VARIATIONS IN PRECIPITATION AND WATER YIELD FOR THE NORTHWESTERN GREAT PLAINS AND ADJACENT ECOREGIONS

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INTRODUCTION

As a result of changes to precipitation, runoff production and land use, water-quality issues due to excessive erosion and transport of sediment are a concern in many areas of the northwestern United States. This area encompasses much of the U.S. Environmental Protection Agency's (EPA) Region 8 and was the subject of a study on "reference" or background sediment-transport rates for the purpose of developing water-quality targets for sediment (Klimetz et al 2009). As part of this study, an investigation of precipitation and discharge trends over the past century was conducted to determine how representative loadings estimates based on available data were to longer termed flow rates. The area covers a number of Level III Ecoregions from which precipitation and discharge data were available: Ecoregion 15, Northern Rockies, 17, Middle Rockies, 42, Northwest Glaciated Plains, 43, Northwestern Great Plains, 46 Northern Glaciated Plains, and 48, Lake Agassiz Plain (Figure 1). Sites across the region were selected based on locations of past and present U.S. Geological Survey (USGS) stream-gauge locations where historical flow and sediment-transport data were available, as part of a background study regarding reference sediment transport rates. Raw mean-daily discharge data from USGS gauging stations were used in combination with raw precipitation data from the National Ocean Atmospheric and Administration (NOAA) and separated by ecoregion. Flow and precipitation data were not necessarily recorded at the same locations. Runoff data were unitized by dividing by drainage area to create a water-yield parameter (in $m^3/s/km^2$) so that basins of different size could be compared. Changes in water yield over the last century may reflect alterations to the landscape (land use), direct modifications to stream channels (ie. channelization, dams), irrigation and changes in precipitation. An attempt was made to incorporate changes in precipitation into the interpretation of changes in runoff or water yield over the past century. The data used in this study cover about a 100-year period and are not intended to make inferences about the broader issue of global climate change.

METHODOLOGY

As part of ongoing research into background or "reference" rates of sediment-transport in the continental United States, a list of over two thousand USGS gauging stations with more than 30 instantaneous suspended-sediment samples and associated discharge data was compiled. This list of gages became the basis for research into temporal changes in water yield throughout the country (Simon *et al*., 2004), and more specifically for this study, the ecoregions within EPA Region 8. Trends in water yield over the past century are a function of changes in land use and flow conveyance (ie. dams, irrigation and channelization) as well as any 100-year trends in precipitation. For this reason trends in precipitation were included in the analysis.

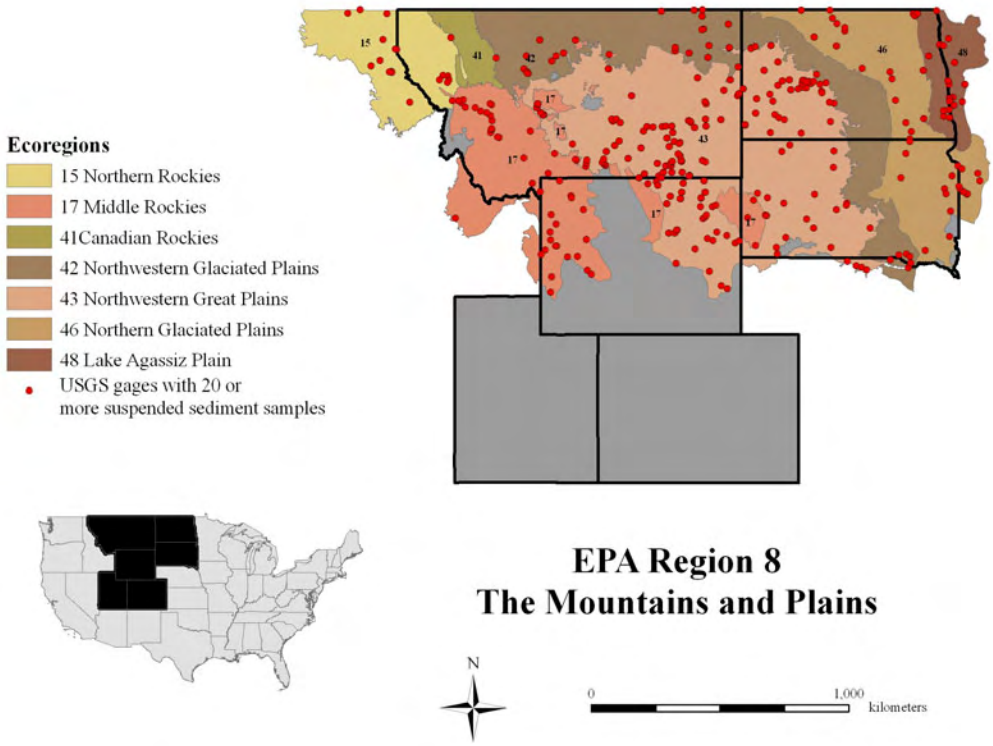

Figure 1 The study area in EPA Region 8: Ecoregion 15, Northern Rockies; 17, Middle Rockies; 42, Northwest Glaciated Plains; 43, Northwestern Great Plains; 46 Northern Glaciated Plains; and 48, Lake Agassiz Plain.

Discharge Data: Daily-flow data for each gage were obtained from the USGS public website http://nwis.waterdata.usgs.gov/nwis/dv and sorted by Level III Ecoregion, the boundaries of which were acquired from http://www.epa.gov/wed/pages/ecoregions/level_iii.htm. For each station, a mean-annual value was calculated for each year of record from the daily discharge data and unitized by dividing by basin area (obtained from http://waterdata.usgs.gov/nwis/inventory) to obtain a water yield. A median water-yield value was then calculated for each year which included every site in a given Level III Ecoregion (for years with at least three gages of data). In this way, a time line of mean-annual water yield was created for each Ecoregion, although the time periods for each ecoregion may differ (Table 1). To make trends more visible, a 5-year moving-average was applied to the data.

Precipitation Data: Precipitation data were obtained from the U.S. Historical Climatology Network (USHCN) operated by the National Climatic Data Center (NCDC) of NOAA; http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html (Karl et al., 1990). This web site provided monthly precipitation data from over 1,000 meteorological stations within the contiguous U.S. As they were from a different source than the flow data, precipitation data were not measured at the same locations as the mean-daily discharge data. Precipitation data were provided by state and organized again by Level III Ecoregion. A file describing the database and quality assurance practices is also available from the same website as well as from: http://cdiac.ornl.gov/epubs/ndp/ushcn/ndp019.html. The precipitation data does not differentiate snowfall and represents total-monthly precipitation expressed to the nearest hundredth of an inch. The monthly precipitation data for each gage were treated in the same way as the discharge data to generate a temporal trend for each ecoregion. As with the discharge data, different time periods are represented for each ecoregion, however the time lines all include the last 100 years (Table 1).

Integration of Data: To differentiate human-induced effects on water yield (runoff production) for each ecoregion from the effects of precipitation changes, each annual water-yield value was divided by the average, annual-precipitation value for the corresponding year within that ecoregion. The result was a parameter describing average, annual water discharge per unit area (water yield) and per unit precipitation. Trends of these data were particularly useful in identifying century-long changes in the hydrologic regimes of these ecoregions. In addition, data on dam construction was obtained from the National Inventory of Dams, organized by the U.S. Army Corps of Engineers. These data was requested through email and made temporarily available via an ftp server. The data and an associated data dictionary can be found at http://crunch.tec.army.mil/nidpublic/webpages/niddatadictionary.html. Data on dam construction obtained were then organized by Level III Ecoregion and sorted into decadal groups.

Table 1 Summary of annual water yield (top) and precipitation data (bottom) used for each ecoregion within the study area. Note: * varies by year.

Level III Ecoregion		Period of average annual water yield	Maximum number of water yield sites*	Average annual water yield in $m^3/s/km^2$
15	Northern Rockies	1929 -2006	15	0.01589
17	Middle Rockies	1924 - 2006	42	0.00995
42	Northwestern Glaciated Plains	1935 - 2007	31	0.002
43	Northwestern Great Plains	1911 - 2007	126	0.0001
46	Northern Glaciated Plains	1929 - 2006	27	0.00034
48	Lake Agassiz Plain	1932 - 2005	14	0.00169

Level III Ecoregion		Period of average annual precipitation record	Maximum number of precipitation sites	Average annual precipitation in mm/y
15	Northern Rockies	1899 - 2006	12	590
17	Middle Rockies	1888 - 2006	22	384
42	Northwestern Glaciated Plains	1891 - 2006	19	379
43	Northwestern Great Plains	1889 - 2006	33	389
46	Northern Glaciated Plains	1888 - 2006	23	530
48	Lake Agassiz Plain	1891 - 2006	8	509

RESULTS

Temporal trends in average-annual precipitation and annual water yield were examined for each of the ecoregions within EPA Region 8. The purpose of this analysis was to investigate decadal-level variations in runoff production as this variable is inherently related to sediment loadings (concentration times discharge).

Precipitation Trends: Precipitation trends over the past 100 years for each of the ecoregion are shown in Figure 2. Variations in the 'Montane' Ecoregions (15 and 17) represent the source of many of the 'Plains' streams and are, therefore, particularly important in interpreting variations in runoff production in the downslope ecoregions. The Dust Bowl era between the mid- to late 1920's and the late 1930's clearly stands out as below average precipitation for all of the ecoregions. Above average precipitation for the

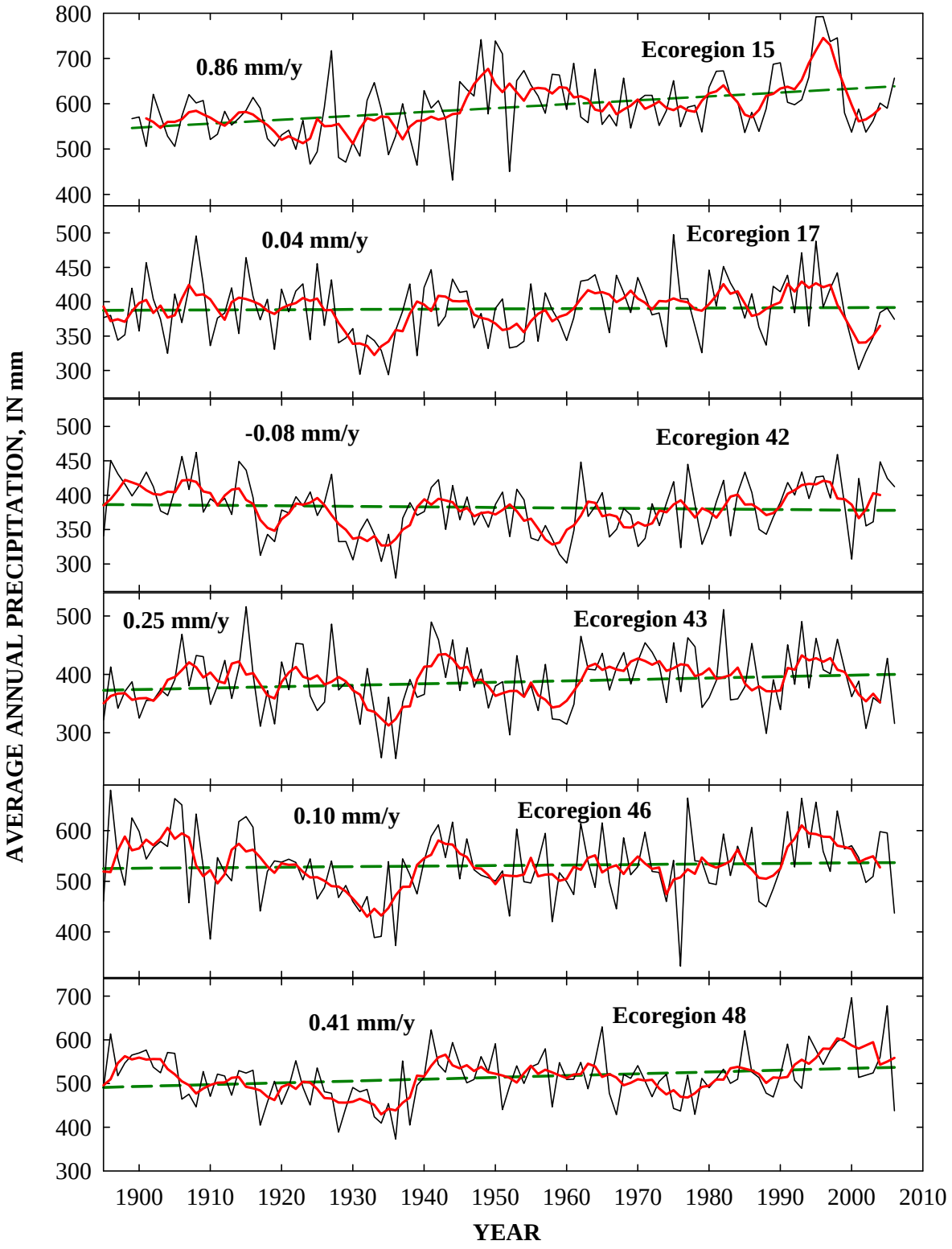

Figure 2 Trends of average-annual precipitation for the Northwestern Great Plains and adjacent Mountain and Plains Ecoregions. The red line is a 5-point moving average; the green-dashed line represents the 100-year trend (also shown as the average annual change in mm/y).

1990's is also apparent. Most recently, however, a marked drier period occurred in Ecoregions 15, 17 and 43. Ecoregions 15 and 48 show the most rapid increases in average, annual precipitation; 0.86 and 0.41 mm/y, respectively (Figure 2). For Ecoregion 15, this converts to an increase of about 3.4 inches over the last century. Only Ecoregion 42 displays a decrease in average, annual precipitation, and this trend is particularly subtle (-0.08 mm/y).

Water-Yield Trends: Trends in annual water yield over the past century are shown in Figure 3 and illustrate the expected order-of-magnitude differences between long-term rates for the 'Montane' and 'Plains' Ecoregions, with the mountainous areas producing more water per unit of drainage area. In the case of water yields, the Dust Bowl era stands out for only several of the ecoregions (15, 43 and 48) while higher mean-daily flows for the 1990's are apparent only for Ecoregions 46 and 48. These differences between trends in precipitation and water yield are probably the result of human influences and disturbances. These differences are more readily apparent by comparing decadal variations in these two parameters. These are shown in a color-coded format in Table 2. What is most interesting to note in comparing these tables is that starting in 1980, water yields in most cases are consistently below the long-term means notwithstanding either average or above average precipitation. This suggests that water withdrawals by irrigation are making a large impact on the amount of water available in the streams.

Table 2 Decadal variations in average-annual precipitation (top) and average-annual water yield (bottom) in the specified ecoregions. Note: '+' signifies above long-term average, '-' signifies below long-term average, and '=' signifies near long-term average.

Ecoregion	1900-1910	1911-1920	1921-1930	1931-1940	1941-1950	1951-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2007
15	-	-	-	-	+	+	=	=	+	+	=
17	=	+	=	-	=	-	+	=	=	+	-
42	+	=	=	-	=	-	-	=	=	+	+
43	=	+	=	-	+	-	+	+	=	+	-
46	+	=	-	-	+	-	=	=	=	+	=
48	+	=	-	-	+	=	=	-	=	+	=

Ecoregion	1900-1910	1911-1920	1921-1930	1931-1940	1941-1950	1951-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2007
15	n/a	=	+	-	=	+	=	-	-	+	-
17	n/a	+	+	=	+	+	+	+	-	-	-
42	n/a	-	-	=	+	+	+	+	-	-	-
43	n/a	+	+	-	=	-	-	-	-	-	-
46	n/a	n/a	n/a	-	-	-	=	=	-	+	+
48	n/a	=	-	-	-	-	=	=	-	+	+

Over the past 100 years all but Ecoregions 46 and 48 show a decrease in runoff per unit drainage area (Figure 3). The most striking aspect of the trends for the other four Ecoregions is that since the 1970s or 1980s, water yield (and runoff) has been well below average, with Ecoregion 17 showing the most consistent and largest percent reduction (Figure 4). Water-yield data expressed as the percent difference from the mean for Ecoregion 43 shows a reduction of similar magnitude with a short respite during the wet period of the 1990s (Figure 4). Water yields for eastern Ecoregions, 46 and 48, which are characterized by large wetland areas, show large peaks in between the mid-1990's and into this century where the 5-year moving average peaks at about 100-300 % above the long-term average. This trend is probably related to large precipitation events and the flooding on the Red River during this period.

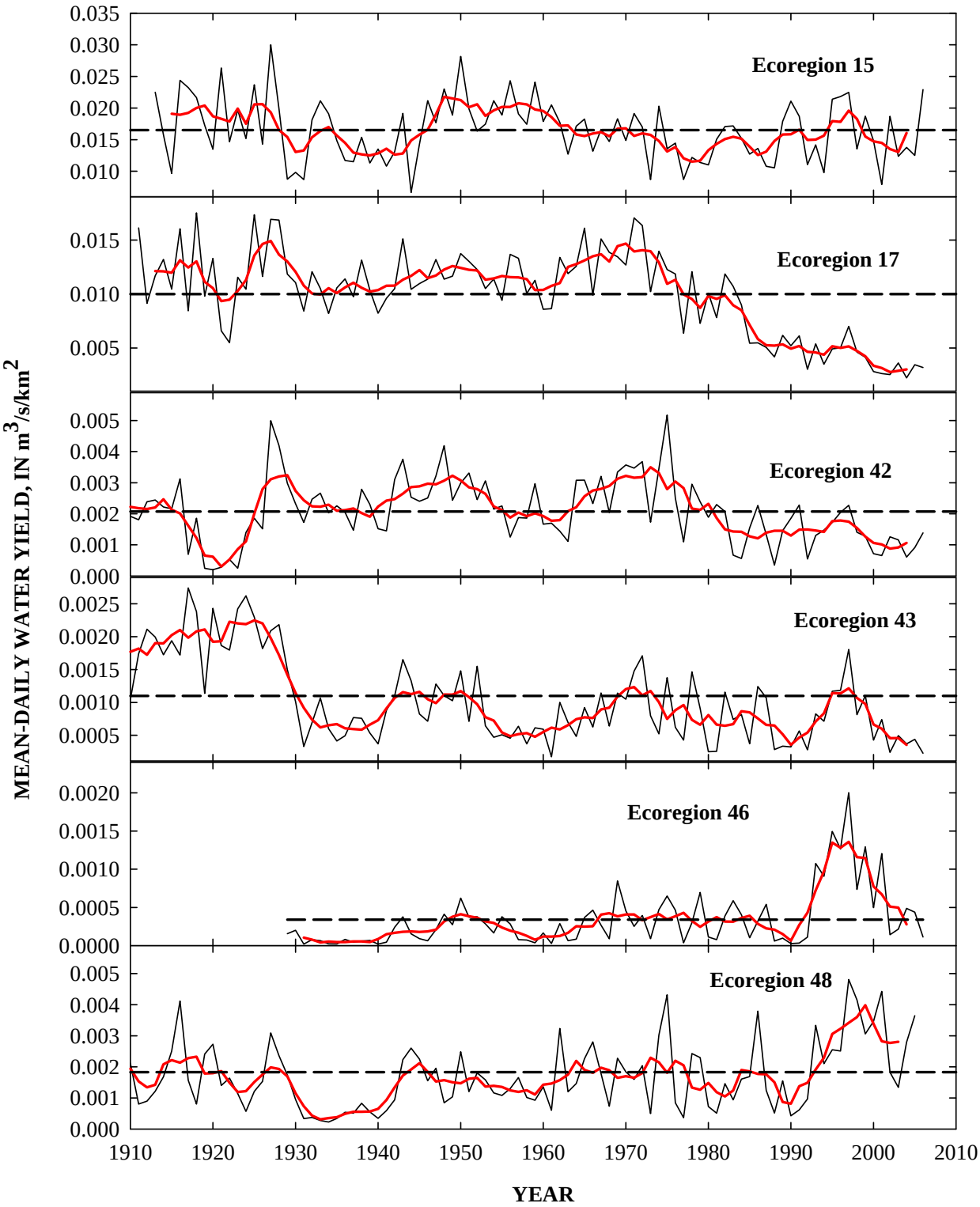

Figure 3 Trends of mean-daily water yield for the ecoregions investigated. The red line is a 5-point moving average; the dashed line is the mean value for all stations over the period of record.

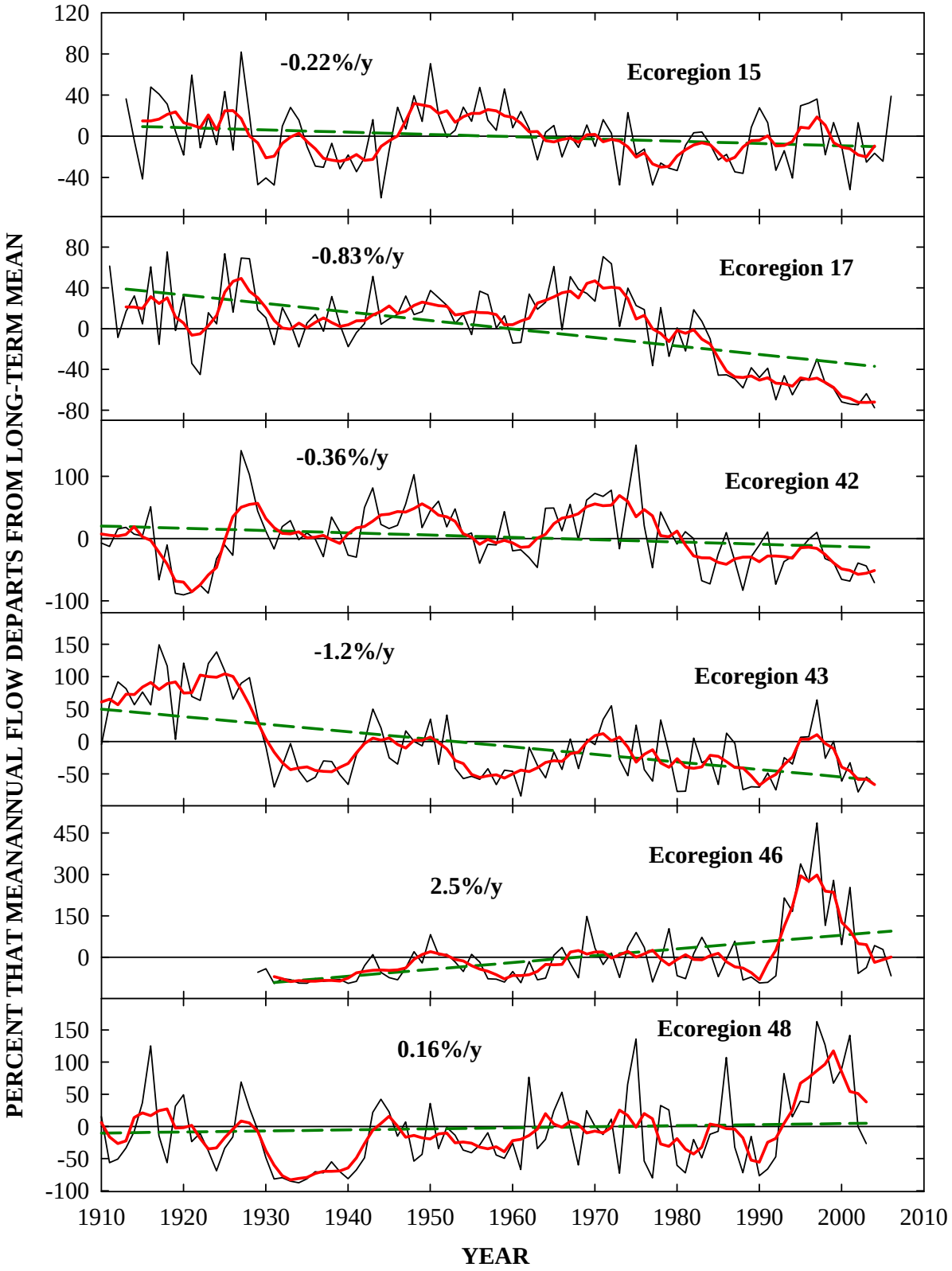

Figure 4 Trends of percent differences in water yield for ecoregions investigated. The red line is a 5-point moving-average; the green dashed line represents the 100-year trend (also shown as average change, in percent per year, %/y).

The magnitude of the variations in water yield for all of the studied ecoregions is more clearly seen in Figure 5. Here one can observe that variations between ecoregions follow similar patterns but are of different magnitudes. Ecoregion 15 shows the most subtle variations around the long-term average perhaps because of the least human disturbance, whereas variations in Ecoregions 46 and 48 seem particularly amplified, perhaps indicating more intense agricultural practices.

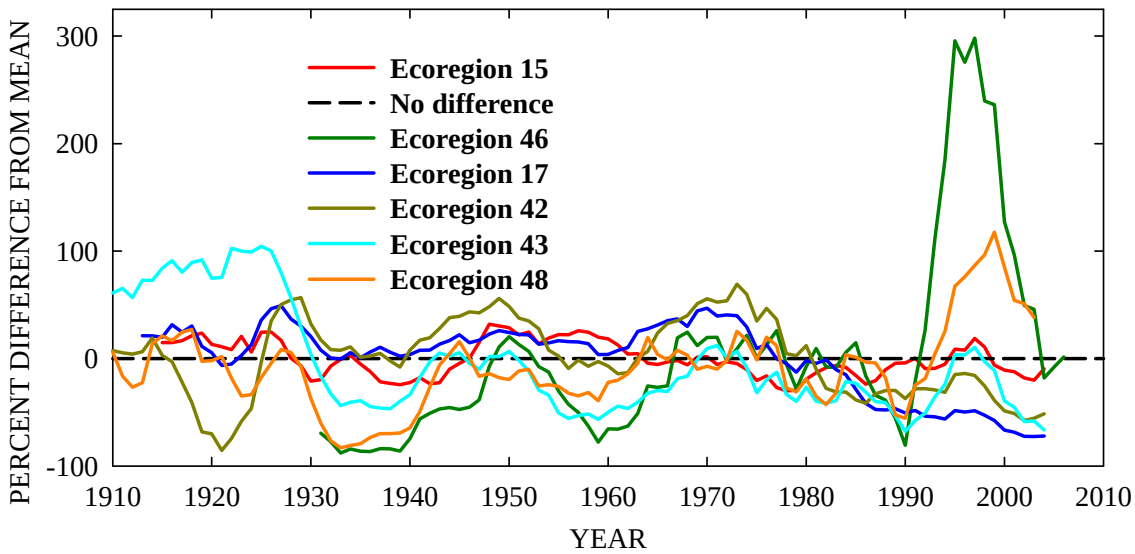

Figure 5 Trends of percent differences in 5-year moving averages of water yield for all of the ecoregions investigated. Note that the pattern of variations is similar, although of different magnitudes.

Regional Trends in a National Context: To place precipitation and water yield trends in the broader, national context, Figures 6 and 7 are provided to show percent changes in these variables over the past 100 years for the continental United States. The Middle and Northern Rockies (Ecoregions 15 and 17)

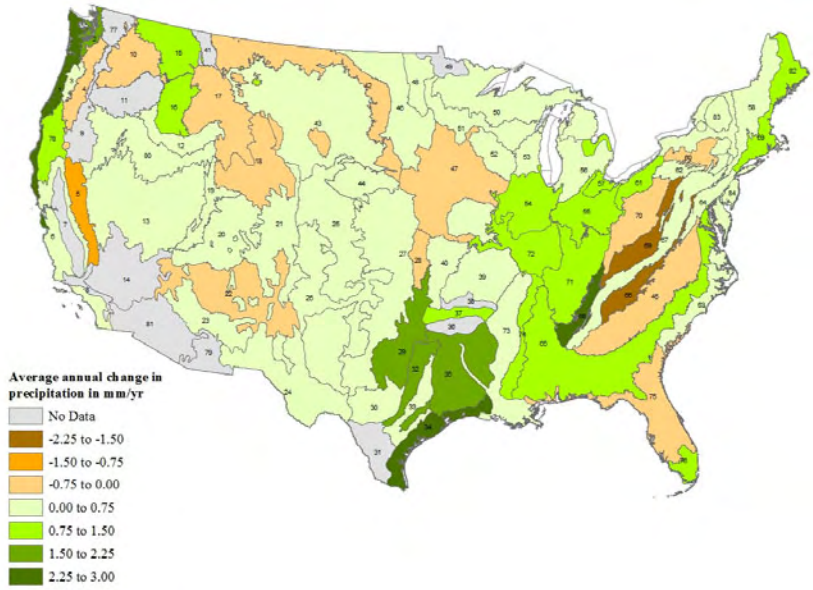

Figure 6 Average, annual change in precipitation (in mm/y) over the past century for Level III ecoregions of the continental United States.

standout along with the Coast Range and areas along the Gulf Coast, areas of Mississippi Valley, Southeastern Plains and the northeast Atlantic Coast having had significant increases in precipitation over the last 100 years (Figure 6). In contrast, the decreasing water yields throughout much of EPA Region 8 and extending south into the Great Plains and Colorado Plateau standout in orange in Figure 7, indicating that these regions have seen the greatest percentage decreases in streamflow per unit area.

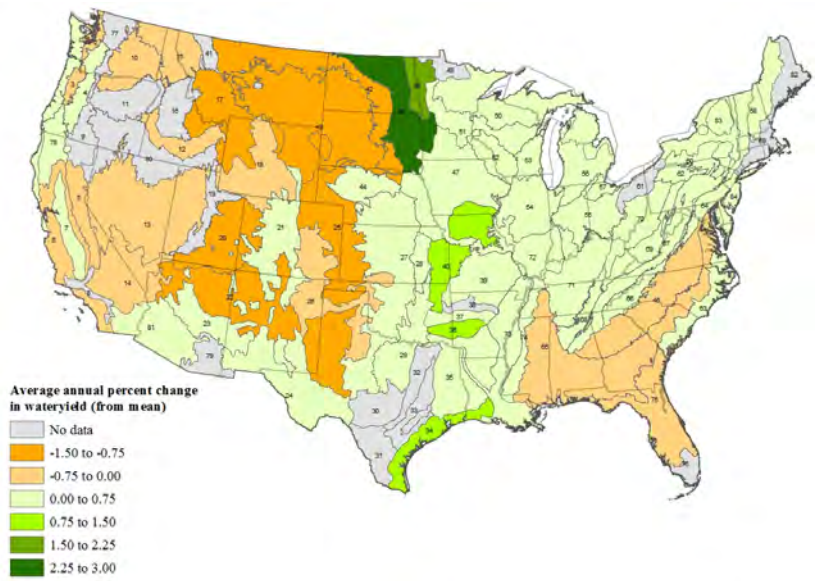

Figure 7 Average, annual percent change (from mean) in water yield over the past century (approximate) for Level III ecoregions of the continental United States.

Water Yield Per Unit Precipitation: To make further inferences regarding changes in water yields over the past century, the effects of variations in precipitation were considered by investigating trends in water yield per unit of precipitation. This was done by dividing the annual water-yield data by mean-annual precipitation and should highlight water yield and runoff changes due to other controls. Results show three different types of trends over the period (Figure 8):

1. Ecoregion 15 which displayed the most subtle changes in water yield, also show only a mild, linear but consistent decrease in water yields per unit precipitation. This could be due to numerous factors of both 'natural' and anthropogenic origin;
2. Ecoregions 17, 42 and 43 display more striking decreases in water yield per unit precipitation, particularly since the 1970s to early 1980s, when precipitation was average, or above average. This supports the previously stated interpretation that the decreases in water yield (and runoff volumes) are the results of anthropogenic changes, including water withdrawals for irrigation and retention of water in the growing number of headwater dams.
3. The eastern-most Ecoregions, 46 and 48 show increased water yields per unit of precipitation. The trend for Ecoregion 46 has been in place since the close of the Dust Bowl period in the 1930s while the trend for Ecoregion 48 is more recent, extending back to the 1960s. Without additional information regarding land use practices and alterations to stream channels (ie. channelization) interpretation as to the causes of this trend would be mere speculation.

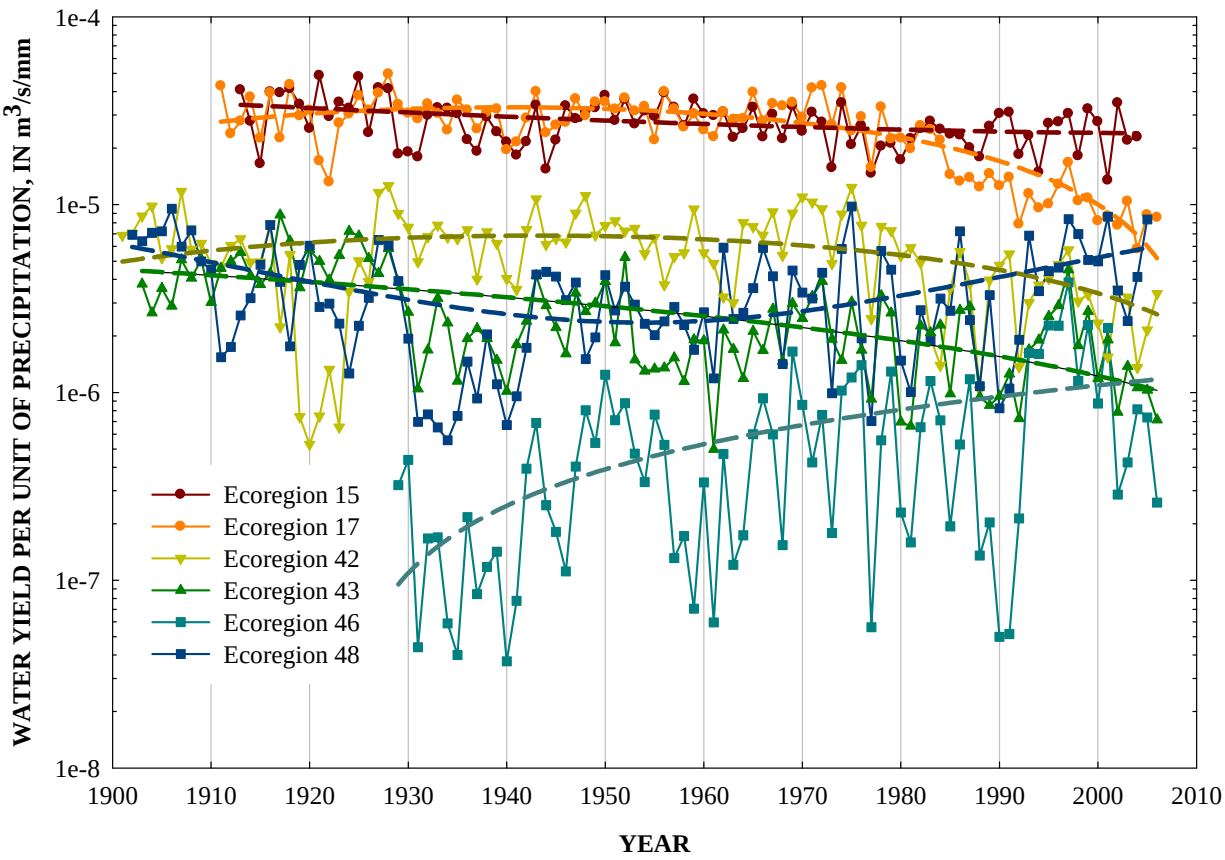

Figure 8 Trends in average-annual water yield per unit of precipitation over the past century for The Mountains and Plains Ecoregions.

Runoff production per unit drainage area and unit precipitation has drastically changed over the last century in some of the Ecoregions (Figure 8). At the turn of the 20th century, the 'Montane' Ecoregions (15 and 17) carried substantially more water than the 'Plains' Ecoregions per unit drainage area and per unit precipitation. Drastic reductions in Ecoregion 17, beginning in the early 1980s have resulted in present-day hydrologic response similar to conditions in Ecoregion 42 at the turn of the 20th century and present conditions in Ecoregion 48. Unitized runoff production in Ecoregion 42, 43 and 48 were quite similar at the beginning of the 20th century but have diverged over the past century, such that order of magnitude reductions in Ecoregion 43 has made it hydrologically similar to Ecoregion 46, which experienced increases of similar magnitude (Figure 8).

At this point we cannot formally provide specific cause and effect answers to these assorted changes over the past century as they are probably the result of a number of important contributing factors, both 'natural' and human induced. As an example, we provide data on the number of dams constructed throughout the region in the past 100 years (Figure 9). About 1600 dams were constructed between 1951 and 1960 in Ecoregion 43 alone. Ecoregions 42 and 43 have the most dams per unit area (about 0.01/km^2) compared to all of the other ecoregions which, by the first decade of the 21st century have about 0.002 dams per km^2. Given the transformation of much of the region to agriculture, the construction of thousands of dams, and the impacts of logging, surface mining, coal-bed methane production, channelization and irrigation, it is not surprising that the documented changes in water yield have occurred. Significant changes in precipitation and water yields have occurred over the past century

(Table 3) and these changes have impacted sediment production and loadings throughout the region (Klimetz et al., 2009).

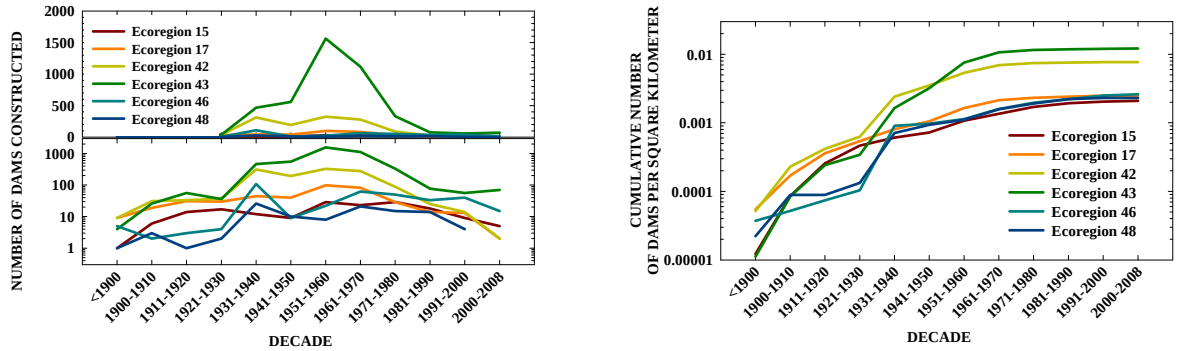

Figure 9 Decadal trends in the number of dams constructed in each of the Mountain and Plains Ecoregions (left) and the cumulative number of dams per unit drainage area (right).

Table 3 Summary of changes in precipitation, water yield and water yield per unit precipitation over the last century in the studied ecoregions. Note: * denotes that data period started during the 1920's or 1930's (Dust Bowl Era), resulting in higher than expected increases.

Level III Ecoregion		Change in precipitation over 100 year period		Change in water yield over 100 year period		Change in water yield per unit precipitation (in percent)
		(in mm)	(in percent)	($m^3/s/km^2$)	(in percent)	
15	Northern Rockies	85.9	15.7	-0.00026	-1.63	-26.4
17	Middle Rockies	-1.31	-0.342	-0.01066	-68.9	-81.8
42	Northwestern Glaciated Plains	-7.74	-2.00	-0.00045	-20.6	-84.9
43	Northwestern Great Plains	24.7	6.64	-0.00131	-79.1	-74.4
46	Northern Glaciated Plains	1.76	0.335	0.00082	3043*	1070*
48	Lake Agassiz Plain	32.7	6.58	0.00261	353*	0

SUMMARY AND CONCLUSIONS

As part of a study on background or "reference" rates of sediment-transport in the Northwestern Great Plains and surrounding ecoregions, decadal and centurial trends of precipitation and water yield (discharge per unit drainage area) were investigated. The purpose of this was to investigate variations in runoff, as related to sediment loadings. Changes in water yield over the last century may reflect alterations to the landscape (land use), direct modifications to stream channels (ie. channelization, dams), irrigation and changes in precipitation. Changes in annual precipitation were incorporated into the interpretation of changes in water yield (or runoff production) by dividing annual values of water yield by the associated annual precipitation, providing an index of changes in runoff production.

The Dust Bowl era between the mid to late 1920's and the late 1930's clearly stands out as below average precipitation in most of the ecoregions. Above average precipitation during the 1990's is also apparent. Most recently however, a marked drier period occurred in Ecoregions 15, 17 and 43. Ecoregions 15 and 48 show the most rapid increases in annual precipitation over the period of record; 0.86 and 0.41 mm/y, respectively. For Ecoregion 15, this converts to an increase of about 3.4 inches over the last century. Only Ecoregion 42 displays a decrease in annual precipitation, and this trend is particularly mild (-0.08

mm/y). Over the past 100 years all but Ecoregions 46 and 48 show a decrease in runoff per unit drainage area. The most striking aspect of the trends for the other four Ecoregions is that since the 1970s or 1980s, water yield (and runoff) has been well below average.

Discharge per unit drainage area and unit precipitation has drastically changed over the last century in some of the Ecoregions. At the turn of the 20th century, the 'Montane' Ecoregions carried substantially more water than the 'Plains' Ecoregions per unit drainage area and unit precipitation. Drastic reductions in runoff production per unit precipitation began in the early 1980s in Ecoregion 17, resulting in present-day hydrologic regimes similar to conditions in Ecoregion 42 at the turn of the 20th century, and present conditions in Ecoregion 48. Unitized runoff production in Ecoregion 42, 43 and 48 appear quite similar at the beginning of the 20th century but have diverged over the past century such that order of magnitude reductions in Ecoregion 43 has made it hydrologically similar to Ecoregion 46, which experienced increases of similar magnitude.

Given the transformation of much of the region to agriculture, the construction of thousands of dams, and the impacts of logging, surface mining, coal-bed methane production, channelization and irrigation, it is not surprising that the documented changes in water yield have occurred. It is quite clear, however, that the significant changes in precipitation and water yields have occurred over the past century and that these changes have impacted sediment production and loadings throughout the region. Current and future analysis of these data sets are incorporating seasonality issues to provide an improved picture of precipitation and water yield trends over the last century throughout the continental United States.

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