Souris Plan of Study

HH10: Forecasting Assessment

Subtask: Assessment of a quantitative index of basin moisture conditions

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Executive Summary

Under the overall supervision of the International Joint Commission (IJC), that oversee jurisdiction over the use, obstruction or diversion of transboundary water between the United States (US) and Canada, the Souris Plan of Study (Souris- POS) is designed to review the existing operating plan for the Souris River Basin (Annex A and B to the 1989 International Agreement) and provide alternatives to maximize flood control and water supply benefits in the Souris River Basin (SRB) (Souris River Basin Task Force, 2013). The Souris-POS is just an initial step to investigate possible and potential improvements to the earlier operating rules established in Annex A of the 1989 Agreement, which upon completion would be forwarded to the governments of Canada and the United States.

The current study *"Assessment of a quantitative index of basin moisture condition"* is a subtask of the Forecasting Assessment (HH10) task. The aim of the sub-task is to develop/assess the feasibility of various moisture indices that would enhance decision making capacity during spring runoff forecast and thus help in reservoir management in the Souris River Basin (SRB).

After careful review of various basin moisture indices, the Standardized Precipitation and Evapotranspiration Index (SPEI)) was considered for further assessment. SPEI estimates the climate water balance, Precipitation minus Evapotranspiration (P - ET). Two scenarios, (a) entire basin level, and (b) subbasin level, were constructed to assess basin moisture condition at various scales. Results of the study suggests that SPEI can be a useable tool for water resources planning and management within the SRB. However, further tests of the technique presented here are recommended before using this as an operation tool.

Contents

Executive Summary 1
List of Figures 3
List of Appendices 4
Acronyms 5
1. Introduction 6
2. Material and methods 7
2.1. Description of the area 7
2.2. Background 10
2.2.1. Standardized Precipitation Index (SPI) 10
2.2.2. Antecedent Precipitation Index (API) 10
2.2.3. Standardized Precipitation and Evapotranspiration Index (SPEI) 11
2.3. Experimental setup 12
3. Results and Discussion 14
3.1. Case 1: Entire Souris River Basin as a lumped system 14
3.2. Case 2: Souris River basin (SRB) condition assessment at subbasin scale 17
3.3. SPEI versus following year spring runoff 23
3.4. On the relationship of spring runoff and SPEI value 26
4. Varying Normal Drawdown (Phase 3.5 alternative 307) Research: An extension of SPEI work 27
5. Conclusion and future recommendation 31
References 33
Appendices 36

List of Figures

Figure 1: Geospatial location of Souris River Basin (SRB) 6

Figure 2: SRB mean monthly average climate over the period 1979- 2016 (derived using WFDEI-GEM-CaPA data set). 8

Figure 3: Comparison between WFDEI-GEM-CaPA (re-analysis data) Vs observed precipitation data. 9

Figure 4: Discretized Souris River Basin along with basins centroid, hydrometric, and WFDEI-GEM-CaPA grid points. 13

Figure 5: Timeseries plot at 6- and 12-months scale for the entire Souris basin over the period 1979-2016 15

Figure 6: Precipitation of the year 2010-2011 in comparison to the long term mean precipitation over the 1979-2016 period. June to December (in blue) presents data of the year 2010 and January to May (in blue) presents data of the year 2011 17

Figure 7: Timeseries plot at 6-months scale for the subbasins in the Souris River Basin (SRB) over the period 1979-2016 19

Figure 8: Timeseries plot at 12-months scale for the subbasins in the Souris River Basin (SRB) over the period 1979-2016 20

Figure 9: Geospatial maps of Souris River subbasins displaying results of 6-month SPEI for April 1st of the identified extreme events 21

Figure 10: Geospatial maps of Souris River subbasins displaying results of 12-month SPEI for April 1st of the identified extreme events 22

Figure 11: Correlation of Runoff vs SPEI (6-month) spring forecast for multiple subbasin 24

Figure 12: Correlation of Runoff vs SPEI (9-month) spring forecast for multiple subbasin 25

Figure 13: Spring runoff versus SPEI for Rafferty reservoir over the 1930 - 2017 period 29

List of Appendices

Appendix 1: Scatter plots of WFDEI-GEM-CaPA vs selected ground based observed precipitation over the 1979 – 2016 period. 37

Appendix 2: Total precipitation, mean annual maximum and minimum across SRB over the period 1979 - 2016 38

Appendix 3: Assessing Souris River Basin (SRB) conditions at 9 and 24-months SPEI scales . 39

Appendix 4: Timeseries plot at 9-month and 24-month scales for the entire Souris basin over the period 1979-2016 40

Appendix 5: Timeseries plot at 9-month scale for the subbasins in the Souris River Basin (SRB) over the period 1979-2016 41

Appendix 6: Timeseries plot at 24-months scale for the subbasins in the Souris River Basin (SRB) over the period 1979-2016 42

Appendix 7: Geospatial maps of Souris River subbasins displaying results of 9-month SPEI for April 1st of the identified extreme events 43

Appendix 8: Geospatial maps of Souris River subbasins displaying results of 24-month SPEI for April 1st of the identified extreme events 44

Appendix 9: Correlation of Runoff vs SPEI (12-month) spring forecast for multiple subbasins. 45

Appendix 10: Correlation of Runoff vs SPEI (24-month) spring forecast for multiple subbasins46

Appendix 11: Spring runoff versus SPEI for Grant Devine Reservoir over the 1930 - 2017 period 47

Appendix 12: Spring runoff versus SPEI for Lake Darling Reservoir over the 1930 - 2017 period 48

Acronyms

API	Antecedent Precipitation Index
CaPA	Canadian Precipitation Analysis
CWB	Climatic Water Balance
FSL	Full Supply Level
GCMs	Global Circulation Models
GEM	Global Environmental Multiscale Model
HH10	Forecasting Assessment task under Souris-POS
MANAPI	Manitoba Antecedent Precipitation Index
Souris-POS	Souris Plan of Study
SPEI	Standardized Precipitation and Evapotranspiration Index
SPI	Standardized Precipitation Index
SRB	Souris River Basin
WFDEI	WATCH Forcing Data ERA Interim
SWSAWSA	Saskatchewan Water Security Agency

1. Introduction

The Souris River originates in the Province of Saskatchewan, Canada and crosses the US-Canada boundary twice, flowing from Saskatchewan, in Canada, to the State of North Dakota, in the US, and back to Canada in Manitoba (Figure 1). The Souris River hosts several critical water control structures namely Rafferty, Grand Devine, Boundary, and Lake Darling dams. The US Fish and Wildlife Service operates Lake Darling Dam, except during declared flood events where the responsibility transitions to the US Army Corps of Engineers, while the other three structures are being operated by the Saskatchewan Water Security Agency (WSA).

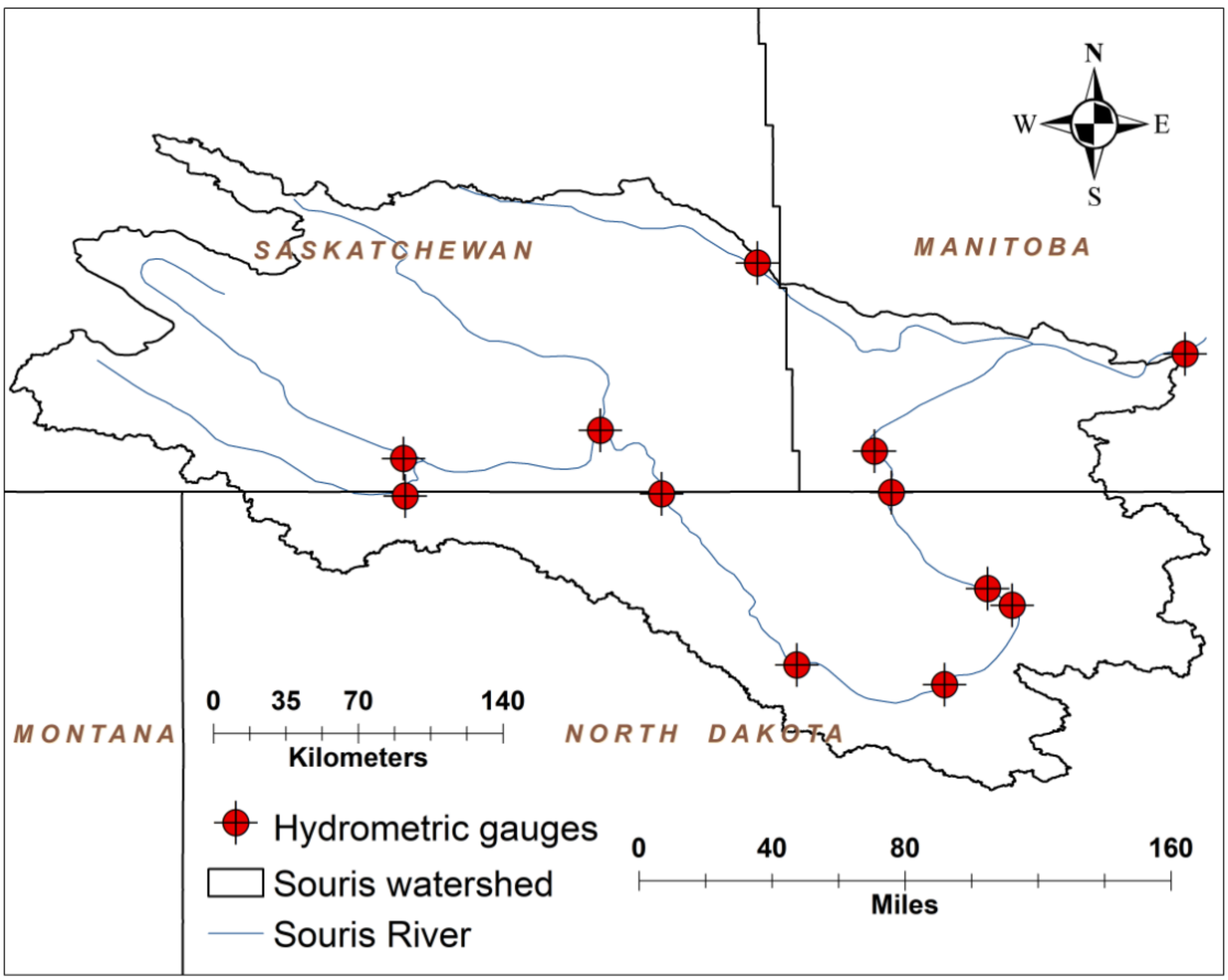

Figure 1: Geospatial location of Souris River Basin (SRB)

In their current operational settings, the major reservoirs within the basin must be drawn down to their normal operating levels before February 1st of each year, regardless of conditions within the basin, to create flood storage. The drawdown operations typically start on or near November 1st by adjusting the outflow from reservoirs targeting the February 1st normal drawdown level. Lowering the reservoir levels reduces the risk of flooding downstream; however, this comes at a risk to the security of the water supply. Thus, there is a pressing need to assess basin moisture conditions and develop an index which could enhance decision making regarding reservoir operations.

This study lies within the context of Souris-POS project HH10: Forecasting Assessment. The study, which is a subtask to the project HH10, looks at assessing/developing various basin moisture indices that could be used in operational decision making for spring runoff forecasts and reservoir drawdown. Quantifying antecedent basin moisture conditions before a runoff event enhances decision-making capacity. The antecedent moisture can have a significant effect on the flow responses during any precipitation event. Antecedent moisture is high when above normal precipitation results in soils that are moist and wetlands that are near capacity. The goal of the study is to identify an index that could be used to bias reservoir operating decisions in the SRB towards water supply security when conditions are dry and towards flood protection when conditions are wet.

2. Material and methods

2.1. Description of the area

The SRB is flat, heavily cultivated, and is classified as semi-arid prairie. The average annual precipitation is 465 mm (~ 18.31 inches), with approximately one third of the precipitation (on average) falling as snow (Fang et al., 2007). The mean annual maximum and minimum temperature is about 10°C (50°F) and -0.3°C (26.6°F) respectively (Figure 2) based on the WFDEI-GEM-CaPA (see Asong et al., 2018).

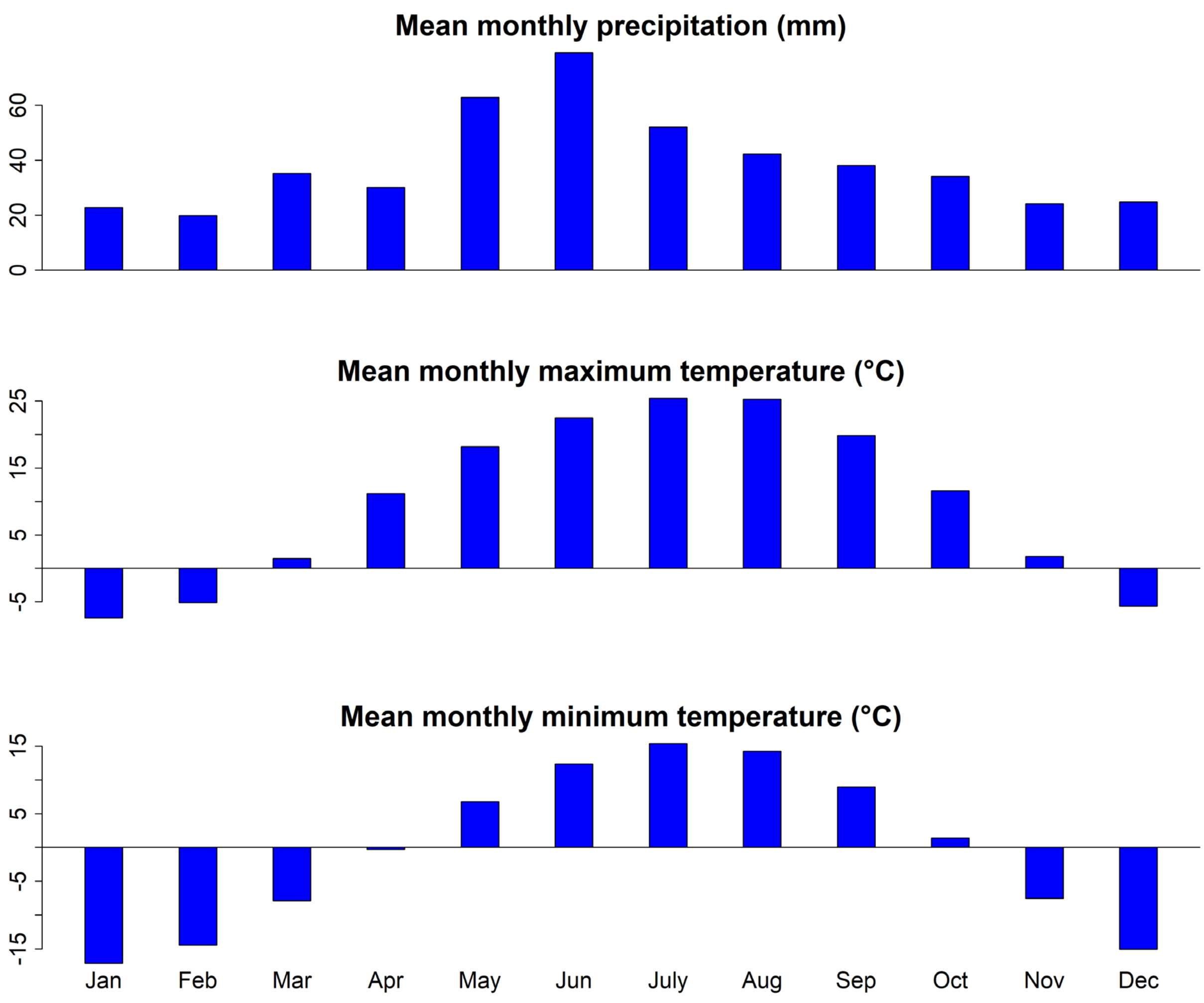

Figure 2: SRB mean monthly average climate over the period 1979- 2016 (derived using WFDEI-GEM-CaPA data set).

WFDEI-GEM-CaPA is a re-analysis gridded data product generated as a result of applying a multi-stage bias correction framework based on quantile mapping technique using the EU WATCH ERA-Interim reanalysis (WFDEI), the Canadian Precipitation Analysis (CaPA), and the Global Environmental Multiscale (GEM) numerical weather prediction model. A preliminary comparative assessment of precipitation with selected ground based meteorological stations indicated a good match between observed and the re-analysis data (Figure 3).

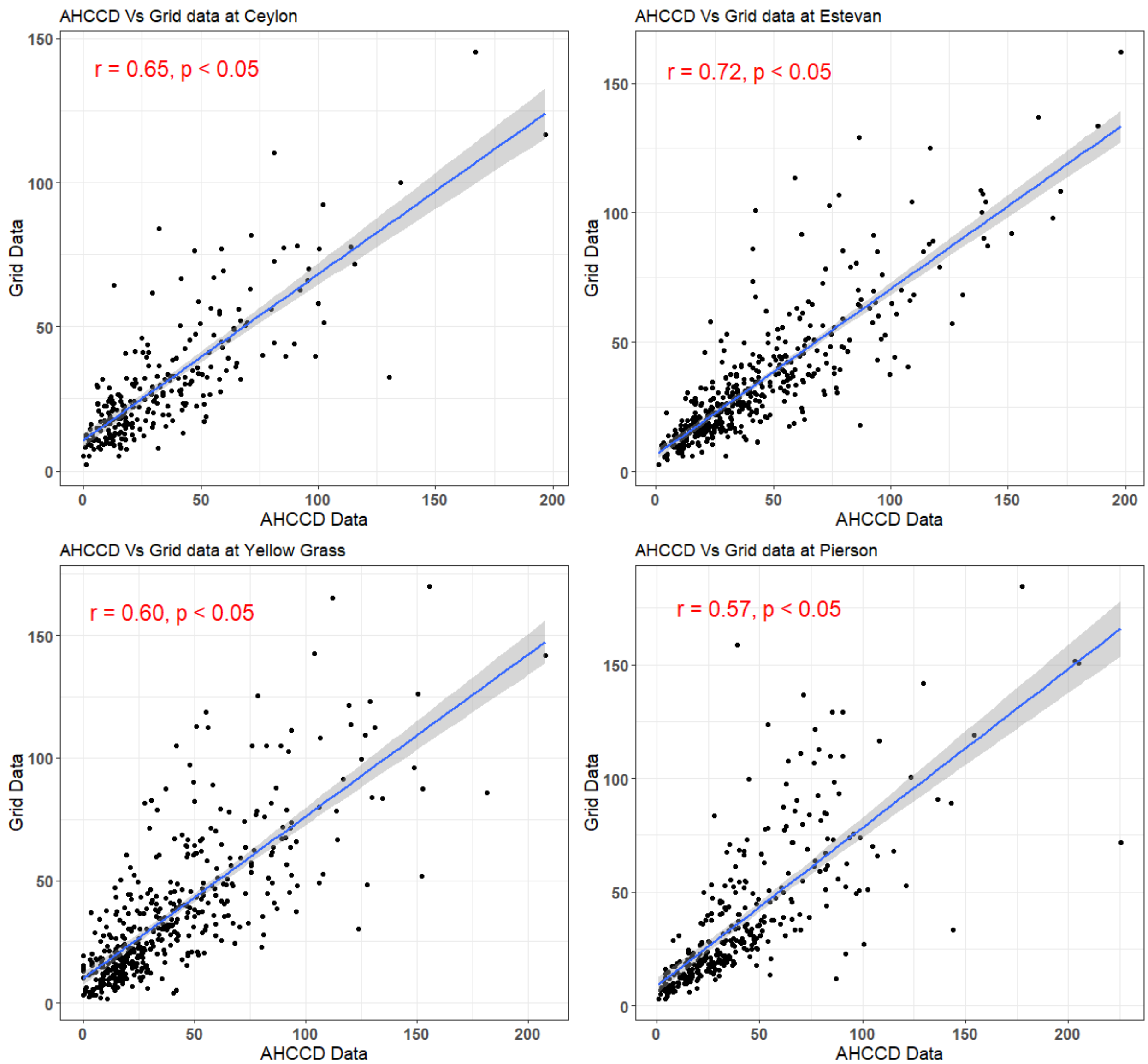

Figure 3: Comparison between WFDEI-GEM-CaPA (re-analysis data) Vs observed precipitation data.

2.2. Background

Several moisture indices were investigated to assess their feasibility for operational use. Of note, the Standardized Precipitation Index (SPI), the Antecedent Precipitation Index (API), and the Standardized Precipitation and Evapotranspiration Index (SPEI) were studied in detail. Here we present a brief overview of each index.

2.2.1. Standardized Precipitation Index (SPI)

Developed by McKee et al., (1993), the SPI for a location of interest is computed using a long term precipitation record for a desired period. The precipitation record is first fit to a gamma distribution, which is then transformed to a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). Values of SPI below zero indicate dry conditions, whereas positive values indicate a wet period. Computationally efficient, the SPI can be calculated for a variety of time scales, thus allowing monitoring of short-term (soil moisture) and long-term (groundwater) water supplies. However, the drawback is that it uses only precipitation and is only loosely connected to ground conditions (Muhammad et al., 2017).

2.2.2. Antecedent Precipitation Index (API)

The Antecedent Precipitation Index (API) is an index of moisture stored within a drainage basin before a runoff event and is often used for estimation of runoff response from rainfall events on watersheds that have a sparse meteorological gauging network. The Province of Manitoba's Hydrologic Forecasting Centre (HFC) uses an API based model, known as Manitoba Antecedent Precipitation Index Model (MANAPI), as an operational tool for monitoring soil moisture. MANAPI is a lumped index model developed in the early 1970s. In its current state, MANAPI is a snowmelt model that uses soil moisture, effective precipitation, and winter precipitation along with multiple regression and unit hydrograph theory for producing snowmelt-based flood hydrographs (Muhammad, 2019). Winter precipitation is the portion of the accumulated precipitation from October to March, which is obtained by applying a scaling coefficient to the total precipitation in each month. The method is based on the principle of establishing a statistical relationship between API and observed streamflow of past years. Floods in the prairie region are often due to the result of rainfall on top of, or shortly after, the snowmelt event. Since MANAPI is a snowmelt-based model it does not have the ability to produce reliable forecasts during rain on snow events or runoff purely due to rainfall (Infrastructure and Transportation, 2013). Further, being an event-based model, MANAPI has much less flexibility in terms of simulating the flood hydrograph that involves significant variation in daily inputs. Also, a number of model intercomparing studies that included MANAPI suggested that it was an average performer (Infrastructure and Transportation, 2013). The Hydrologic Forecasting Centre of Manitoba (HFC) is moving away from MANAPI for estimating spring runoff because spring runoff is becoming very subjective (Unduche, F personal discussion).

2.2.3. Standardized Precipitation and Evapotranspiration Index (SPEI)

SPI and API use precipitation as the only input for assessing basin moisture conditions - variables such as temperature, relative humidity, evapotranspiration, wind speed, etc. are not considered.

The SPEI developed by Vicente-Serrano et al., (2010) addresses limitations noted in aforementioned drought indices. Beguería et al., (2014) and Vicente-Serrano et al., (2012) have provided complete theoretical descriptions of the SPEI and its comparison with other drought indices and is thus not repeated here. Several other researchers (Parsons et al., 2019; Wable et al., 2019) evaluated and recommended the use of SPEI over other drought indices. Using SPI as the basis, SPEI considers the difference between precipitation and reference evapotranspiration (P – ET). The climatic water balance (P – ET) thus provides a more reliable measure of basin moisture conditions compared to indices that only incorporate precipitation inputs. SPEI has an intensity scale in which both positive and negative values are calculated, identifying wet and dry events respectively. SPEI can be calculated for timesteps of as short as one month up to several years. A classification table (Table 1) can be used to categorize the level of drought severity or excess moisture.

Table 1: Standardized Precipitation and Evapotranspiration Index (SPEI) classification system (Based on SPI)

SPEI values	Classification
2.0 +	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Very dry
-2.0 or less	Extremely dry

2.3. Experimental setup

The feasibility of SPEI for assessing basin moisture condition in the SRB was tested using two scenarios. In Case 1 the SRB was considered as a lumped unit while in Case 2 the SRB was split into 12 subbasins (Figure 4). For Case 1, all data grid points that fall within the basin were averaged resulting in one point representing average climatic conditions of the basin. In Case 2, the point that falls nearest to the centroid of the subbasin was used for SPEI computation. That means 12 points, each representing the centroid of a subbasin, is utilized for assessing the subbasin conditions.

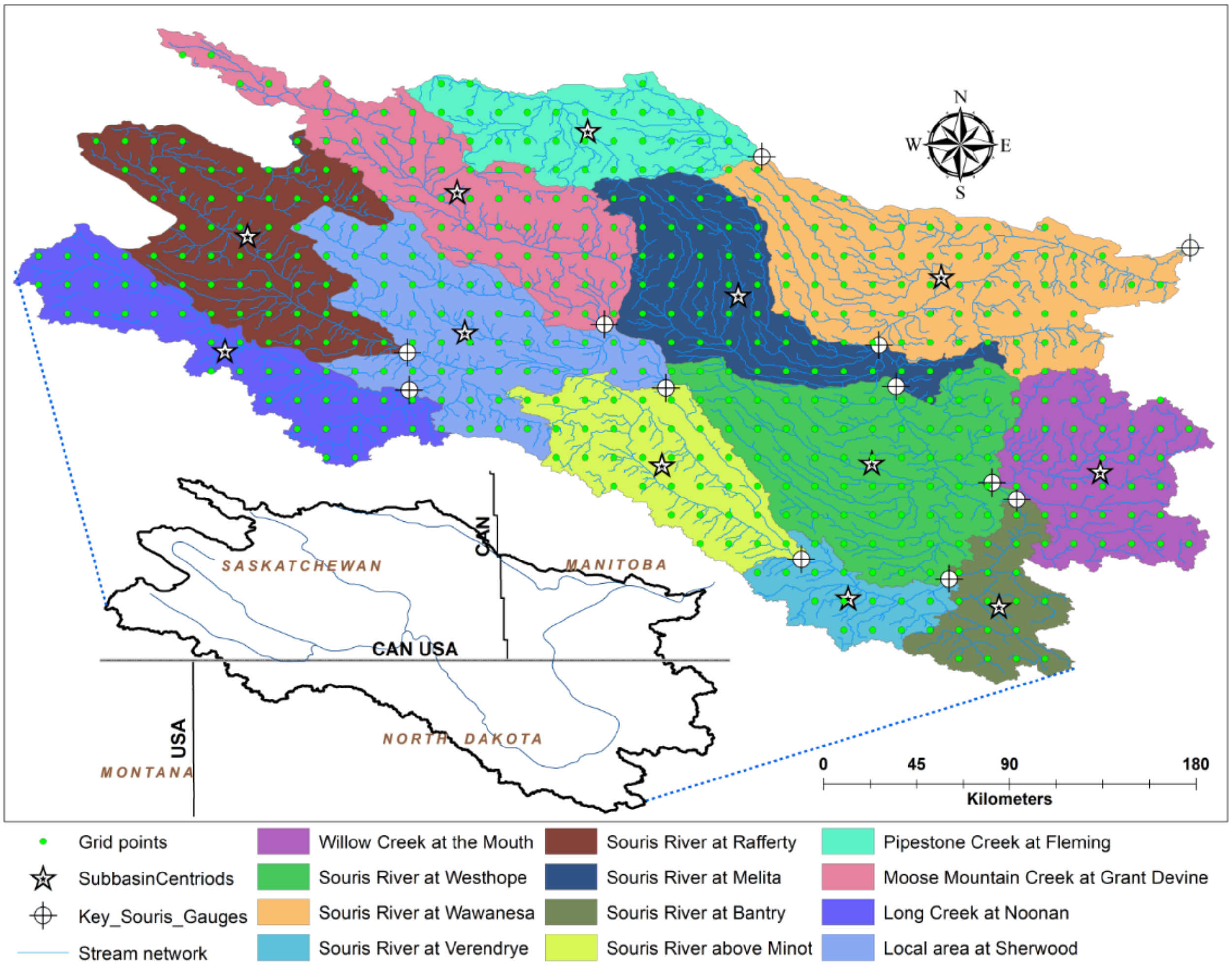

Figure 4: Discretized Souris River Basin along with basins centroid, hydrometric, and WFDEI-GEM-CaPA grid points.

Furthermore, assessment of basin moisture condition was completed at multiple timescales of 6, 9, 12, and 24 months, which is important as timescale matters when assessing impacts on the availability of water resources. For example, soil moisture anomalies respond to precipitation anomalies on a relatively short timescale while reservoir and wetland storage would reflect changes in precipitation on a longer timescale (World Meteorological Organisation, 2012). Please note, a 6-month SPEI provides a comparison of the precipitation over a specific 6-month period with the precipitation totals from the same 6-month period for all the years included in the historical record. In other words, a 6-month SPEI at the end of March compares the October 1 to March 31 precipitation totals in that particular year with the October 1 to March 31 precipitation totals of all the years on record for that location (World Meteorogical Organisation, 2012).

3. Results and Discussion

3.1. Case 1: Entire Souris River Basin as a lumped system

The aim of assessing conditions at the basin scale was to identify all years where extreme conditions were present in the basin. In particular, we were interested in assessing the ability of the SPEI in representing these extreme conditions at various timescales. Please note that the result at 6 and 12-month timescales are presented and discussed here. The readers are referred to Appendices 3 to 10, for SPEI results at 9 and 24-month timescales.

Figure 5 shows SPEI result for the entire SRB at 6 and 12-months between 1979 - 2016. A number of dry and wet episodes are identified at both timescales. For example, the late 1980's period is identified as an extreme drought/dry situation under both timescales. Similarly, the year 2010-2011 is identified as extremely wet conditions under both timescales. A high degree of fluctuation in SPEI can be seen at the 6-months scale compared to 12-months. This may be due to the fact that moisture entering the system has a quicker response than moisture leaving the system. On the other hand, it takes longer for precipitation deficiency to have any visible impact on reservoir or streamflow depletions.

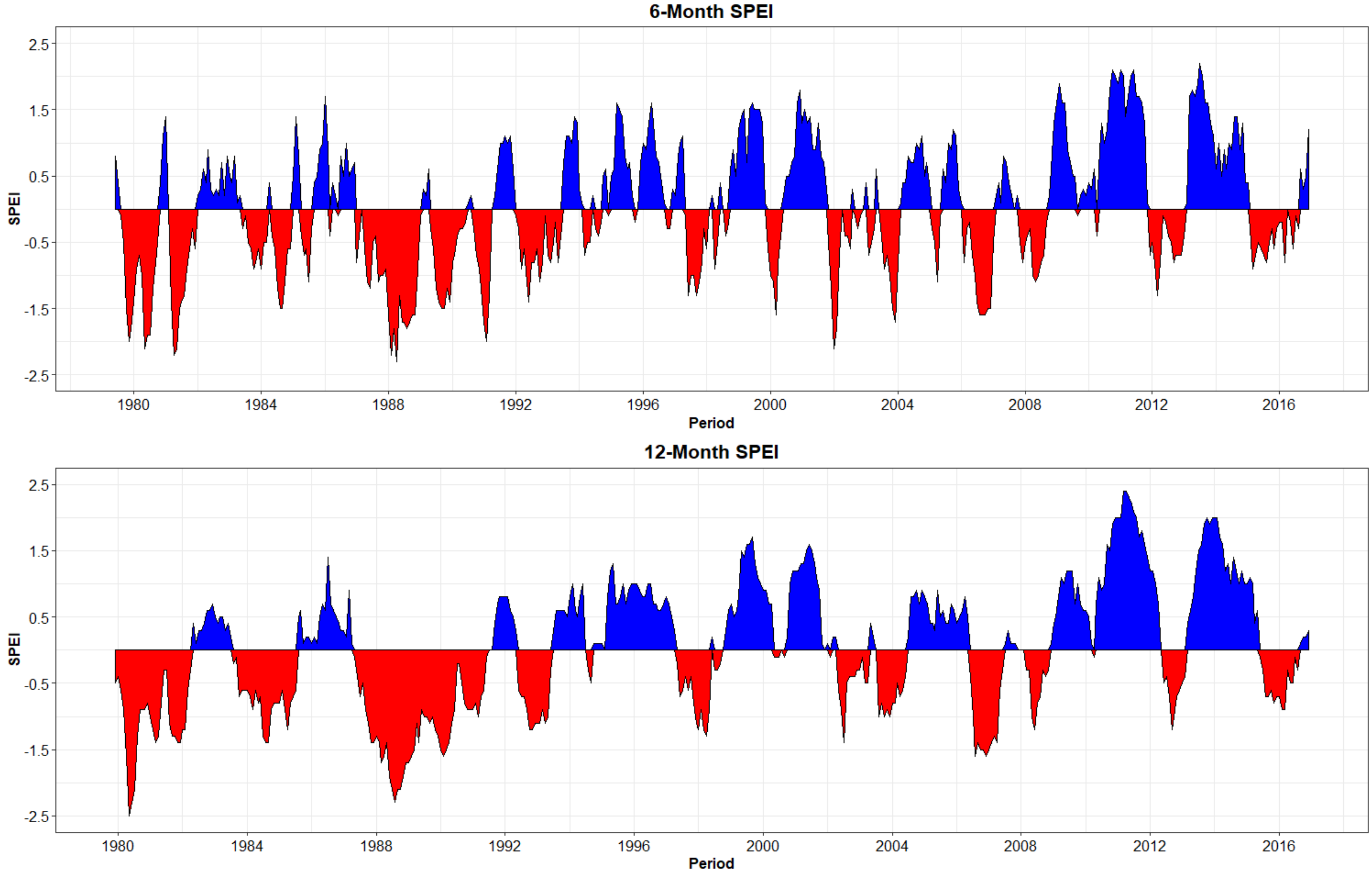

Figure 5: Timeseries plot at 6- and 12-months scale for the entire Souris basin over the period 1979-2016

Previous literature indicates that, among the identified wet and dry spells, the years 1988 and 2002 were the driest (Bonsal and Wheaton, 2005) while the years 2011 and 2014 were the wettest (Dumanski et al., 2015). Thus, the interests were narrowed down to these periods only. Table 2, present presents basin conditions at 6 and 12-month timescales for those identified extreme years over the 1979 – 2016 period.

Table 2: Assessing Souris River Basin (SRB) conditions at 6 and 12-months SPEI scale

SPEI Time scale	**Dry**		**Wet**	
	1988	**2002**	**2011**	**2014**
6-months	-1.84	-0.66	1.35	0.46
12-months	-1.73	0.23	2.36	1.71

A few differences can be observed while assessing the basin conditions at 6 and 12-month timescales. For example, the basin is assessed as moderately wet for the year 2011 at 6-month scale while extremely wet at 12-month scale. Figure 6 helps to explain these differences. The SRB was extremely wet before freeze-up with well above normal precipitation in both the summer and fall of 2010 (~ 150 to 200%) followed by heavy winter precipitation. This paved the way for a well above normal spring runoff in the basin. The 6-month scale SPEI captures the climate water balance (CWB) conditions of the preceding six months (Sep – Mar), thus it misses the heavy precipitation that occurred over the summer. On the other hand, SPEI at the 12-month scale considers CWB conditions of the preceding 12 months, thus categorizing the basin as extremely wet. Since basin moisture conditions at freeze-up plays a large role in the snowmelt runoff potential within the prairie pothole region, calculating the SPEI for a period greater than six months is likely necessary (in this case) if assessing runoff potential at the end of the winter season. This would ensure that the periods that consider the antecedent moisture conditions prior to freeze up are included.

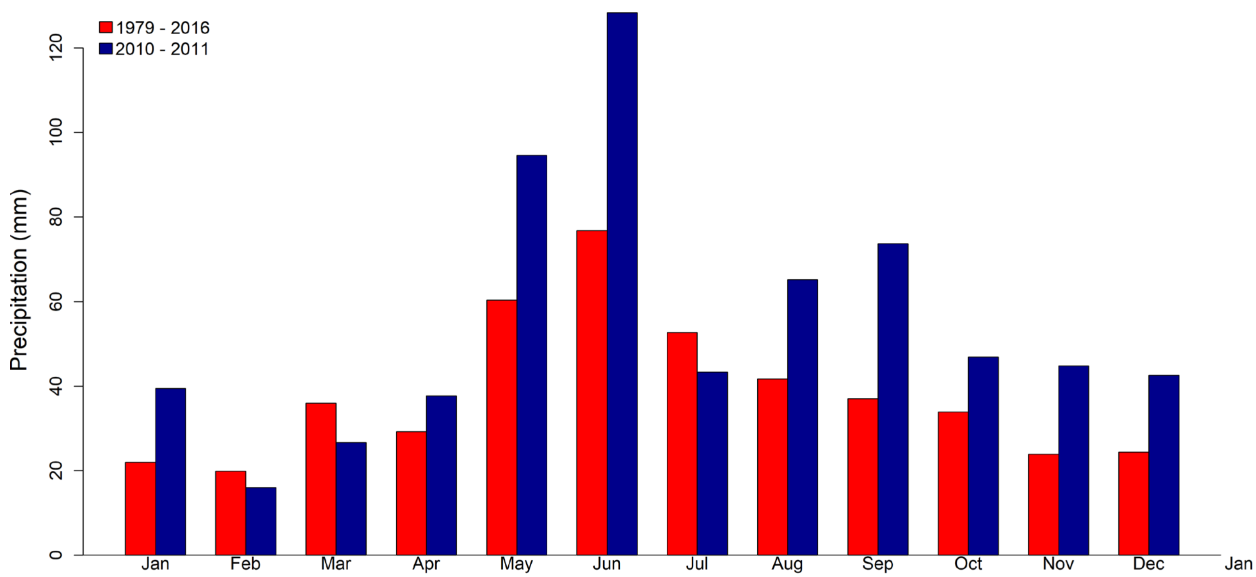

Figure 6: Precipitation of the year 2010-2011 in comparison to the long term mean precipitation over the 1979-2016 period. June to December (in blue) presents data of the year 2010 and January to May (in blue) presents data of the year 2011.

3.2. Case 2: Souris River basin (SRB) condition assessment at subbasin scale

Modeling the SRB at the basin scale helped identify extreme events and the level of dry/wet severity. However, it does not provide information on the spatial extent of these extreme events and the variability across the subbasins. The SRB was therefore split into 12 subbasins (see Figure 4) with the aim of assessing moisture conditions and the variability among them. These subbasins were established at important control points in the system (reservoirs and the international crossings).

Figure 7 shows SPEI result for all the subbasins at a 6-month scale. As can be seen from the figure, all subbasins experienced wet and dry episodes. The extreme events identified in Case 1 are also captured at the subbasin level. However, the level of severity differs from basin to basin.

For example, at the 6-month scale, the Souris River at Verendrye sub-basin appears to be going through extremely dry conditions whereas the Souris River at Melita subbasin is at moderately dry conditions during the 1988-89 drought period. Likewise, for the extreme wet conditions during 2010-2011, the Long Creek at Noonan subbasin appears to be wetter in comparison to the Willow Creek at the Mouth subbasin. In Figure 8, SPEI result at 12-month scale are presented. Like Figure 6, several wet and dry episodes can be seen. The extreme events in the year 1988-89 and 2010-11 are well replicated. Like the 6-month scale, the variability in basin conditions among the subbasin is clearly visible. For example, During the year 1988-89, Souris River at Noonan is categorized as being relatively dry in comparison to the Souris River at Melita subbasin, while during the extreme wet episode of 2010-11, Pipestone Creek at Fleming is categorized as being much wetter than Willow Creek at the Mouth (confluence with Souris River).

Assessing basin moisture conditions at the subbasin level also provides a good indication of the magnitude and duration of these extreme events for different regions. An extreme event duration is a period when SPEI is continuously below or above the extreme threshold value as identified in Table 1. For example, the duration of dry conditions at the 12-month scale (Figure 8) for the Souris River at Verendrye subbasin is longer than that of Souris River at Melita.

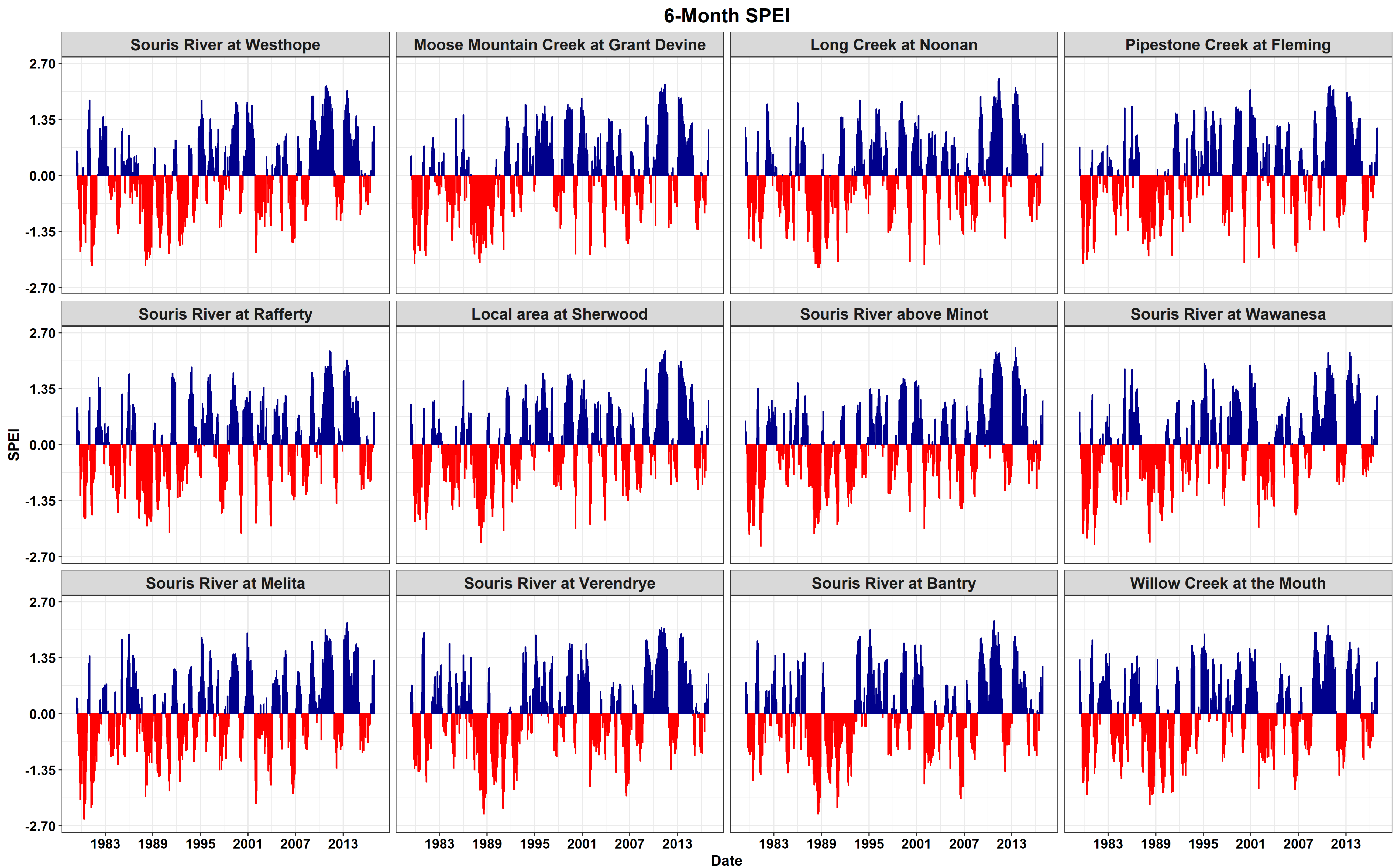

Figure 7: Timeseries plot at 6-months scale for the subbasins in the Souris River Basin (SRB) over the period 1979-2016

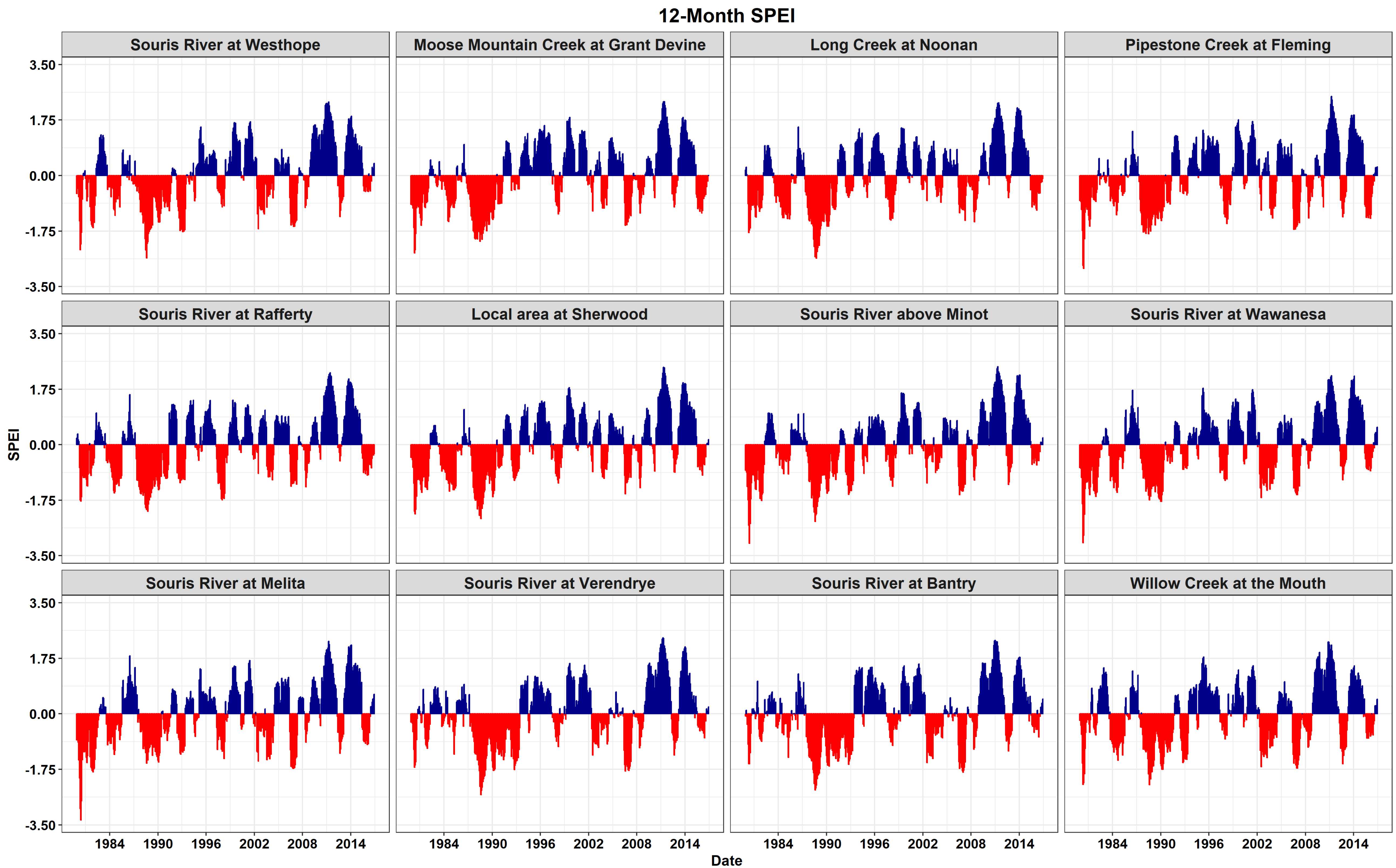

Figure 8: Timeseries plot at 12-months scale for the subbasins in the Souris River Basin (SRB) over the period 1979-2016

Because the central focus of basin moisture condition assessment was the spring season, the analysis was further narrowed down to the April 1st forecast. Figure 9 shows geo-spatial maps of SPEI for all 12 subbasins of the Souris River at a 6-month timescale for select years ranging from extremely dry to extremely wet.

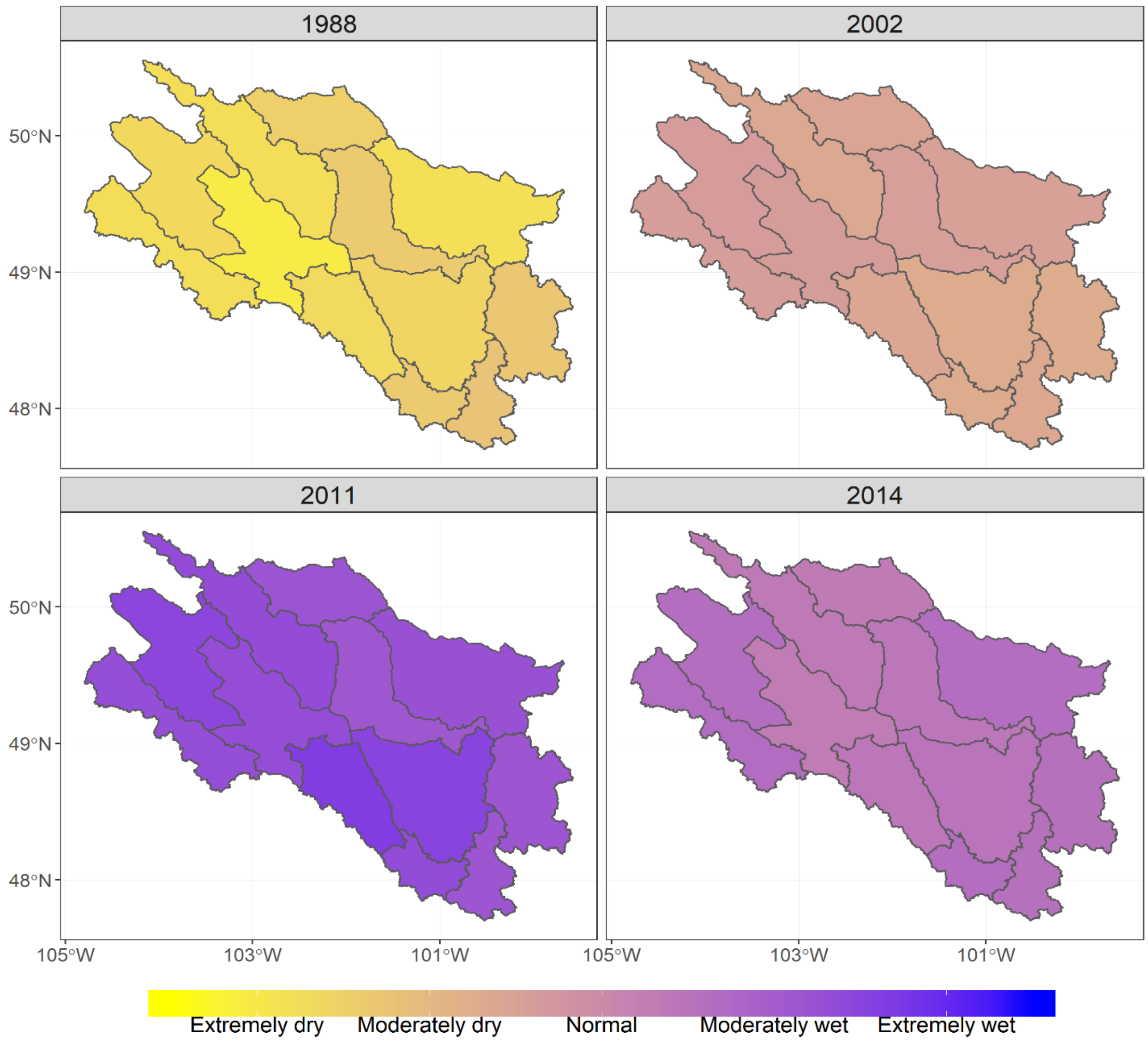

Figure 9: Geospatial maps of Souris River subbasins displaying results of 6-month SPEI for April 1st of the identified extreme events

The entire basin during the year 1988 is categorized as extremely dry to moderately dry in general with minimal variability in the level of severity among the subbasins. The differences in the level of severity could be due to convective precipitation, which are localized precipitation events over a smaller area, causing differences among the subbasin moisture conditions. During the year 2011, the basin can be categorized as moderately to extremely wet, which is mainly due to heavy precipitation during the preceding six months.

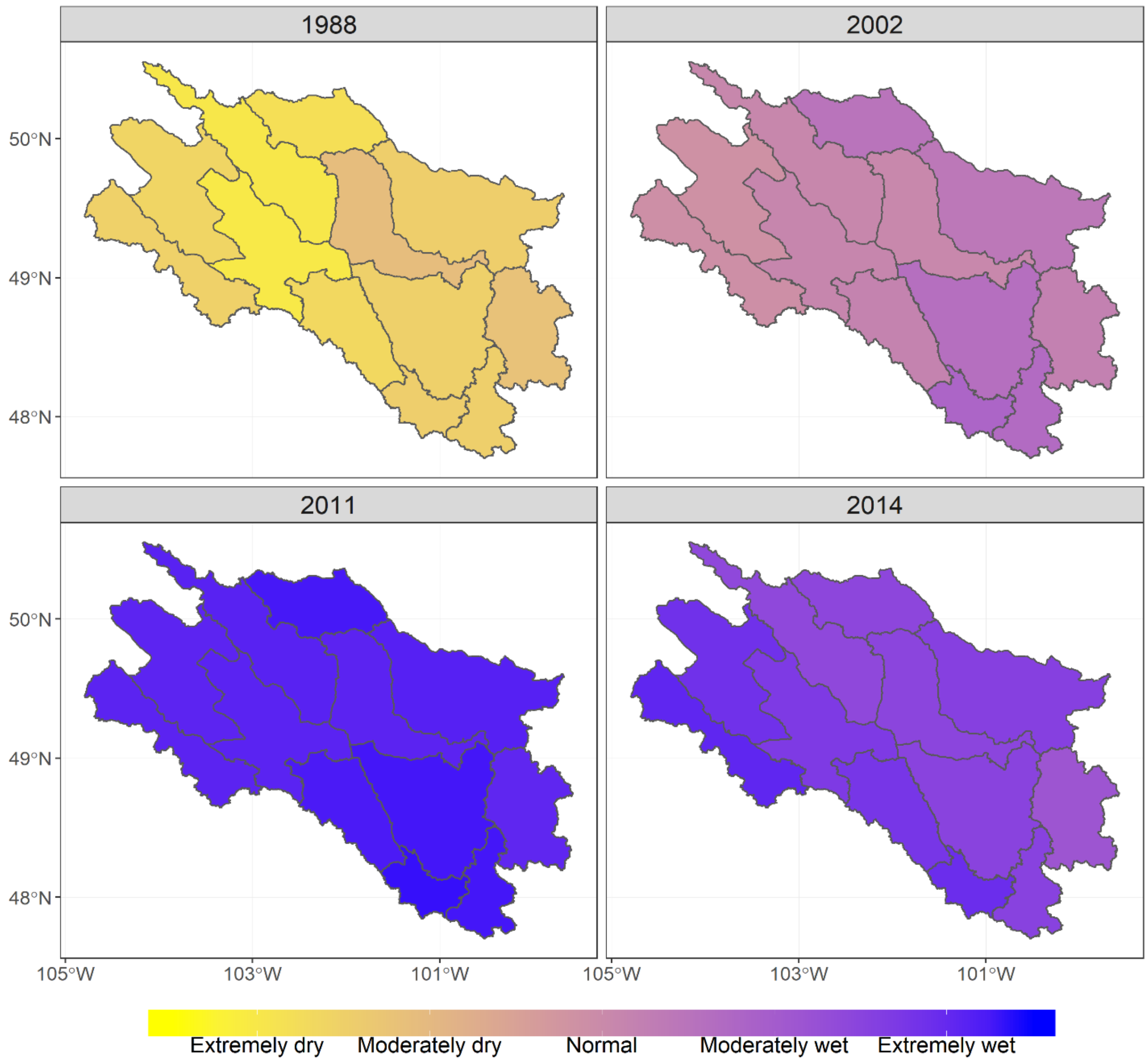

Figure 10: Geospatial maps of Souris River subbasins displaying results of 12-month SPEI for April 1st of the identified extreme events

In comparison to Figure 9, the year 2011 in Figure 10 is categorized as extremely wet due to the heavy precipitation in summer as well as fall during the year 2010 and winter precipitation of the year 2011. In the analysis, a moisture gradient northwest to southeast was notices, with northwest being relatively drier in comparison to the southeast portion of the basin. These results were found consistent with Millett et al., (2009) and Waiser, (2012) who observed a similar trend.

3.3. SPEI versus following year spring runoff

The importance of antecedent moisture in estimating watershed runoff is well established. Therefore, an attempt to correlate SPEI computed at multiple timescales with runoff was made. The runoff data utilized here was generated under Souris-POS Task HH1: Regional & Reconstructed Hydrology for the period of 1979-2016. We used the total runoff generated in the spring snowmelt period (March-April-May). The SPEI computed at multiple timescales for April 1st was then regressed against spring runoff to determine the strength of the SPEI verses runoff. The analysis at multiple SPEI timescales also aids in determining the duration where SPEI has the strongest relation with spring runoff.

Figure 11 shows the results of linear regression analysis of 6-month (Oct to Mar) SPEI vs spring runoff. Four subbasins were picked to test the strength of this relationship. Furthermore, to determine the significance of the strength between SPEI and runoff, we utilized p-value for our hypothesis test. Here the null hypothesis is that there is no relationship between SPEI and runoff. The alternative hypothesis, what we believe, is that a relationship exists between the two. The p-value provides us confidence regarding our claim and thus help us defend the strength we get between SPEI and runoff. Here the strength is determined using the coefficient of determination (R^2). For ease of comparison both R^2 and p-value are displayed on the figures.

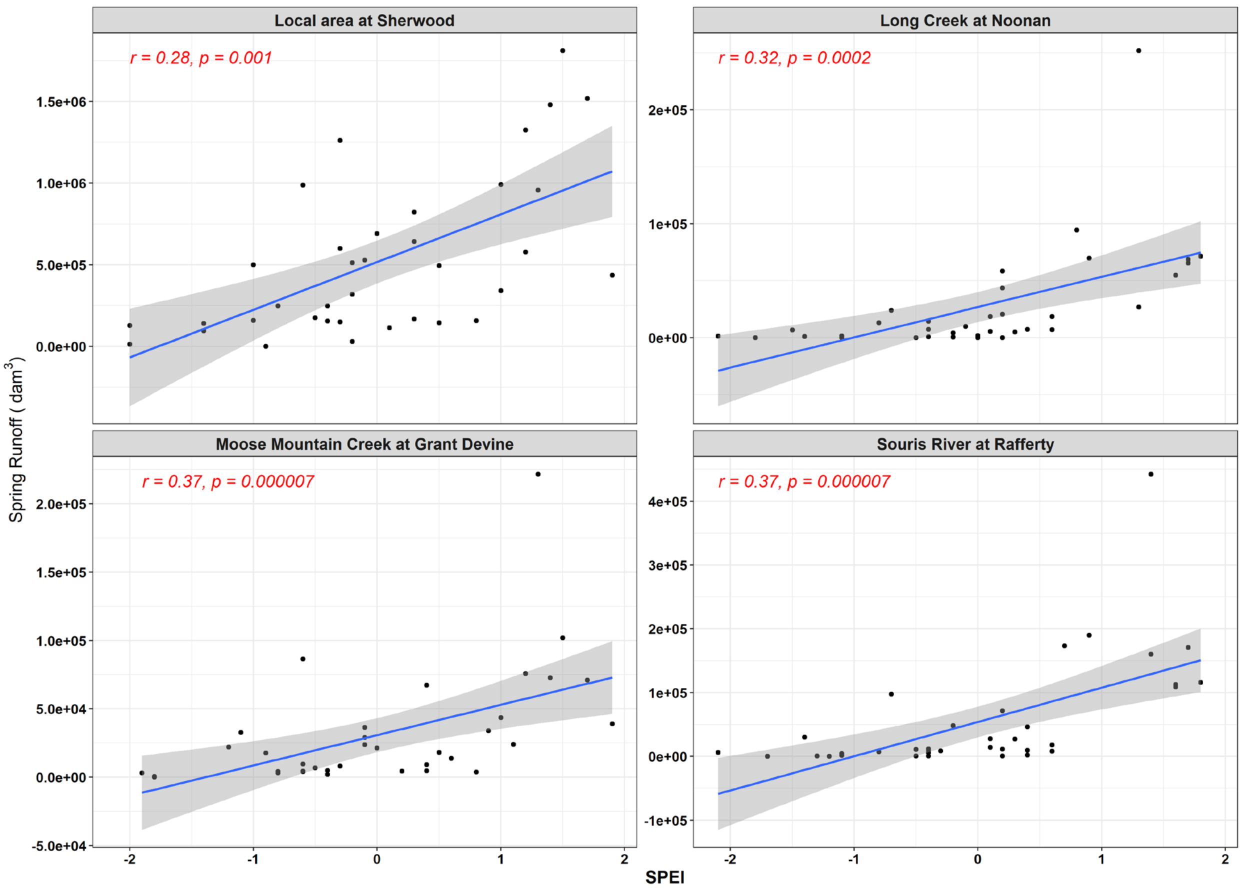

Figure 11: Correlation of Runoff vs SPEI (6-month) spring forecast for multiple subbasin

From the Figure 11, it is clear that positive correlation exists between SPEI and spring runoff. That means when conditions are wet, we would expect positive SPEI ultimately leading to high spring runoff. The relationship, however, is not strong and in general only 30 percent of the variability can be explained. The p-value is quite low, which gives us the confidence that the results are not by chance and that these results are quite significant. Figure 12 shows the results of linear regression analysis of 9-month (Jul to Mar) SPEI vs spring runoff.

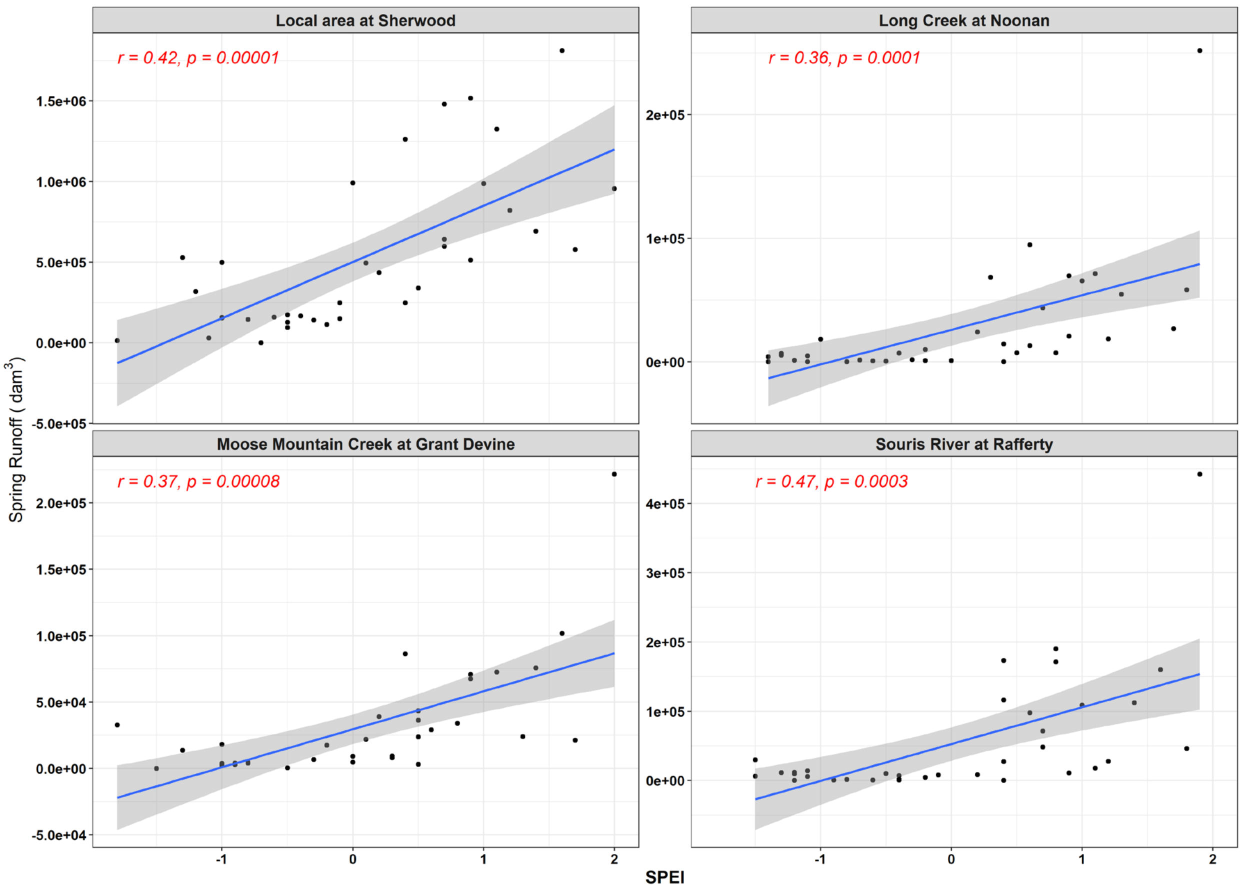

Figure 12: Correlation of Runoff vs SPEI (9-month) spring forecast for multiple subbasin

In comparison to Figure 11, we see slightly improved correlation between runoff and SPEI at 9-months timescale (Figure 12) with significant confidence (low p-value). This could be due to the fact of considering basin moisture condition before freeze-up as SPEI at 9-month scale would consider preceding 9-month basin conditions (July – March). What is obvious from all these correlation plots is that whenever we have a wetter condition, that is when SPEI is positive, we see runoff. When SPEI is below zero, drier conditions, we hardly see any runoff from any of the subbasins. This is an essential aspect as quantification of both dry and wet are equally important for water resource planning and management in the SRB. Results for the 12 and 24-month scale are attached as an appendix to this report and are not discussed here, due to better results at a 9-months scale compare to longer time periods.

3.4. On the relationship of spring runoff and SPEI value

There could be a number of reasons as to why the relationship between spring runoff and SPEI was low. The following are our hypotheses on why the relationship was not stronger:

- In this study, the data for the grid point that fell closest to the centroid of the basin was used to establish the relationship between basin moisture index and runoff at the outlet. All the basins are large and convective precipitation is not un-common. Thus, representing basin condition using a single point may have led to a low association with runoff. However, using point data from climate stations is likely how the tool would be used operationally.
- Basin moisture condition was assessed using the blended grid data WFDEI-GEM-CaPA product (for detail: Asong et al., (2018)) due to a sparse observation network. While the data has been verified, it still does not fully replicate climatology of the region. Thus, using the WFDEI-GEM-CaPA data set may have impacted the relationship.
- A low sample size (38 points in total) was utilized to derive the relationship between SPEI and runoff. Although there is no concrete evidence that would explain how sample size would impact correlation, a low number of observations may not fully represent the entire population. Thus, it is possible that our results may have been impacted by sample size.
- We attempted to establish a relationship with spring runoff using basin conditions up until the end of March. While the antecedent moisture condition has an impact on spring runoff, the moisture index does not consider any snow/rain event occurrence during the spring

season. Thus, there is a great deal of uncertainty which may have impacted the strength of SPEI vs Runoff relationship.

- The SPEI does not account for the melt conditions. The rate of melt can dramatically impact the runoff yield.

4. Varying Normal Drawdown (Phase 3.5 alternative 307) Research: An extension of SPEI work

This section was not part of the original scope of this study but was added in response to the need for a tool to assess antecedent moisture conditions at freeze-up for the HEC-ResSim modelling work. An index was needed to classify the moisture conditions at freeze-up that can be used to make winter drawdown decisions. Antecedent fall conditions, based on SPEI on October 31st, was computed for 3, 6, 9, and 12 -month periods and regressed against spring runoff volumes (March 1 to May 31). The goal was to develop a relationship between SPEI on October 31st and spring runoff volumes in the subsequent spring and determine thresholds that can be used to determine reservoir drawdown levels for February 1st.

The three major reservoirs: Rafferty, Grant Devine, and Lake Darling were all assessed. SPEI values for a climate station that fell within each catchment were computed for the 1930 – 2017 period. The Yellow Grass meteorological station was used for Rafferty, Carlyle and Oxbow stations were used for Grant Devine, and the Foxholm station was used for Lake Darling to generate SPEI values. The reconstructed hydrology dataset, created under Souris-POS task HH1, was used for computing spring runoff volumes. The runoff data was then plotted against SPEI values for October 31st and the results were analyzed. In this report, results for the Rafferty reservoir is presented and discussed. For Grant Devine Lake and Lake Darling please see Appendix 10 and 11 respectively.

Figure 13 shows spring runoff for Rafferty versus SPEI generated at 3, 6, 9, and 12-month scales for October 31st over the 1930-2017 period. The red dashed line represents the volume between full supply and normal drawdown level (47,242 dam^3 or 0.0113 mile^3). After presenting preliminary results to the POS's Plan Formulation Committee, it was suggested to also examine averaging the 3 and 12-month SPEI to put more weight on the most recent precipitation as well as to consider the longer-term conditions. Results of the regression analysis are also provided in Table 3.

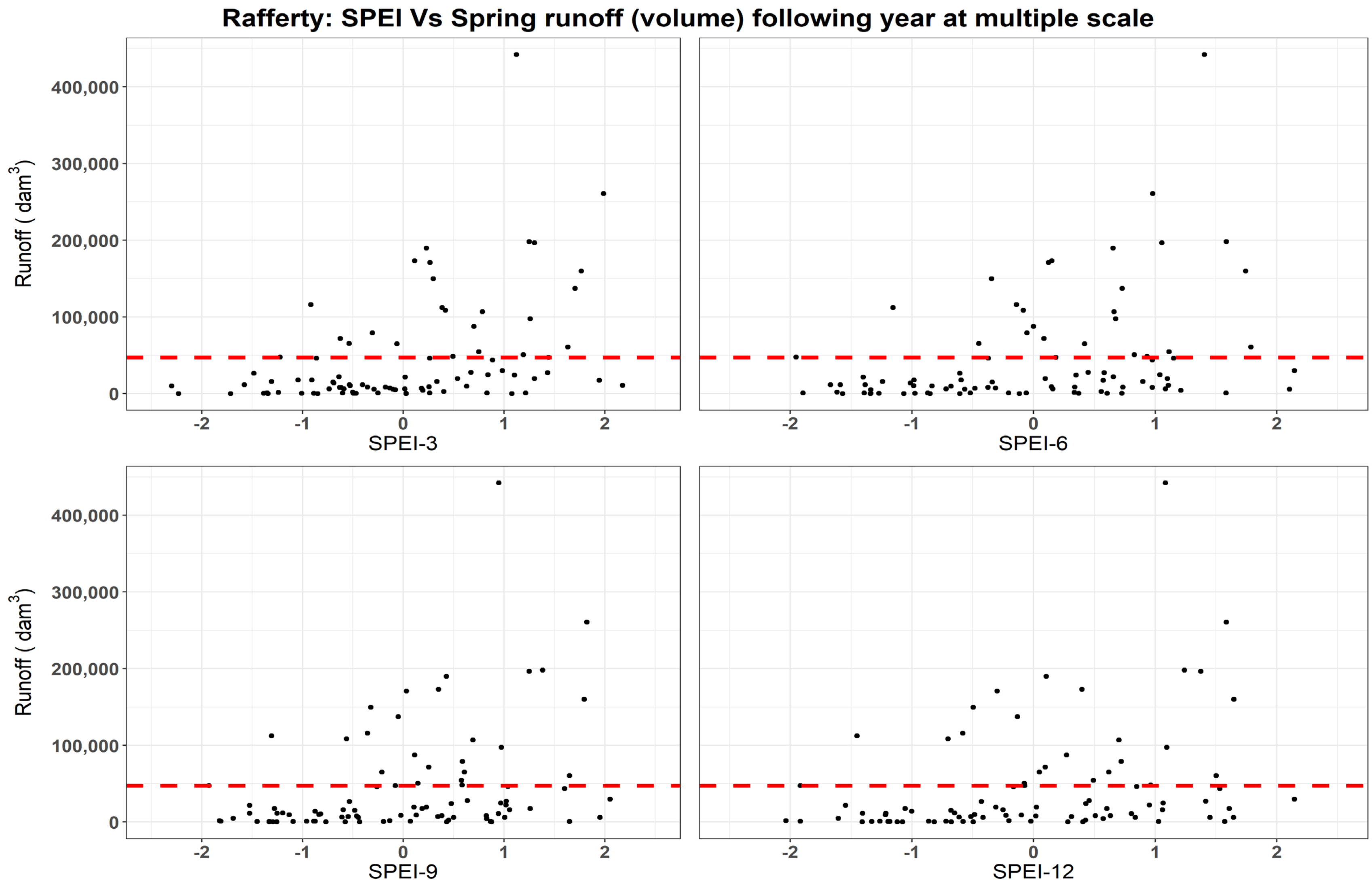

Figure 13: Spring runoff versus SPEI for Rafferty reservoir over the 1930 - 2017 period

Table 3: SPEI at Freeze-up vs Spring Runoff Regression Analysis Results

SPEI Time Scale (Months)	**R^2 (p-value)**		
	Rafferty	**Grant Devine**	**Lake Darling**
3	0.17 (< 0.05)	0.28 (< 0.05)	0.05 (< 0.05)
6	0.12 (< 0.05)	0.28 (< 0.05)	0.04 (> 0.05)
9	0.11 (< 0.05)	0.25 (< 0.05)	0.03 (< 0.05)
12	0.10 (< 0.05)	0.23 (< 0.05)	0.03 (< 0.05)
Average of 3 and 12	0.18 (<0.05)	0.34 (< 0.05)	0.05 (<0.05)

From the Figure 12 and Table 3, the correlation between spring runoff and SPEI for all of the SPEI timescales are not great. For example, with increasing SPEI values (wet basin conditions) one would always expect increasing spring runoff. However, the figure shows weak association. This is mainly due to the complex nature of snowmelt runoff in the Prairie Pothole Region where a single variable is not sufficient to fully explain the runoff generation mechanism with such a long lead time, which in this case is five months. For example, in Figure 12, there are instances where SPEI is greater than 2, however, little to no spring runoff can be observed. The reasoning for this could be that a wet fall is followed by a dry winter which causes little to no runoff. There is however some insight that can be extracted from the plots. For example, when the SPEI value is below -0.5 there is a high likelihood that the spring runoff volume in the following year will be insufficient to bring the reservoir up to the FSL if the reservoir is drawn to the normal drawdown level (NDL) and a low risk of a large runoff event. Which means the reservoir should not be drawndown to the NDL level if this SPEI threshold is not met.

The same analysis was completed for Grant Devine and Lake Darling. The results are attached as Appendix 10 and 11, with similar conclusions.

5. Conclusion and future recommendation

Antecedent moisture before freeze-up and winter precipitation are among the key contributing factors that determine the severity of floods on the Prairies. After review of several indices, the Standardized Precipitation and Evapotranspiration Index (SPEI) was identified as the most suitable index for estimating moisture conditions within the Souris River Basin. It has the potential to improve spring runoff forecasts and thus enhance decision-making capacity regarding water resources planning and management within the basin.

In this study, the SPEI was tested to simulate basin moisture conditions at basin and subbasin levels. Testing SPEI at the basin level allowed for the identification of extreme wet and dry conditions while implementing SPEI at the subbasin scale helped define the spatial extent, magnitude, and severity of these events. Furthermore, an attempt was made to establish relationship with spring runoff forecast.

The result at both basin and subbasin scale correctly replicated all the historical extreme events with variation in the level and magnitude of these events basin to basin. We noticed that there is a moisture gradient from northwest to southeast, with southeastern areas receiving higher precipitation. On the regression plot of spring runoff vs SPEI, the strength of the relationship was low in general, however, statistically significant in all cases. Further, it was observed that SPEI at the 9-month scale has better relationship with spring runoff forecast in comparison to all other timescale of SPEI. In addition, significant runoff was observed only when conditions were wet, as defined by the SPEI.

The use of SPEI to assess antecedent conditions can greatly enhance decision-making capacity regarding reservoir drawdown before spring runoff. The analysis undertook suggests that if the SPEI values are below -0.5 at 6-month scale or when SPEI is below -1.0 at 3-month scale, it is very unlikely that the spring runoff would be sufficient to bring the reservoir level at FSL, thus a likely decision would be to draw down to the NDL.

A limitation of the study was the availability of reliable data and prior research, which limited the scope of the analysis. For a comprehensive moisture index assessment, following future research areas are recommended to be explored.

- Comparison of SPEI vs other drought indices such as Palmer Drought Severity Index (PDSI), Effective Drought Index (EDI), Evaporative Demand Drought Index (EDDI), and MANAPI etc,
- This study utilized the log-logistic distribution for fitting precipitation data and Hargrave for computing potential evapotranspiration (PET). We recommend exploring other distribution fitting and physically based PET estimation techniques while computing SPEI.
- The SPEI threshold selected is based on visual inspection of graphs. These thresholds could be set based on probabilistic analysis.
- Spring runoff was the main interest point during the study, it is however, recommended to test the technique on other time periods, such as for summer events.
- Research ways to incorporate more variables such as wind speed, solar radiation, and soil moisture.
- Research ways to use SPEI as a proxy for soil moistures in forcing hydrologic models could also be completed.

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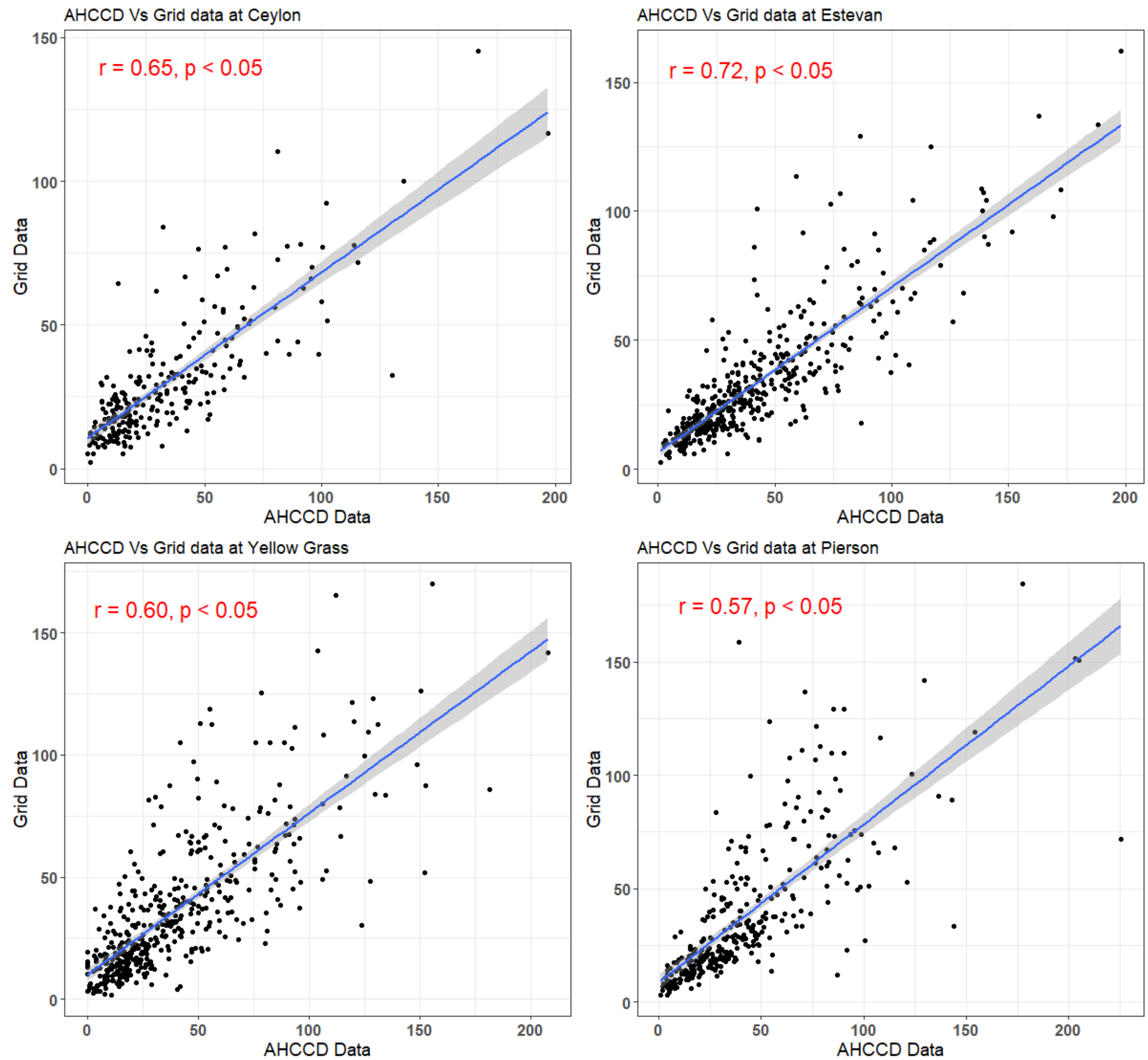
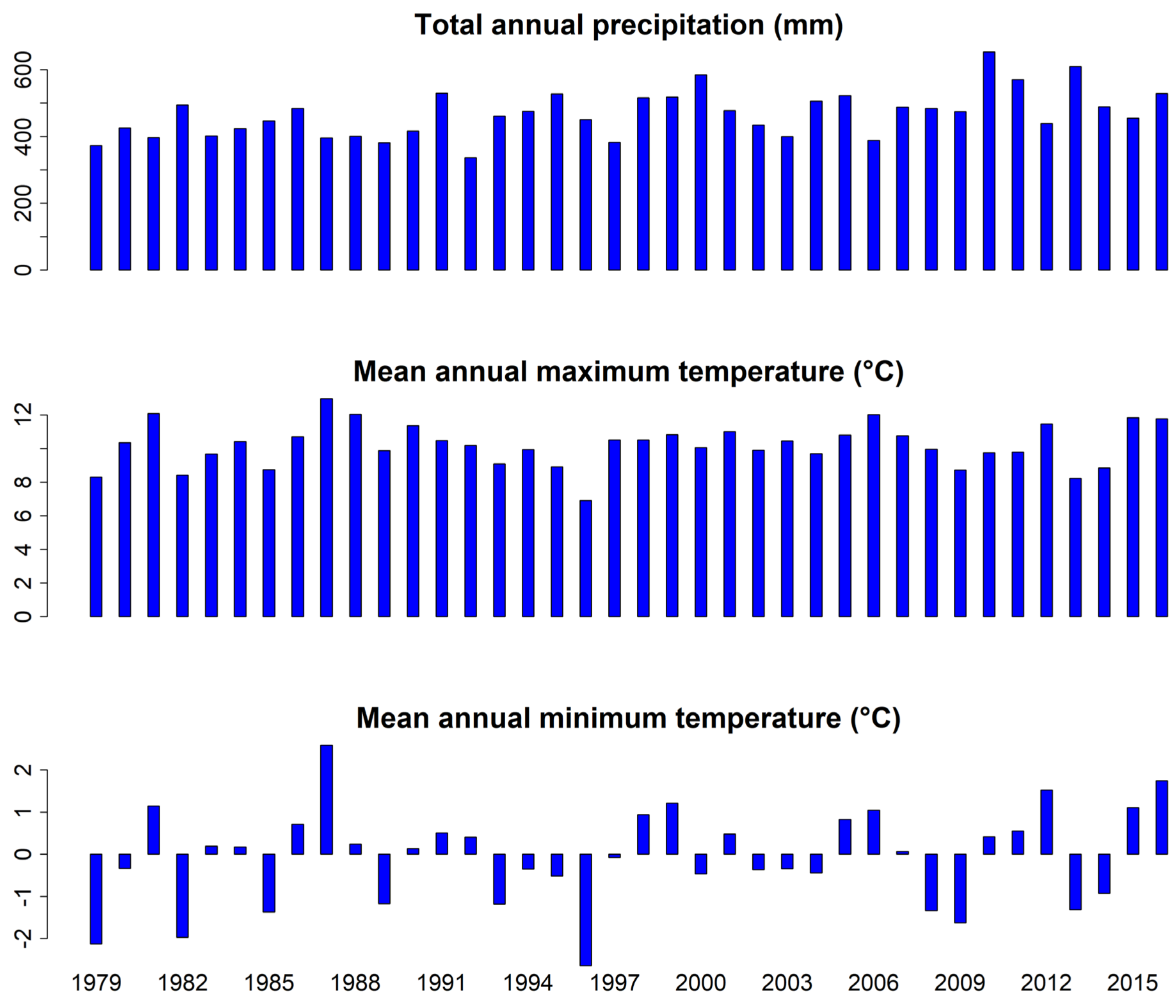
Appendices



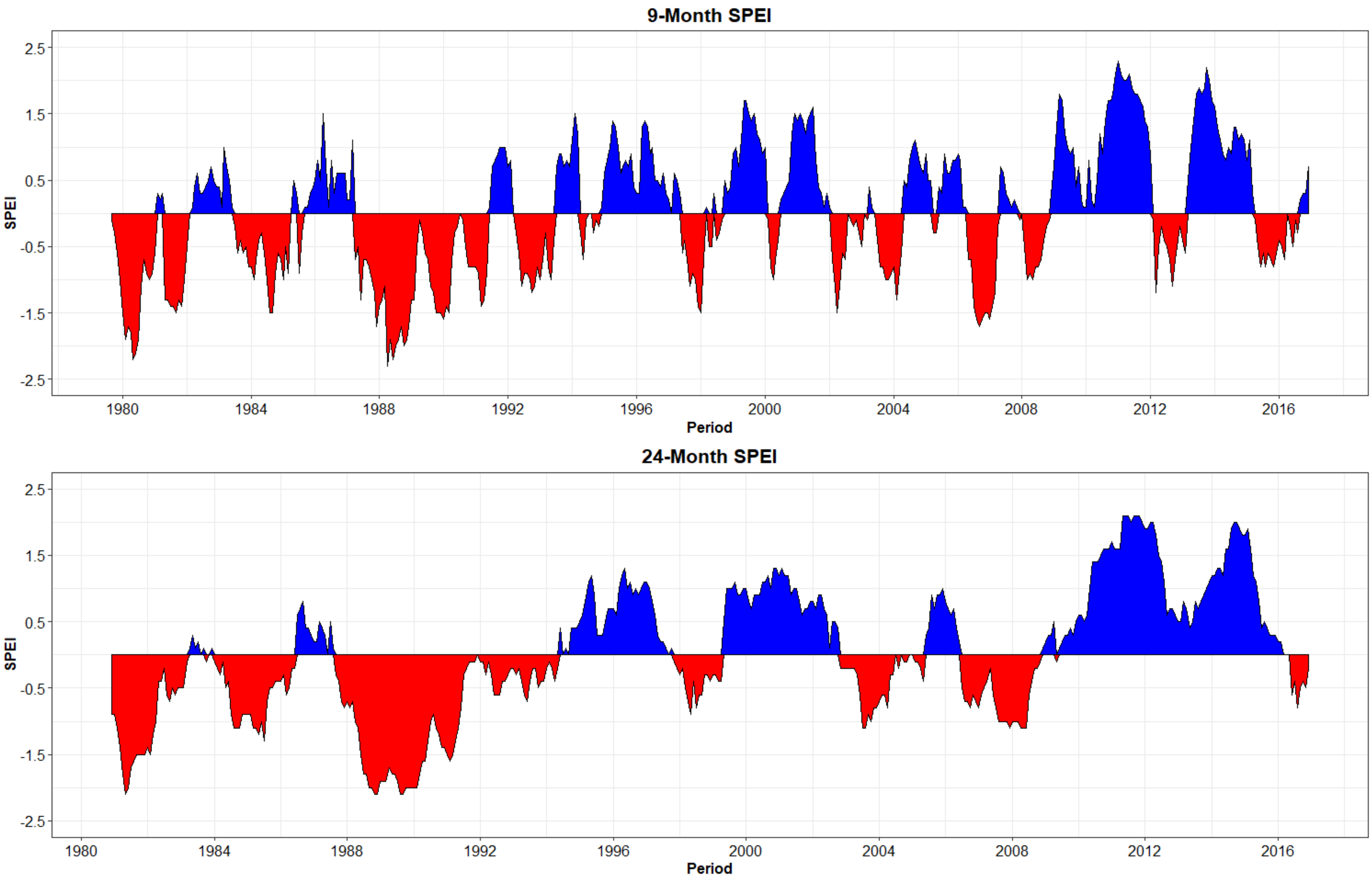
Appendix 1: Scatter plots of WFDEI-GEM-CaPA vs selected ground based observed precipitation over the 1979 – 2016 period.



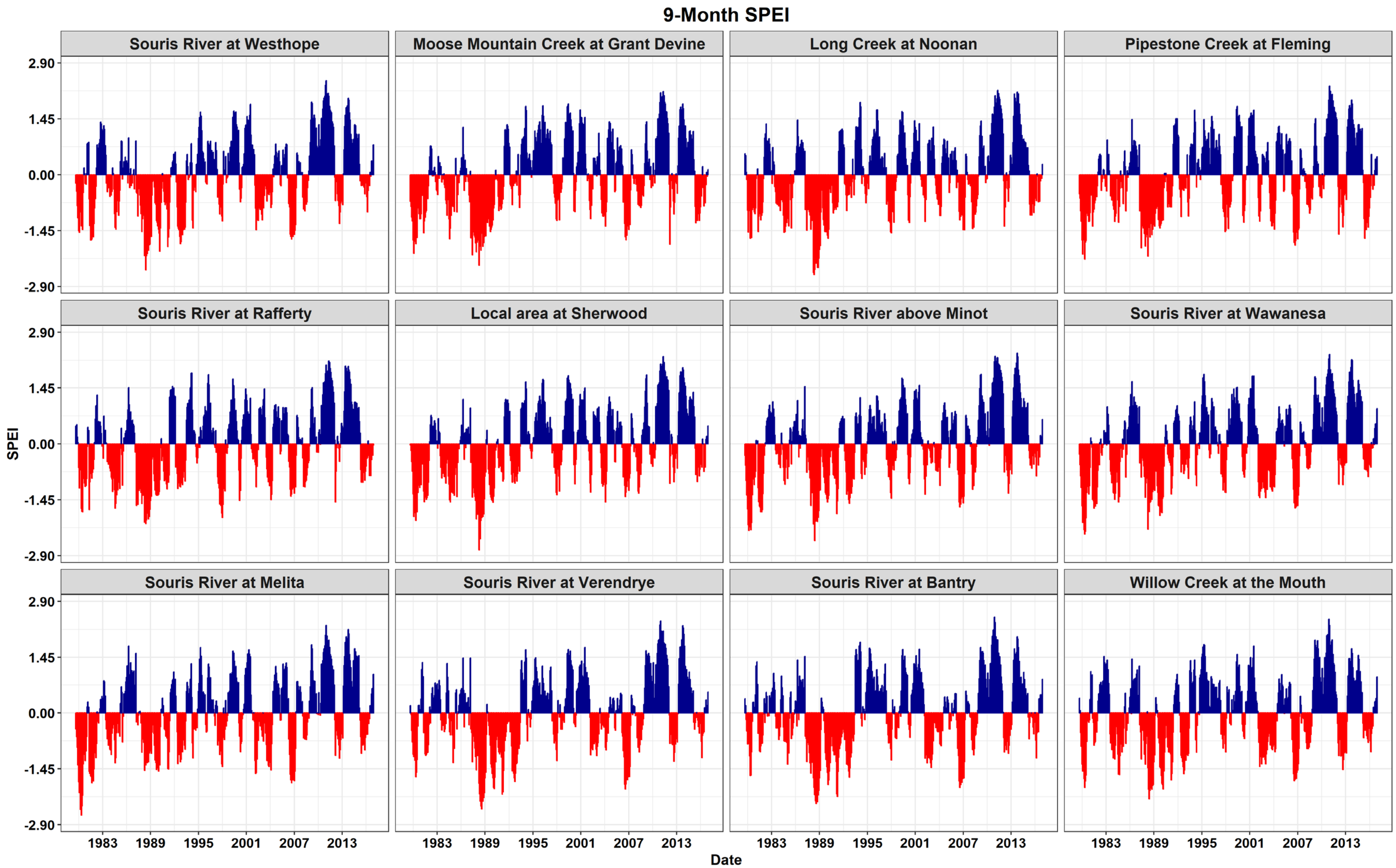
Appendix 2: Total precipitation, mean annual maximum and minimum across SRB over the period 1979 - 2016

SPEI Time scale	Dry		Wet	
	1988	**2002**	**2011**	**2014**
6-months	-1.84	-0.66	1.35	0.46
12-months	-1.73	0.23	2.36	1.71

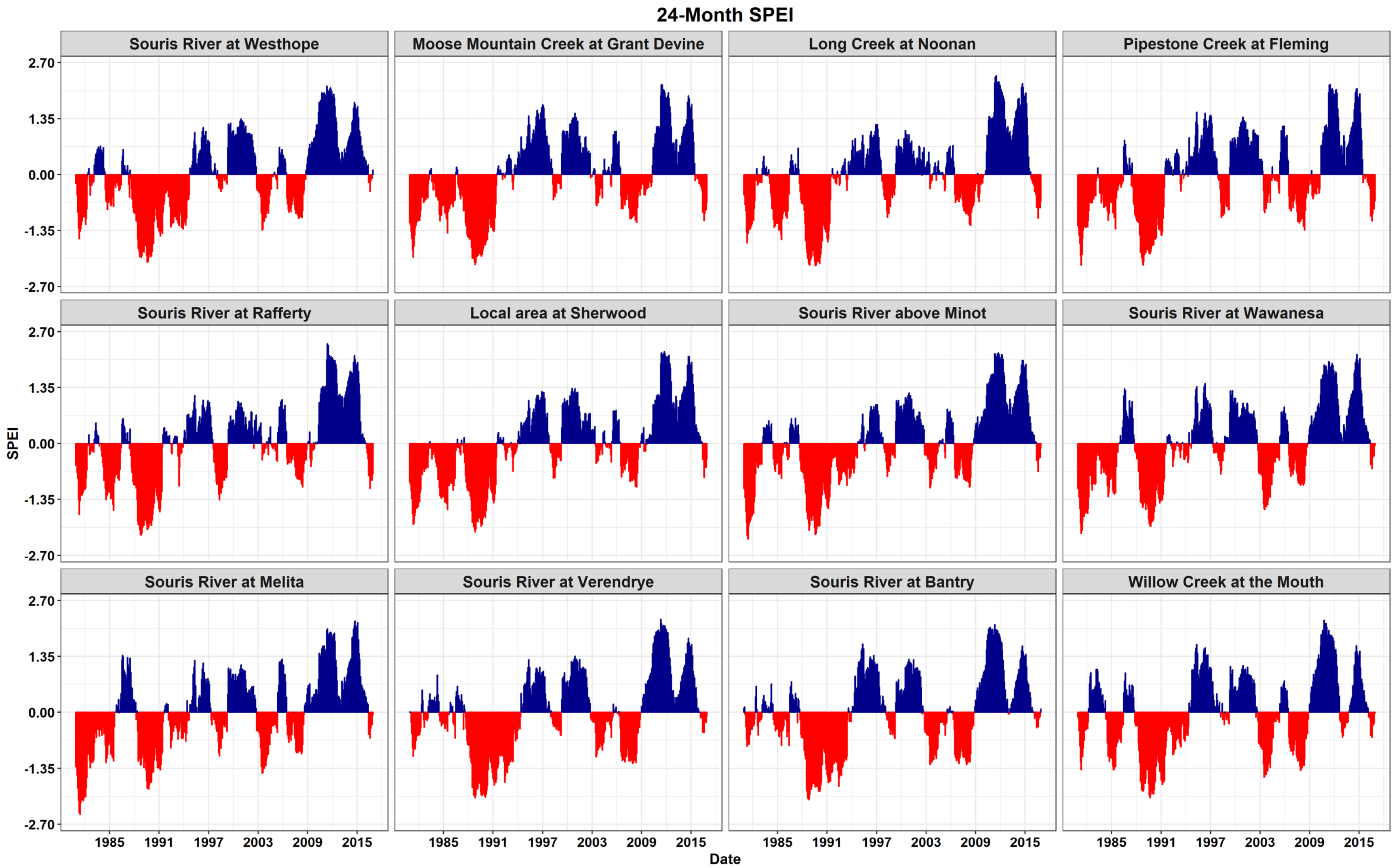
Appendix 3: Assessing Souris River Basin (SRB) conditions at 9 and 24-months SPEI scales



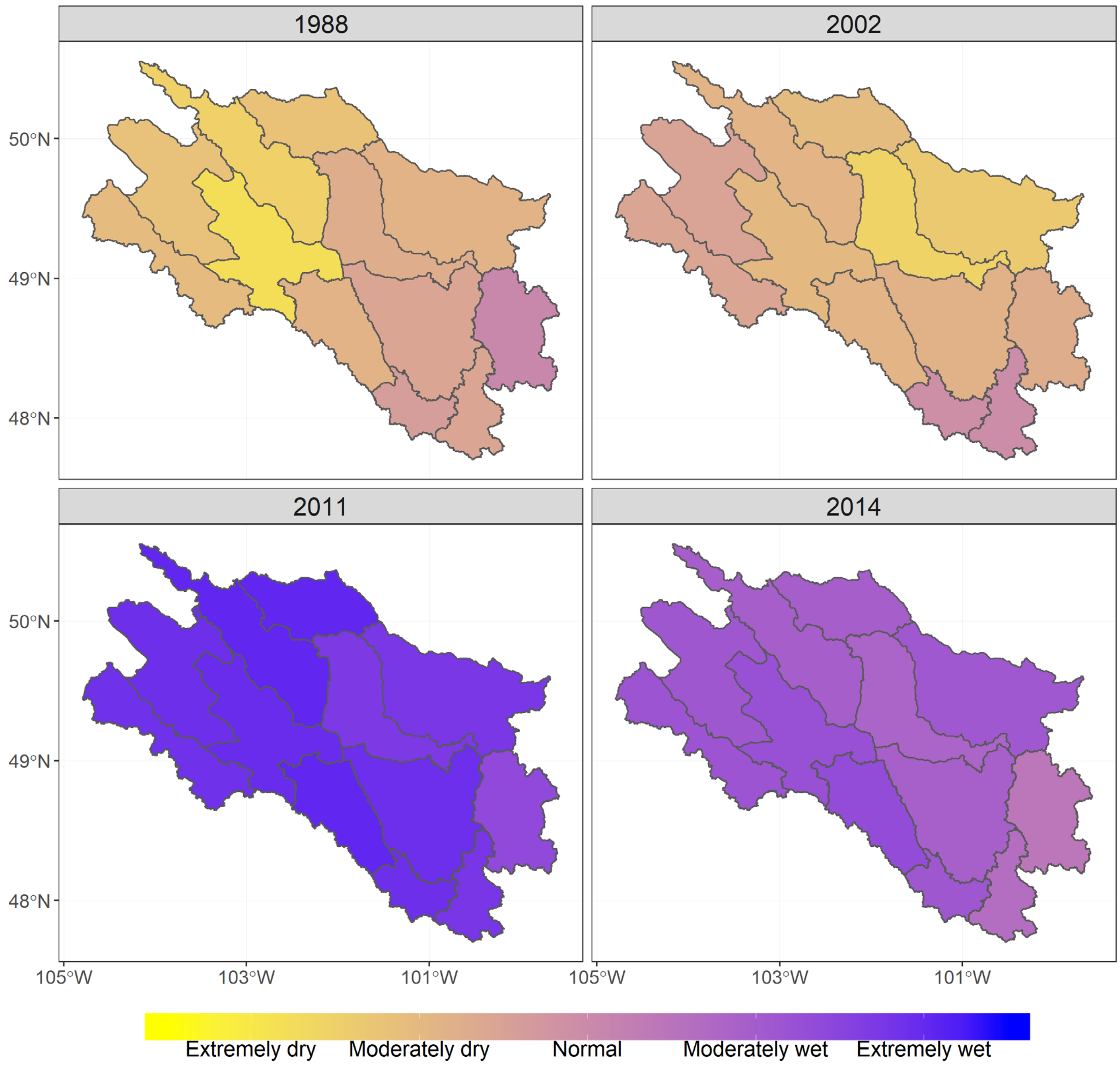
Appendix 4: Timeseries plot at 9-month and 24-month scales for the entire Souris basin over the period 1979-2016



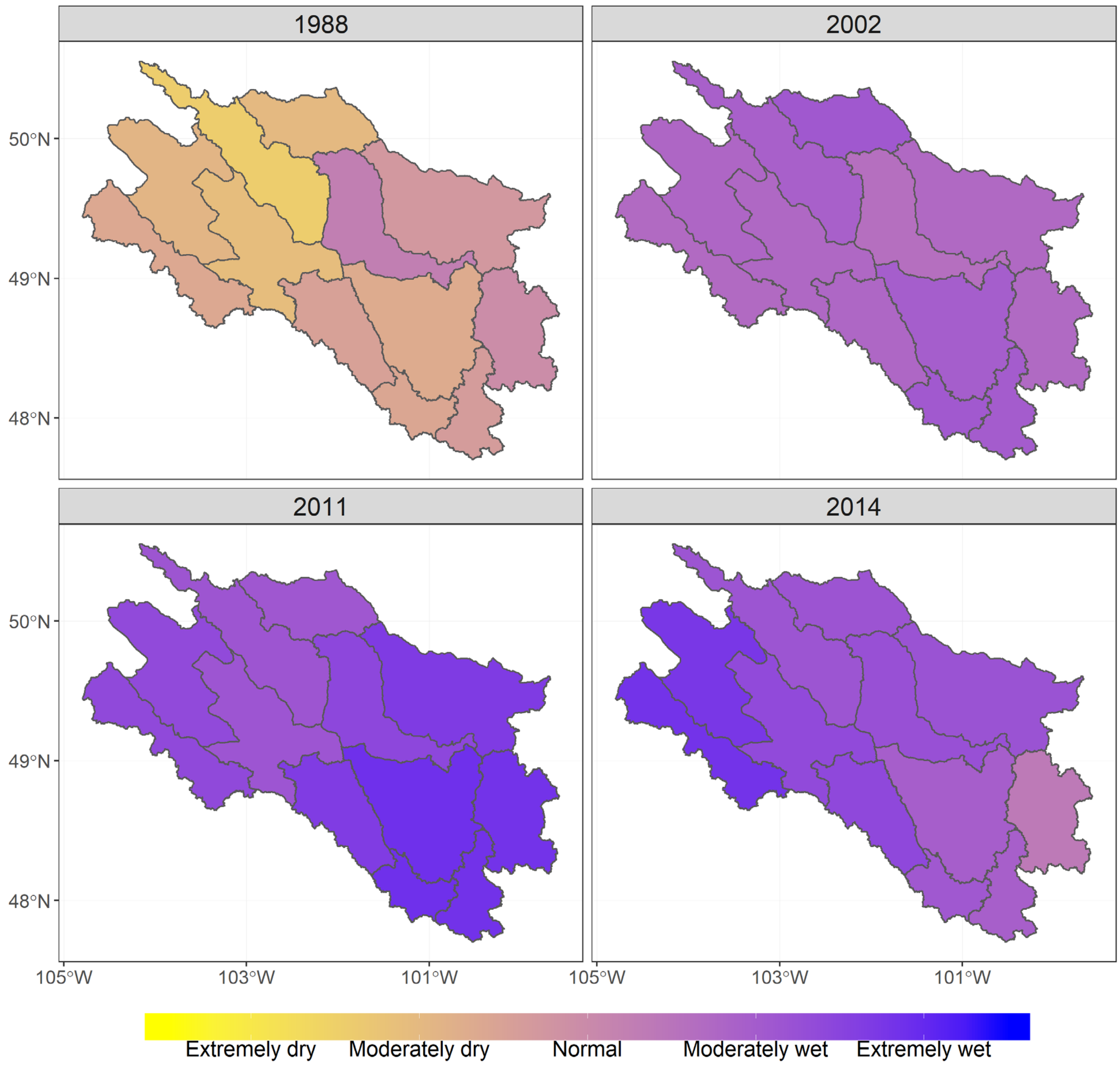
Appendix 5: Timeseries plot at 9-month scale for the subbasins in the Souris River Basin (SRB) over the period 1979-2016



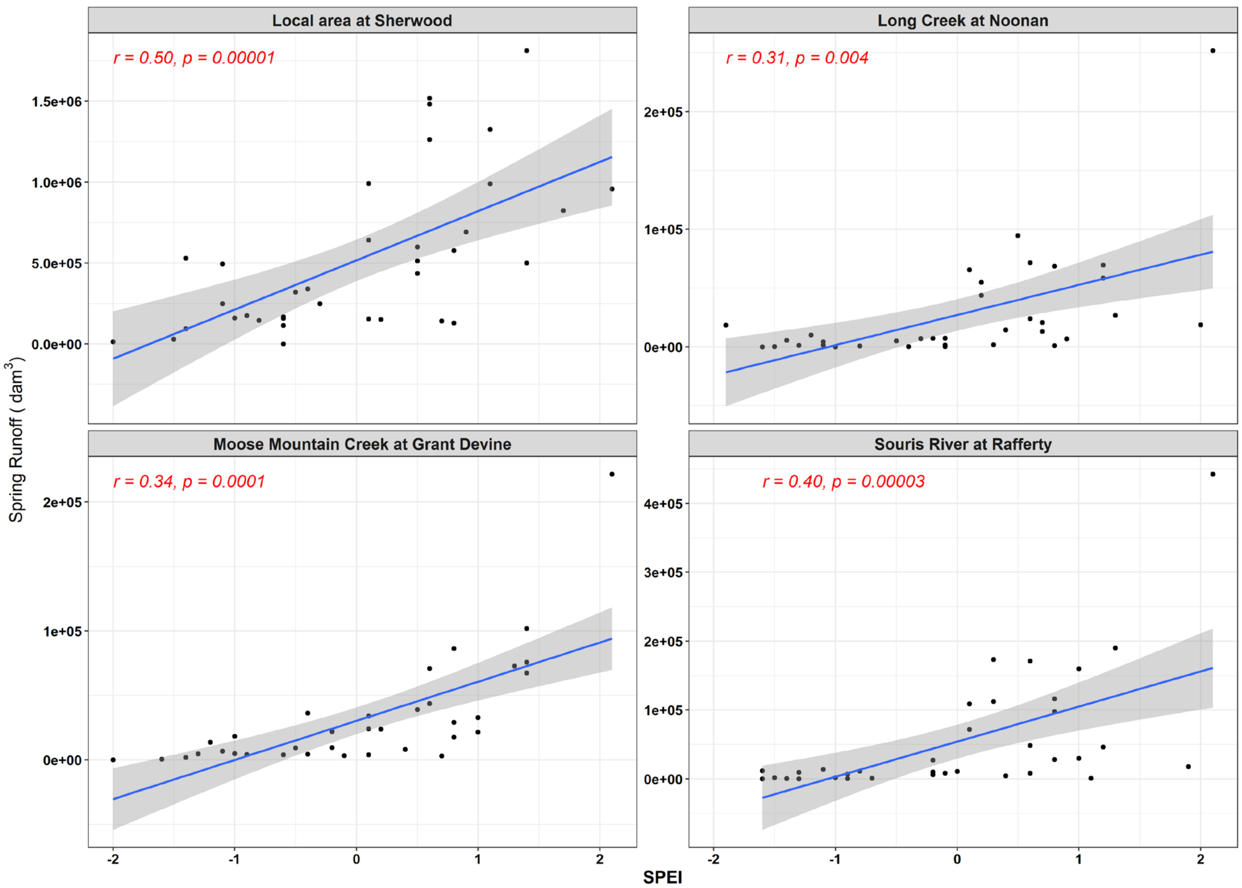
Appendix 6: Timeseries plot at 24-months scale for the subbasins in the Souris River Basin (SRB) over the period 1979-2016



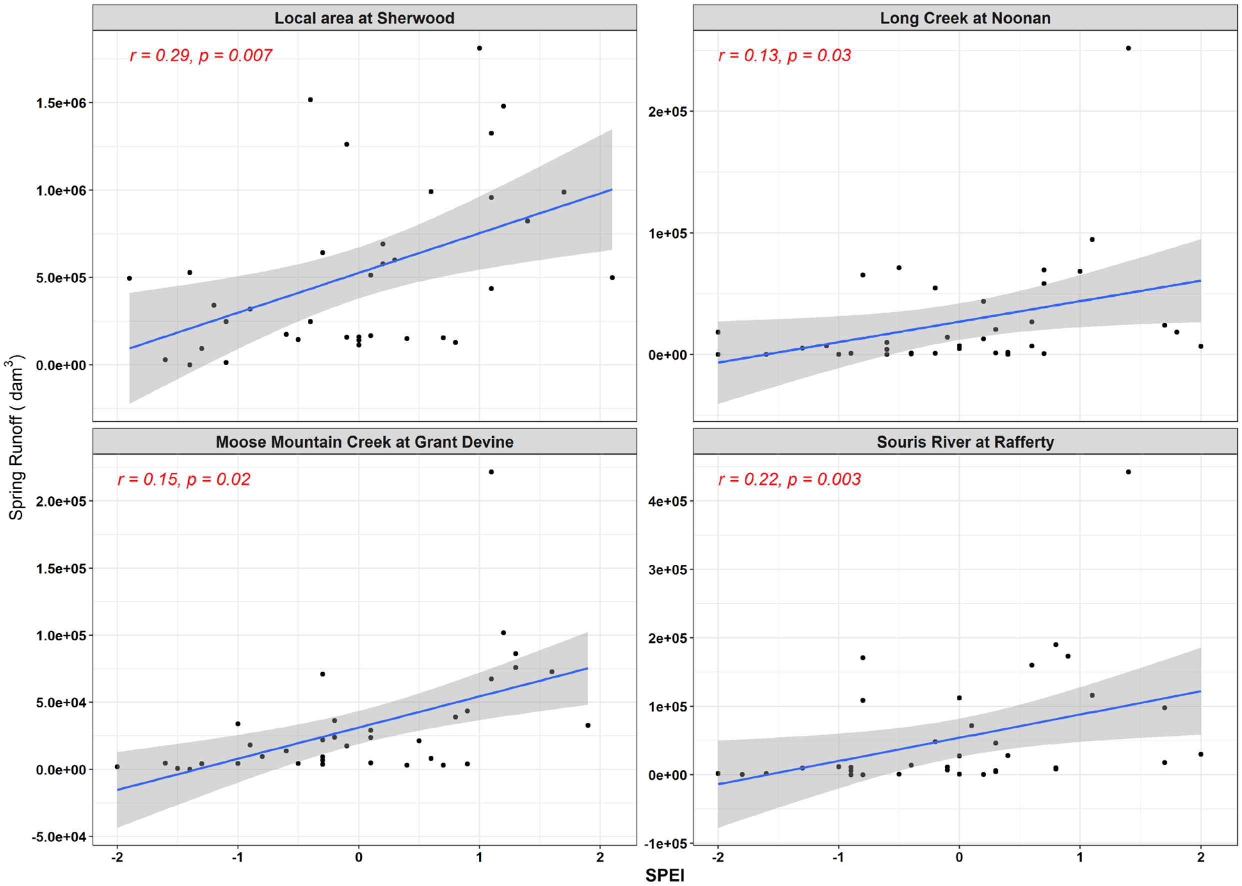
Appendix 7: Geospatial maps of Souris River subbasins displaying results of 9-month SPEI for April 1st of the identified extreme events



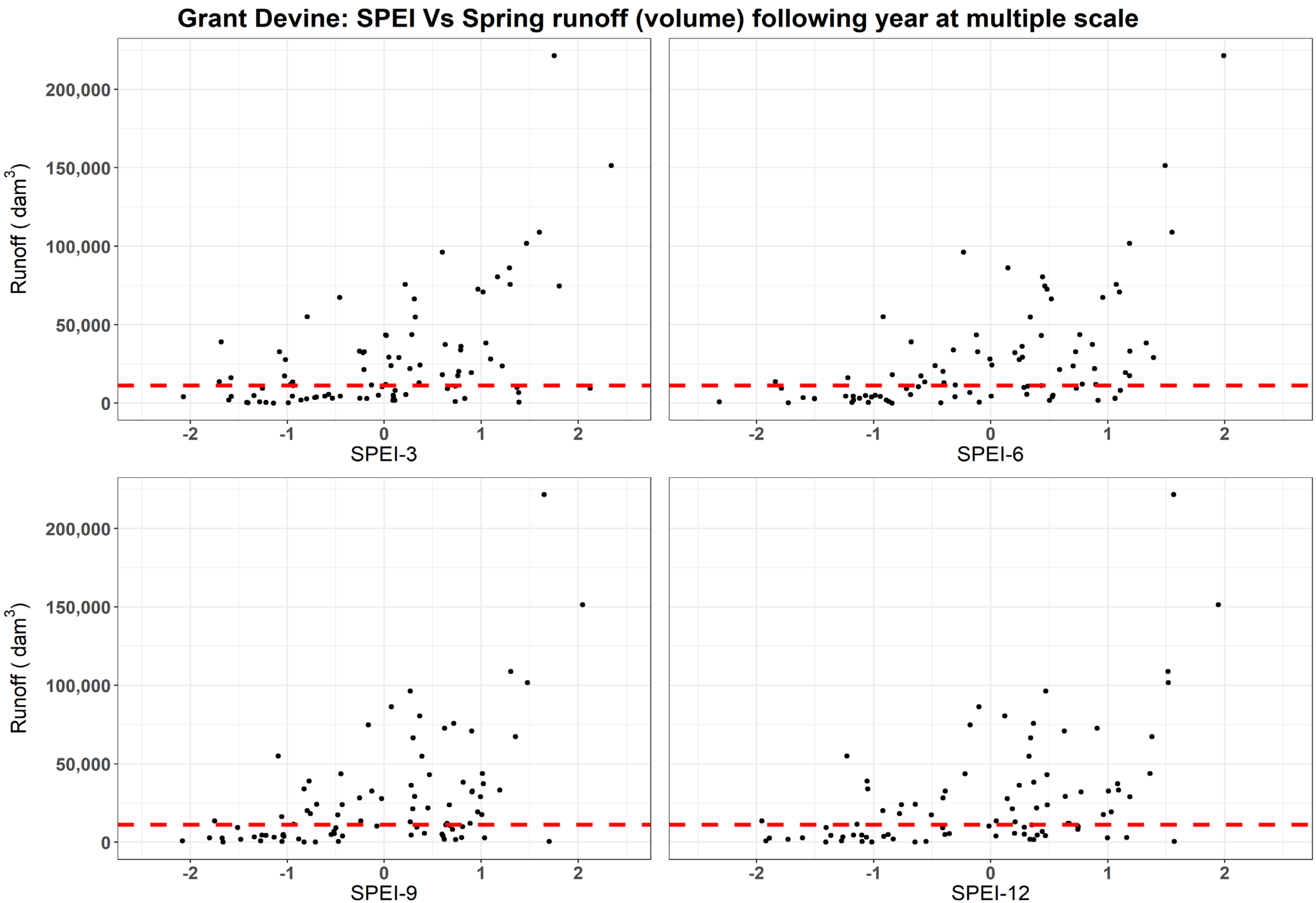
Appendix 8: Geospatial maps of Souris River subbasins displaying results of 24-month SPEI for April 1st of the identified extreme events



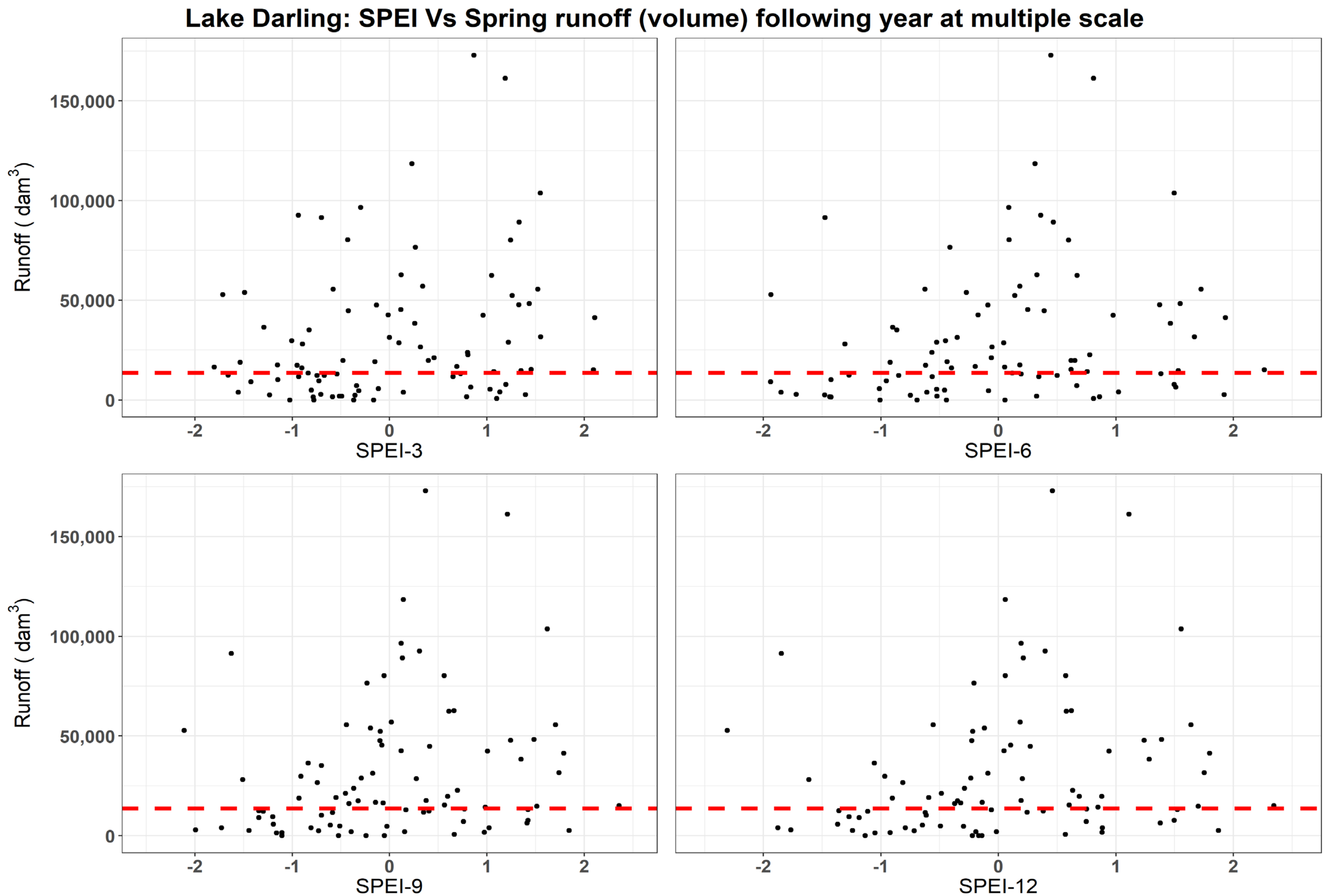
Appendix 9: Correlation of Runoff vs SPEI (12-month) spring forecast for multiple subbasins



Appendix 10: Correlation of Runoff vs SPEI (24-month) spring forecast for multiple subbasins



Appendix 11: Spring runoff versus SPEI for Grant Devine Reservoir over the 1930 - 2017 period



Appendix 12: Spring runoff versus SPEI for Lake Darling Reservoir over the 1930 - 2017 period