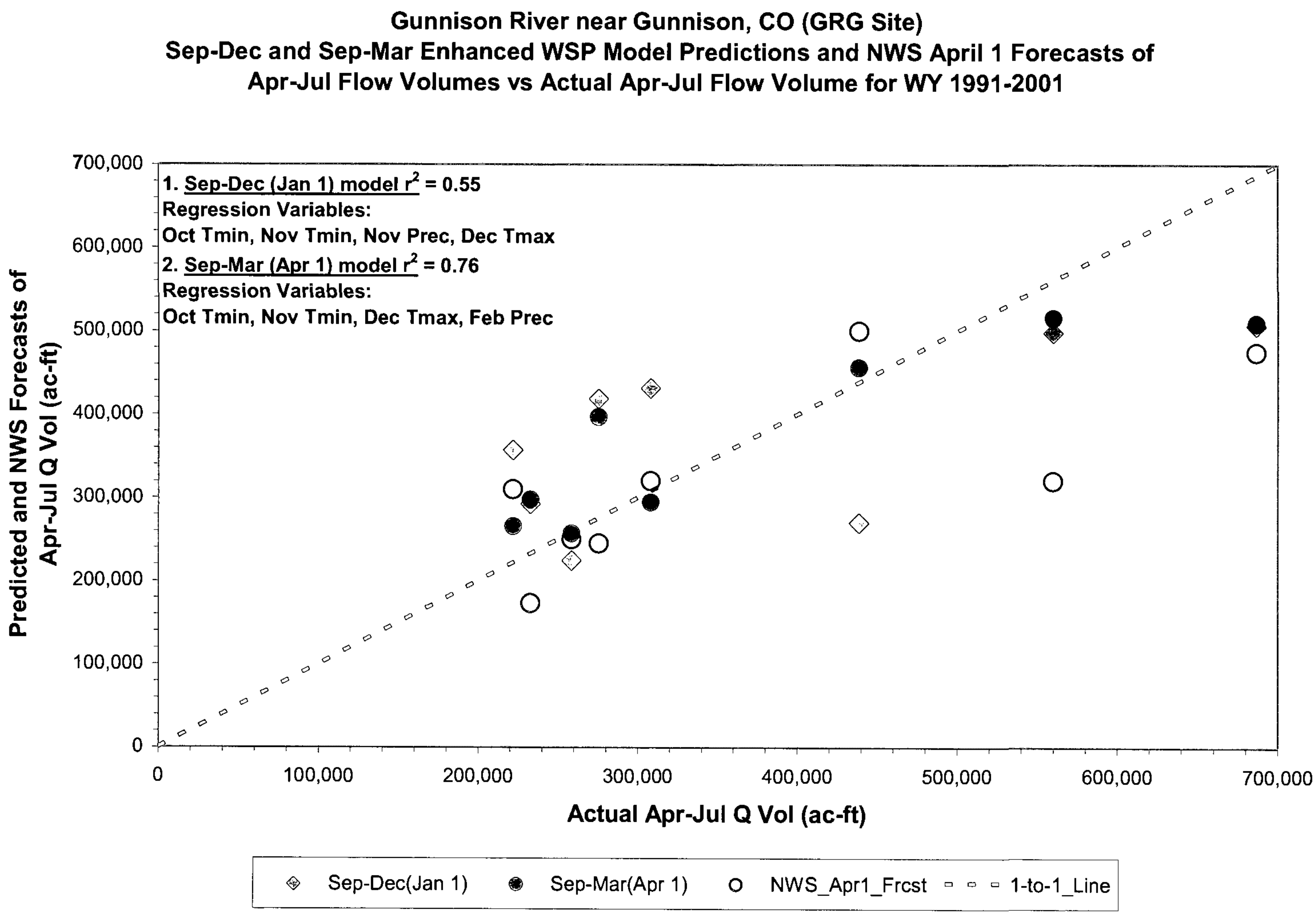


Figure 4.6 Sep-Dec (Jan 1; solid diamond) and Sep-Mar (Apr 1; solid circles) Enhanced WSP predictions and NWS Apr 1 forecasts of Apr-Jul flow volumes are plotted against actual Apr-Jul flow volumes for WY 1991-2001, when NWS Apr 1 forecasts are available for the GRG site. Similar to the Enhanced WSP model predictions, the NWS Apr 1 forecasts also exhibit some tendencies to over- and under-predict in drier and wetter conditions, respectively.

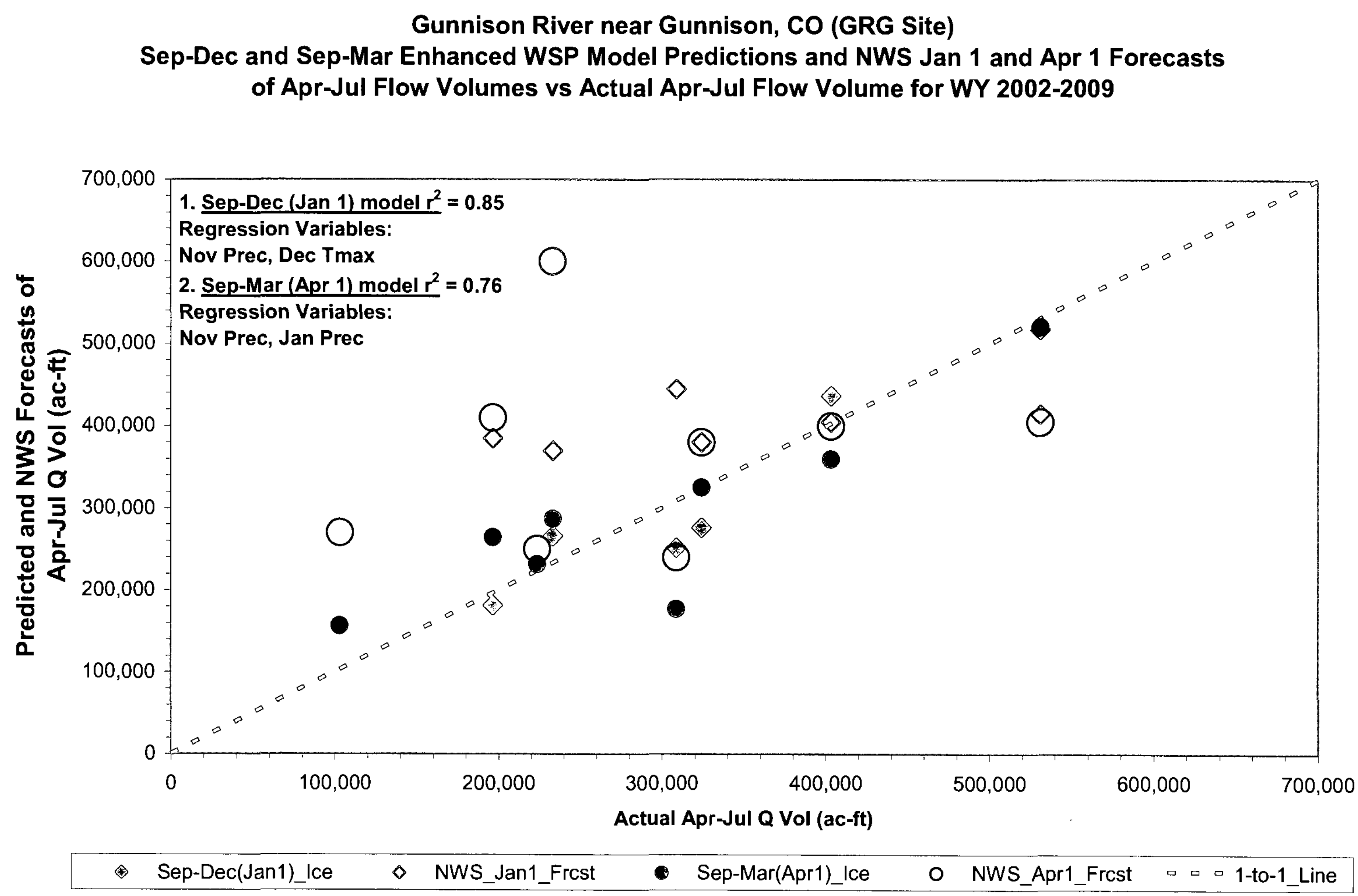


Figure 4.7 Sep-Dec (Jan 1; solid diamond) and Sep-Mar (Apr 1; solid circles) Enhanced WSP predictions and NWS Jan 1 and Apr 1 forecasts of Apr-Jul flow volumes are plotted against actual Apr-Jul flow volumes for WY 2002-2009, when NWS Jan 1 and Apr 1 forecasts are available for the GRG site. The Jan 1 Enhanced WSP model explains more variance and is more accurate in predicting Apr-Jul flow volumes than the Apr 1 Enhanced WSP model and NWS Jan 1 forecasts. The Jan 1 and Apr 1 Enhanced WSP models do not tend to under- and over-predict, as during the WY 1975-2001 period of record at the GRG site. But the NWS Jan 1 and Apr 1 forecasts tend to over-predict in drier years.

Gunnison River near Gunnison, CO (GRG Site)
Sep-Dec and Sep-Mar Enhanced WSP Model Predictions of
Reconstructed Undepleted Apr-Jul Flow Volume vs Actual Undepleted Apr-Jul Flow Volume
for the Altered Basin-Cool/Wet Climate Regime (WY 1975-2001)

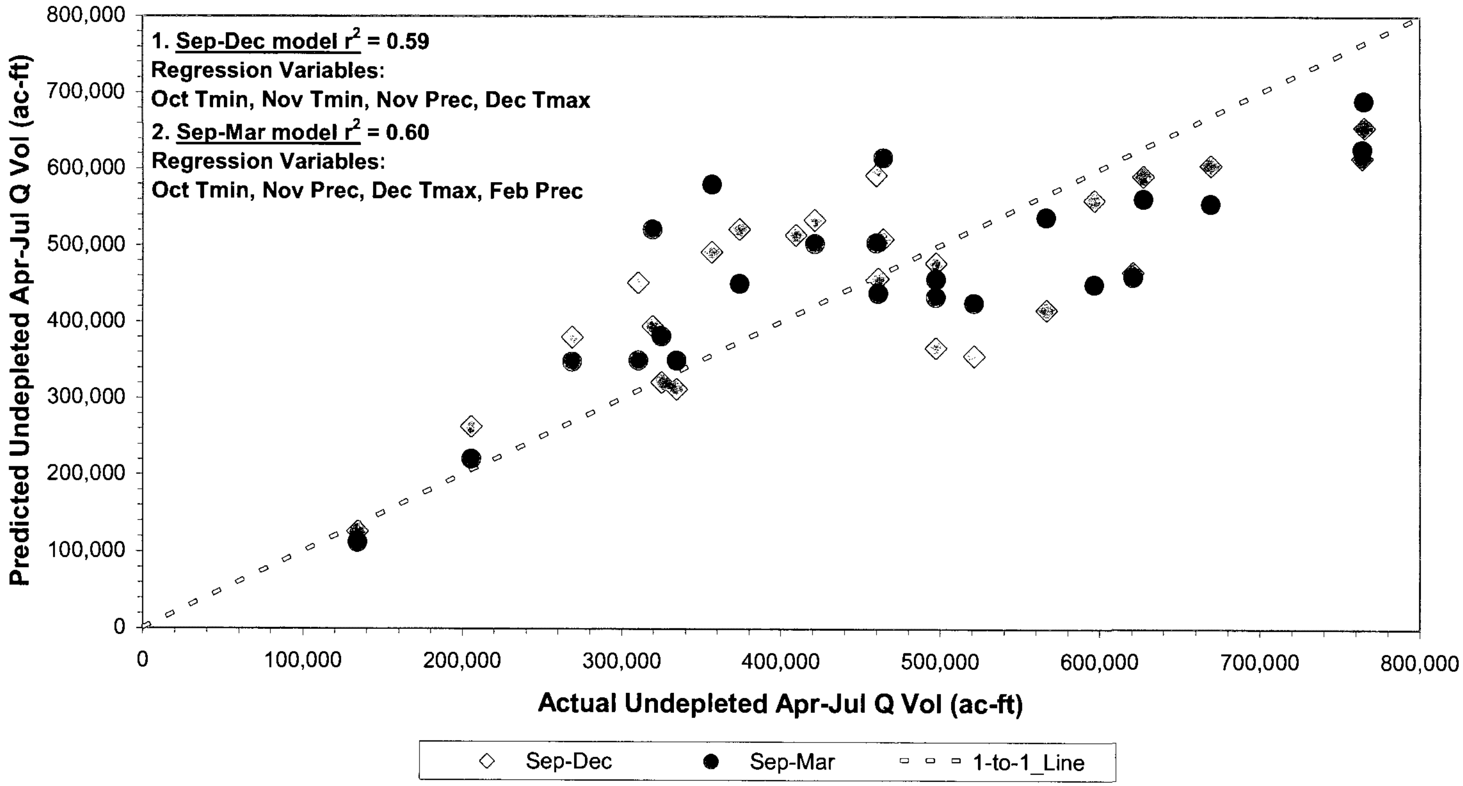


Figure 4.8 Sep-Dec (solid diamond) and Sep-Mar (solid circles) Enhanced WSP predictions of reconstructed undepleted Apr-Jul flow volumes are plotted against actual reconstructed undepleted Apr-Jul flow volumes for WY 1975-2001 at the GRG site. The Sep-Dec and Sep-Mar Enhanced WSP models tend to over-predict in drier conditions and under-predict in wetter conditions, similar model predictions of actual gauge Apr-Jul flow volumes (see Fig. 4.5). The models also explain similar amounts of variance in Apr-Jul flow volumes. Thus, adjusting gauge flows for water management activities does not significantly improve predictions at the GRG site.

CHAPTER 5: CONCLUSIONS

5.1 Summary

Results of this research show that individual climate regimes are a useful basis upon which to characterize hydroclimatic variability, and demonstrate that hydroclimatic variability is more deterministic than previously thought. The underpinnings of hydroclimatic variability in the Upper CRB involve complementary temperature and precipitations patterns that accompany wetter or drier hydroclimatic conditions on climate regime and annual scales. Combined effects of relevant climate modes influencing hydroclimate in the CRB shape climate regimes which are characterized by complementary temperature and precipitation patterns (i.e., cool/wet or warm/dry) for each river basin. The complementary patterns for climate regimes of the same type (e.g., cool/wet) are similar, and they differ from complementary patterns for climate regimes of the opposite type (e.g., warm/dry). In addition, although complementary temperature and precipitation patterns accompanying climate regimes share similarities between basins, they also differ because of the unique physiography of each river basin and the external forcings relevant to each basin.

Since natural and anthropogenic external forcings influence climate modes that shape climate regimes, they also influence the complementary temperature and precipitation patterns characterizing climate regimes, changing some details of complementary temperature and precipitation patterns for climate regimes of the same type (i.e., cool/wet or warm/dry). So the complementary patterns not only change cyclically with climate regimes, but they also exhibit changes over the 20th Century. Some of the changes are consistent with anticipated or observed effects of some anthropogenic external forcings. Temperatures generally increase over the 20th Century at both sites, which is consistent with anticipated effects of anthropogenic climate change, and other research (e.g., Gershunov and Cayan, 2003; Wang and Schimel, 2003; Chen and Grasby, 2009), which show that temperatures increase during two periods of the century. The first temperature increase occurred during the 1940's, which corresponds to the increase in temperature between the UB-Cool/Wet and AB-Warm/Dry climate regimes, and the second increase occurred since the 1970's (e.g., Gershunov and Cayan, 2003; Wang and Schimel, 2003; Chen and Grasby, 2009), which corresponds to the observed increase in temperature over the 20th Century (i.e., between the UB- and AB-Cool/Wet climate regimes).

In contrast to generally increasing temperatures in the CRB, Tmax between December and March at the YRS site either decreases or exhibits no significant change. Combined effects of wintertime temperature inversions and sulfate aerosols from sulfur dioxide in emissions from upwind coal fired power plants (Ramanathan et al., 2001) and vehicles may contribute to depressed Tmax at the YRS site.

While temperatures increase over the 20th Century, median annual precipitation decreases at the YRS and GRG sites, although the decreases at each site occur at different times during the century. The decrease in median annual precipitation at the YRS site coincides with the transition to the AB-Warm/Dry climate regime. But instead of precipitation increasing again during the AB-Cool/Wet climate regime, lower median annual precipitation persists through the century. The AB-Cool/Wet climate regime is also when median annual precipitation decreases at the GRG site, which is contrary to expectations for a cool/wet climate regime. Decreases in precipitation at the GRG and YRS sites in the later part of the 20th Century may be related to anthropogenic climate change, but may also be related to other factors, such as sulfate aerosols derived from sulfur dioxide in coal fired power plant and vehicular emissions (Jacobson, et al., 2007; Unger et al, 2009).

Streamflow also changes over the 20th Century on seasonal and annual scales at the GRG and YRS sites. Median ABY at both sites decreases earlier in the century, between the UB-Cool/Wet and AB-Warm/Dry climate regimes, yet ABY does not increase again during the following cool/wet climate regime (i.e., AB-Cool/Wet climate regime). While decreases in ABY coincide with the warm/dry climate regime, persistently lower flows through the 20th Century may be caused by the cumulative effects of land and water resource development and other external forcings in the upper Yampa and Gunnison river basins.

Shifts in timing of annual flow volumes coincide with persistently lower ABY through the later part of the century. Between the AB-Warm/Dry and AB-Cool/Wet climate regimes, the WY 1/3-Flow Date shifted significantly earlier at the GRG site and shifted later at the YRS site. Since the WY 1/3-Flow Date showed no discernible change earlier in the 20th Century when median ABY decreased, this may suggest that the relationship between magnitude and timing of annual flow volumes may be relatively invariant between climate regimes, providing that other changes in the basin are occurring at sufficiently low magnitude and rate. Anthropogenic external forcings may disrupt the relationship between magnitude and timing of annual flow volumes, causing timing of flow volumes to shift earlier or later, depending on the anthropogenic external forcings affecting basin hydrology. Effects of anthropogenic external forcings may also be amplified or dampened by natural external forcings (e.g., solar variability or volcanic eruptions) or internal climate variability (e.g., climate regimes shaped by climate modes).

Accompanying each of the three climate regimes during the 20th Century at the two sites are unique complementary temperature and precipitation (T and P) patterns which evolve on annual scales between fall and early spring, and are associated with upcoming precipitation and ABY. The complementary T and P patterns establish by the fall and are: (a) detectable as early as September; (b) persistent through early spring (March); (c) associated with relative magnitudes of upcoming precipitation and ABY; (d) unique to climate regime type; (e) specific to each river basin; and (f) influenced by external forcings, including climate change, solar variability, air pollution (e.g., sulfate aerosols), and modifications to land use, land cover and water use. Complementary T and P patterns evolving between fall and early spring are consistent with research by Hidalgo and Dracup (2003) and Archer and Fowler (2008) who found that April-September streamflow for the upper CRB and the River Jhelum in Pakistan, respectively, is more correlated with total precipitation for October-January than with any other time period (e.g., October-March, December-March, January-March, or October-September). The Upper CRB and the River Jhelum are both snowmelt-dominated river systems and are influenced by ENSO during at least the winter months.

Complementary T and P patterns depict temperature and precipitation conditions between September and March accompanying extreme conditions (i.e., wetter or drier) during each climate regime, thus wet years evolve differently during a cool/wet climate regime than during a warm/dry climate regime, and likewise for dry years. The complementary T and P patterns also represent dynamic patterns in temperature and precipitation that evolve between September and March, and are associated with upcoming precipitation and ABY. Sep-Dec and Sep-Mar Enhanced WSP models, developed from characteristics of the complementary T and P patterns during Sep-Dec and Sep-Mar, respectively, accurately predict ABY for each climate regime at the two sites. While r^2 for the Sep-Mar Enhanced WSP models is often higher than for the Sep-Dec models, the Sep-Dec Enhanced WSP models explain proportionately more of the variance in upcoming ABY. Thus, much of the predictive information about upcoming ABY is detectable in the fall, well before substantial snowpack development. So even though winter snowpack is the main source of water supply in the CRB, significant predictive information about the upcoming water supply is detectable as early as September, which may advance forecast lead time as much as six months; from April 1 to October 1 of the previous year.

Like actual gauge flows, the temperature and precipitation signals accompanying the AB-Cool/Wet climate regime are also evident on annual scales in the CWCB reconstructed undepleted flows for the YRS and GRG sites. However, the signals are not consistently evident on seasonal scales for Fall-Early Winter and Winter-Early Spring. Despite the fact that reconstructed undepleted flows are adjusted for water management activities, applying the Enhanced WSP models to reconstructed undepleted flows does not consistently and substantively improve predictions of ABY at either the YRS or GRG sites. Plus, Enhanced WSP model results for reconstructed undepleted ABY for the GRG site exhibit similar tendencies to over-predict in drier years and under-predict in wetter years as observed in results for actual gauge flows. This suggests that other factors not considered in development of reconstructed undepleted flows are influencing relationships between climate signals and streamflow. For example: (a) effects of changes in land use, land cover, as well as water use on basin water balance; (b) related water losses, such as those associated with diversions, conveyance, reservoir storage, and irrigation, may be more significant than expected; and (c) transbasin diversions, including headwater diversions, and subsequent effects on basin groundwater recharge. Those factors also vary with climate regimes and anthropogenic climate change, and subsequent combined effects on the inherent capacity of river basins to moderate the effects of wetter or drier conditions may be analogous to the effects of draining wetlands on intensifying drought or flood conditions (Galatowitsch and van der Valk, 1994; McAllister et al., 2000).

If magnitude and rates of change in climatic, water use, land use and land cover in a river basin are sufficiently low, then the relationship between hydroclimatic conditions and streamflow may be maintained. Begueria et al. (2003) and Dow (2007) found that streamflow "flashiness" and flood frequency decreased as changes in land use and land cover subsided. Amount and rate of change in the Upper Gunnison Basin may have been sufficiently low during the AB-Cool/Wet climate regime because Enhanced WSP model predictions of reconstructed undepleted ABY are about as accurate as model predictions of actual gauge ABY. In addition, Enhanced WSP model predictions of reconstructed undepleted ABY also tend to over-predict in drier years and under-predict in wetter years, similar to Enhanced WSP model predictions of actual gauge ABY. In addition to the factors potentially causing the Enhanced WSP models to over- and under-predict, prediction accuracy for reconstructed undepleted ABY may be affected by disaggregation methods used to generate daily reconstructed undepleted flows values from monthly values. In conclusion, adjusting actual gauge flow for water management activities may not substantively improve accuracy of prediction of streamflow volumes.

Hydroclimate in the Gunnison River Basin is considered among the most variable in the CRB because the basin is uniquely situated relative to boundaries of climate modes influencing hydroclimate in the Upper CRB (Woodhouse, 2003). In that case, the GRG site may represent a "worst case scenario" for detecting climate signals. Since the methodology used in this research was successful in characterizing temperature and precipitation patterns on climate regime and annual scales that are related to wetter or drier conditions, and in indicating long-term change over the 20^{th} in the Gunnison River Basin, then the methods are likely to be successful in other tributaries of the CRB.

The Sep-Dec (Jan 1) and Sep-Mar (Apr 1) Enhanced WSP model predictions of Apr-Jul flow volumes for WY 1991-2001 and WY 2002-2009 at the YRS and GRG sites are reasonably accurate and compare favorably to NWS Jan 1 and Apr 1 forecasts. In addition, Enhanced WSP model results for actual gauge flow volumes at the YRS and GRG sites are generally equally or more accurate than Enhanced WSP model predictions of reconstructed undepleted flow volumes. Hence, like predictions of reconstructed undepleted ABY, adjusting actual gauge flows for water management activities and other factors does not substantively improve Enhanced WSP model predictions of Apr-Jul flow volumes. This may be related to accurately estimating water losses related to land and water resource activities and how the losses vary with climate regimes and anthropogenic climate change.

Influences of anthropogenic land and water resource activities on water losses in the basin, and subsequent effects on temperature and precipitation relationships with variations in streamflow may be most evident in the upper Gunnison River Basin. Enhanced WSP model predictions for the YRS site are typically more accurate than those for the GRG site, and NWS forecast accuracy is generally lower for the GRG site than for the YRS site.

The Enhanced WSP models for the GRG site also tend to be more accurate at predicting ABY than Apr-Jul flow volumes. Differences in Enhanced WSP model accuracy between the

YRS and GRG sites may be related to differences in physiography, as well as in differences in type and rate of changes in land use, land cover, and water use between the upper Yampa and Gunnison river basins. Combined effects of physiographic characteristics and type and rates of change in land and water resources in the upper Yampa River Basin may have been such that the relationship between variations in streamflow and hydroclimatic conditions has remained fairly steady, and accordingly, Enhanced WSP model accuracy is reasonably high. In contrast, physiographic characteristics of the upper Gunnison River Basin, including permeable soils (CSU Cooperative Extension, 2000) and characteristic valley drainage winds (Sato and Kondo, 1988), may predispose hydrologic processes in the upper Gunnison Basin to be more susceptible to the combined effects of changes in climate (i.e., changes in climate regimes and anthropogenic climate change), land use, land cover and water use and water management. Activities including headwater diversions, timber harvesting and clearing for ski areas and other development, as well as water use and management activities and associated water losses affect total water losses in the system. Water losses associated with water use and management activities include evaporation and seepage from reservoir storage, change in timing of releases, transmission and application of water for urban and agricultural irrigation. In addition, the amount of water lost varies with changes in climate (i.e., changes in climate regimes and anthropogenic climate change). Hence, losses may be greater in drier conditions and lower in wetter conditions, and correspondingly, the Enhanced WSP models for the GRG site tend to over-predict in drier years and under-predict in wetter years. The Enhanced WSP models may predict ABY more accurately than Apr-Jul flow volumes at the GRG site because of upstream reservoir storage and diversions that occur between April and July, which affect Apr-Jul flow volumes, but reservoir releases and return flows to the river occur throughout the growing season, so over the water year, total flow volumes are more representative of hydroclimatic conditions. In conclusion, the relatively high hydroclimatic variability in the upper Gunnison River Basin (Woodhouse, 2003) and lower forecast accuracy may then be due more to the combined effects of changes in climate (i.e., changes in climate regimes and anthropogenic climate change) and effects of the modifications to land and water resources in the basin than solely to climatic variability.

Application of the Sep-Dec (Jan 1) and Sep-Mar (Apr 1) Enhanced WSP models to predict Apr-Jul flow volumes for the YRS and GRG sites during WY 2002-2009, the earlier part of the ongoing AB-Warm/Dry-21 climate regime, shows that complementary T and P patterns accompanying climate regimes and associated with upcoming Apr-Jul flow volumes establish early in the climate regime. Yet, even though the complementary T and P patterns may establish early, they may also continue to evolve as climate modes change phase and solar variability occurs during the climate regime. The Sep-Dec Enhanced WSP models explain more variance in Apr-Jul flows than the Sep-Mar Enhanced WSP models at both sites. This may suggest that, in general, during warm/dry climate regimes or the early stage of warm/dry climate regimes, hydroclimatic conditions between September and December may be more indicative of upcoming Apr-Jul flow volumes than hydroclimatic conditions between January and March.

Overall, the Jan 1 and Apr 1 Enhanced WSP models are equally or more accurate than NWS Jan 1 and Apr 1 forecasts of Apr-Jul flow volumes during WY 2002-2009. Lower accuracy of NWS forecasts during this time period may be related to the 30-year reference period of record used to estimate long-term mean/median values for NWS forecast procedures. The 30-year reference period is generally the preceding 30 years, which in this case, entails more than half of the previous cool/wet climate regime, plus the early part of the following warm/dry climate regime. Since the complementary T and P patterns are different for the AB-Cool/Wet and AB-Warm/Dry-21 climate regimes, then estimating mean/median values for periods of record encompassing more than one climate regime or for climate regimes other than the current one is likely to result in mean/median values that are not representative of hydroclimatic patterns accompanying the current climate regime, which in turn, may adversely affect forecast accuracy.

Results of this research suggest alternative strategies which may be integrated into existing water supply forecast procedures to improve forecast accuracy and advance lead time by as much as six months; from April 1 to October 1 of the previous year. Some alternative strategies include:

(a) Define the 30-year flow reference period used by the NRCS to determine long-term mean/median conditions to coincide with the current climate regime, a climate regime of the same type as the current regime, or a simulated climate regime of the same type as the current regime, plus relevant external forcings and climate variability.

(b) Extend the period of analysis from primarily December-March (DJFM) to September-March to incorporate the early indicators and evolution of the complementary T and P pattern associated with upcoming precipitation and ABY.

(c) Select regression variables of the complementary T and P patterns associated with ABY for the current climate regime and specific river basin.

(d) Reconstructed undepleted, or "natural," flow datasets may be improved by taking into consideration the appropriate climate regime and subsequent effects of climate change and other external forcings.

Determining and understanding the underpinnings of hydroclimatic variability in the CRB may lead to long-range decadal climate forecasts (Pagano and Garen, 2005). Since the complementary T and P patterns and the Enhanced WSP models for each climate regime depict the result of interactions among factors influencing hydroclimate at the YRS and GRG sites over periods of time, and based on that foundation, the physical mechanisms underlying the relationships may be determined.

5.2 Conclusions

Climate regimes, which are shaped by the combined effects of climate modes, such as AMO and PDO, are a fundamental source of hydroclimatic variability that are evident in double mass plots of cumulative precipitation versus cumulative streamflow. Natural and anthropogenic external forcings, including solar variability, anthropogenic climate change, sulfate aerosols, and modifications to land use, land cover and water use, affect climate regimes by influencing climate modes. This research demonstrates that by characterizing hydroclimate variability according to climate regimes, coherent complementary patterns in temperature and precipitation emerge that are associated with wetter or drier hydroclimatic conditions on climate regime and annual scales. Differences in complementary temperature and precipitation patterns for climate regimes of the same type (e.g., cool/wet) may be attributed to external forcings. Even though increasing hydroclimatic variability over the 20th Century in the CRB has been attributed primarily to anthropogenic climate change, this research shows that the hydroclimatic variability during the 20the Century is not entirely random, but rather entails deterministic processes.

Stochastic process, including precipitation and streamflow, are part deterministic and part random. The deterministic component entails what is known about the physical processes, and the random component includes that which is unknown about the physical processes. This research advances the understanding of the physical underpinnings of hydroclimatic variability and lays the foundation for further knowledge and understanding about the interactions between climate modes and effects of external forcings that shape and influence hydroclimate in the CRB. The results may be used to improve accuracy and reduce uncertainty in water supply forecasts, as well as increase lead time up to six months. In addition, since the results reveal drivers of variability in hydroclimate over the 20th Century, this research may also be used in developing long-range decadal climate forecasts. Improved forecast accuracy, longer lead time and longer-range forecasts will assist water managers, farmers, and municipalities plan for, use and manage water resources more efficiently and effectively.

Even though this research furthers understanding of the deterministic aspects of hydroclimatic variability, there is always more to discover and understand, and hence, there will always be a random component to stochastic processes, as well. Improved understanding of the physical components may also be used to: (a) improve existing methods which are based on the assumption of stationarity; (b) modify how the methods are applied; and (c) to develop new methods.

Results of this research may also have applications in downscaling climate models, and in river restoration and management.

5.3 Recommendations for Future Research

This dissertation research answers fundamental questions about hydroclimatic variability in the Upper Colorado River Basin, and in turn, new questions emerge offering opportunities for increasing knowledge and understanding of hydroclimatic processes influencing water resources in the Colorado River Basin and elsewhere. New areas of investigation and application of the results include:

(a) Expand the application of the research methodology to determine complementary T and P patterns for seasons throughout the entire year.

(b) Use Spearman's Rho to determine correlations between precipitation and streamflow.

(c) Apply more sophisticated methods (e.g., multiple linear regression, Principal Components Analysis, Backward Artificial Neural Network) to determine interrelationships among variables and to refine how the complementary temperature and precipitation patterns evolve.

(d) Apply the methods to other tributaries of the Colorado River Basin.

(e) Apply the methods to other snowmelt-dominated river systems and other types of rivers systems, such as rain-on-snow.

(f) Findings of this research may be used to improve reconstructed undepleted or natural flow datasets.

(g) Work backwards from results of this research (i.e., right-hand side of the equations) to determine interactions among relevant climate modes and external forcings during the evolution of each climate regime in the river basin of interest (i.e., left-hand side of the equation). For instance, determine the phase and stage of the phase (e.g., early, middle, and late) of AMO, PDO and ENSO throughout each stage of evolution of the climate regime, and coincident influence of natural and external forcings on climate modes. Results may be used to downscale climate models and for longer-range forecasts.

5.4 References

Archer, D.R, Fowler, H.J., 2008. Using meteorological data to forecast seasonal runoff on the River Jhelum, Pakistan. Journal of Hydrology 361, 10-23.

Begueria, S., López-Moreno, J.I., Lorente, A., Seeger, M. Garcia-Ruiz, J.M., 2003. Assessing the effect of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. Ambio 32, 283-286.

Chen, Z., Grasby, S.E., 2009. Impact of decadal and century-scale oscillations on hydroclimatic trend analyses. Journal of Hydrology 365, 122-133.

Colorado State University (CSU) Cooperative Extension, 2000. Improving forage yields and quality in Colorado. Agronomy News 20, 1-14.

Dow, C.L., 2007. Assessing regional land-use/cover influences on New Jersey Pinelands streamflow through hydrograph analysis. Hydrological Processes 21, 185-197.

Galatowitsch, S.M., van der Valk, A.J., 1994. Restoring Prairie Wetlands an Ecological Approach. Iowa State University Press, Ames, IA.

Gershunov, A., 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.

Hidalgo, H.G., Dracup, J.A., 2003. ENSO and PDO effects on hydroclimatic variables of the Upper Colorado River Basin. Journal of Hydrometeorology 4, 5-23.

Jacobson, M.Z., Kaufman, Y.J., Rudich, Y., 2007. Examining feedbacks of aerosols to urban climate with a model that treats 3-D clouds with aerosol inclusions. Journal of Geophysical Research 112, D24205, doi:10.1029/2007JD008922.

McAllister, L.S., Peniston, B.E., Leibowitz, S.G., Abbruzzese, B., Hyman, J.B., 2000. A synoptic assessment for prioritizing wetland restoration efforts to optimize flood attenuation. Wetlands 20, 70-83.

Pagano T., Garen, D., 2005. A Recent Increase in Western U.S. Streamflow Variability and Persistence. Journal of Hydrometeorology 6, 173-179.

Ramanathan, V., Crutzen, P.J., Kiehl, J.T., Rosenfeld, D., 2001. Aerosols, climate, and the hydrological cycle. Science 294, 2119-2124.

Sato, T., Kondo, J., 1988. A simple model of drainage flow in a valley. Boundary-Layer Meteorology 45, 355-369.

Unger, N., Shindell, D.T., Wang, J.S., 2009. Climate forcing by the on-road transportation and power generation sectors. Atmospheric Environment 43, 3077-3085.

Wang, G., and Schimel, D., 2003. Climate change, climate modes, and climate impacts. Annual Review of Environmental Resources, 28: 1-28.

Woodhouse, C.A., 2003. A 431-yr reconstruction of western Colorado snowpack from tree rings. Journal of Climate 16, 1551-1560.