Supplementary Materials

Hydrologic-Land Surface Modelling of a Complex System under Precipitation Uncertainty: A Case Study of the Saskatchewan River Basin, Canada

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1.0 MESH new features

In order to enable MESH to model complex and highly managed basins (e.g. SaskRB), new water management features (irrigation, reservoir operation, and diversion) have been integrated recently into the MESH framework.

The irrigation algorithm is based on the soil moisture deficit approach, similar to that of Pokhrel et al. (2016). The net irrigation water demand is estimated as the difference between target soil moisture content (θ_T) and the simulated actual soil moisture (θ_k).

$$IR = \frac{\rho_w}{\Delta t}\sum_{k=1}^{n}\{\max[(\theta_T - \theta_k), 0] * D_k\} \qquad \text{(S1)}$$

where IR [kg m^{-2} s] is the net irrigation demand, ρ_w[kg m^{-3}] is the density of water; Δt is model time step; θ_T is given as $\alpha * \theta_{FC}$; θ_{FC} and θ_k [m^3 m^{-3}] are the field capacity and simulated actual volumetric soil moisture content, respectively; α [-] is the parameter that defines the upper soil moisture limit which has been used varyingly from 0.5 to 1; and D_k [m] is the thickness of κ^{th} soil layer, n represents the number of soil layers considered in the calculation. In order to represent irrigation effects, the standard CLASS three soil layer configuration has been changed to four soil layers so that the bottom of the third soil layer is set to around 1m. The thickness of each soil layer is 0.1, 0.25, 0.7, and 3.05 m. The top three layers are considered for irrigation with a crop root depth of 1.0m. The estimated irrigation demand is applied to the soil as rain between 0600 and 1000 local time each day in a similar approach as Ozdogan et al., (2010) and Pokhrel et al., (2016). The excess irrigation water (return flow) is assumed to join the nearest river system in the form of interflow and bottom-layer soil drainage.

Reservoir regulation is represented by the Dynamically Zoned Target Release (DZTR) scheme which uses a parametric piecewise-linear function to approximate actual reservoir release rules (Yassin et al., 2019). The DZTR scheme divides reservoir storage into five zones, dead storage (Zone 0), critical storage (Zone 1), normal storage (Zone 2), flood storage (Zone 3) and emergency storage (Zone 4). Whenever storage is below full supply storage zone, the release only occurs at the bottom outlet, but when storage is within flood storage, the release happens from both outflow outlet and spillway. The dead storage (Zone 0) amount is assumed 10 % of the maximum storage or a dead storage value from the reservoir characteristics data. In general, where no operational information is available, the other storage zones is estimated from historical time series of storage by defining some non-exceedance probability value for each zone or by optimizing these zones to reproduce the observed storage and release time series. Target releases for each zone are obtained in a similar fashion. These target storages and releases are allowed to vary each month (or on any other arbitrarily selected time step) to allow a better representation of the seasonality of reservoir operation.

Zone 0 $$Q_t = 0 \qquad [S_t < 0.1S_{max}] \qquad \text{(S2)}$$

Zone 1 $$Q_t = min\left(Q_{ci}, \frac{S_t - 0.1S_{max}}{\Delta t}\right) \qquad [0.1S_{max} < S_t \le S_{ci}] \qquad \text{(S3)}$$

Zone 2 $$Q_t = Q_{ci} + (Q_{ni} - Q_{ci})\frac{(S_t - S_{ci})}{(S_{ni} - S_{ci})} \qquad [S_{ci} < S_t \le S_{ni}] \qquad \text{(S4)}$$

Zone 3A $$Q_t = Q_{ni} + (Q_{mi} - Q_{ni})\frac{(S_t - S_{ni})}{(S_{mi} - S_{ni})} \qquad [S_{ni} < S_t \le S_{mi}] \qquad \text{(S5A)}$$

Zone 3B $Q_t = Q_{ni} + max\{(I_t - Q_{ni}), (Q_{mi} - Q_{ni})\} \frac{(S_t - S_{ni})}{(S_{mi} - S_{ni})}$ $[S_{ni} < S_t \leq S_{mi}]$ (5B)

Zone 4 $Q_t = min([max\left(\frac{(S_t - S_{mi})}{\Delta t}, Q_{mi}\right)], Q_{mc})$ $[S_{mi} < S_t]$ (S6)

where I_t, Q_t and S_t are inflow, release and storage at time step t. S_{ci} , S_{ni} and S_{mi} are critical, normal and maximum storage targets for month i. Q_{ci} , Q_{ni} and Q_{mi} are critical, normal and maximum release targets for month i. Q_{mc} is maximum channel capacity parameter.

We also developed a flow diversion process within MESH to represent water transfer across the basin via engineered works, for various purposes including irrigation. Flow diversion is the water transfers within-basin from one river node to another, water transfers from outside basin to within-basin river node, and water withdrawals from river node to irrigated areas. The flow diversion implementation in MESH is divided into two types depending on the location of source and sink of diverted water: type 1 has either a water source or sink located outside the whole basin; type 2 has both sources and sink located within the basin. To divert water from one point to another, the locations of source and sink and the amount to be diverted at each time step are provided as input to the model. However, in the case of flow diversion for irrigation, the amount of water for diversion is estimated using the irrigation demand algorithm discussed above.

Table S1: Summary of major reservoirs in Saskatchewan River Basin that are accounted for in the modelling

No	Dam/Reservoir Name	Year	Main Purpose[1]	Long (°)	Lat (°)	Dam height (m)	Capacity (MCM)	C =Capacity/MAI
1	St. Mary	1951	IR	-113.12	49.37	62	394.7	0.492
2	Waterton	1963	IR	-113.68	49.33	55	172.7	0.258
3	Oldman	1991	IR	-113.90	49.57	76	490.0	0.446
4	McGregor	1954	IR	-112.83	50.28	14	326.1	
5	Travers	1954	IR	-112.72	50.18	41	317.0	
6	Chain lakes			-114.16	50.27		17.3	
7	Upper Kananaskis	1943	HP	-115.14	50.69	24	160.4	
8	Spray Canyon	1951	HP	-115.37	50.89	60	421.9	
9	Cascade	1942	HP	-115.50	51.25	35	387.3	
10	Barrier lake			-115.06	51.00		24.0	
11	Ghost	1929	HP	-114.71	51.22	42	132.0	0.048
12	Bearspaw			-114.30	51.14		17.0	
13	Glenmore	1933	WS	-114.10	51.00	27	19.6	
14	Dickson	1983	WS	-114.21	52.05	40	203.0	0.167
15	Big Horn	1972	HP	-116.33	52.31	150	1770.0	0.747
16	Brazeau	1962	HP	-115.59	52.97	89	490.0	
17	Gardiner	1968	IR	-106.86	51.27	69	9870.0	1.460
18	E.B. Campbell	1962	HP	-103.40	53.66	34	2200.0	0.153

[1]Main purpose: **WS**-Water Supply, **HP**-Hydropower **IR**-Irrigation **FC**-Flood Control

Table S2: Summary of irrigation districts in Alberta and reservoirs in Saskatchewan

Name of Irrigation Districts	Province	Irrigation District Number	Year Established	Irrigated area (acres)	Source
Mountain View	AB	1	1931	1052 (426)	Belly River
Leavitt	AB	1	1944	4601 (1862)	Belly River
Aetna	AB	1	1959	1929 (781)	Belly River
United	AB	2	1923	17 277 (6992)	Belly and Waterton River
Magrath	AB	4	1900	11 188 (4528)	St. Mary, Waterton, Belly
Raymond	AB	4	1900	32 258 (13 055)	St. Mary, Waterton, Belly
Lethbridge Northern	AB	3	1923	122 378 (49 526)	Oldman River
Taber	AB	8	1917	76 872 (31 110)	St. Mary, Waterton, Belly
St. Mary River	AB	4	1900	342 757 (138 712)	St. Mary, Waterton, Belly
Ross Creek	AB	4	1954	1055 (427)	Ross Centre Creek
Bow River	AB	5	1920	198 196 (80 209)	Bow River
Western	AB	7	1907	67 643 (27 375)	Bow River
Eastern	AB	6	1914	274 940 (111 267)	Bow River
Hillcrest	SK	9	1988	3497	Lake Diefenbaker
South Saskatchewan River	SK	9	1966	38 349	Lake Diefenbaker
Macrorie	SK	9	1989	2388	Lake Diefenbaker
Luck Lake	SK	8	1984	10 771	Lake Diefenbaker
Riverhurst	SK	8	1987	15 228	Lake Diefenbaker
Grainland	SK	8	1979	2237	Lake Diefenbaker

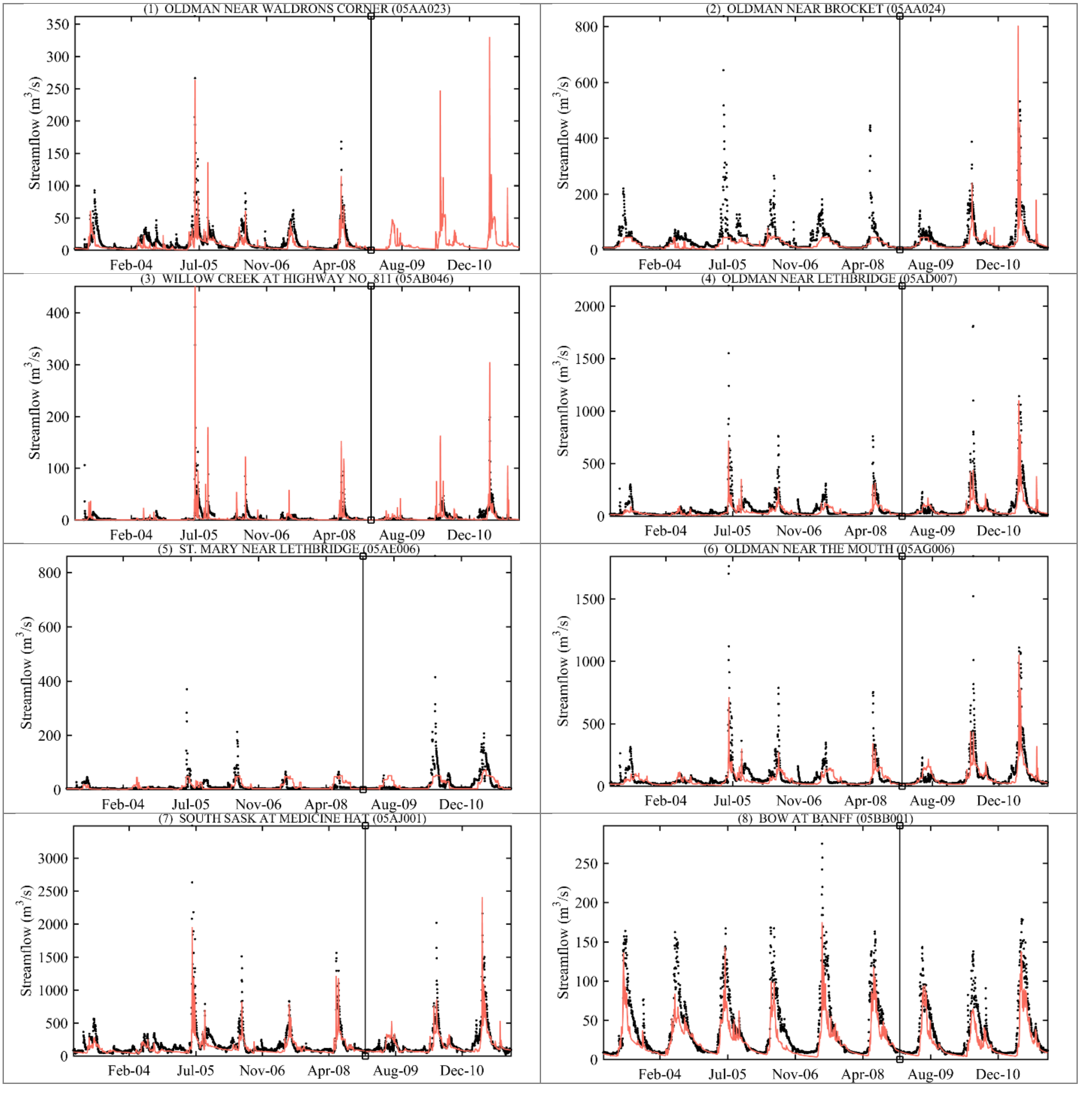
Table S3: Streamflow stations for calibration and validation of the model

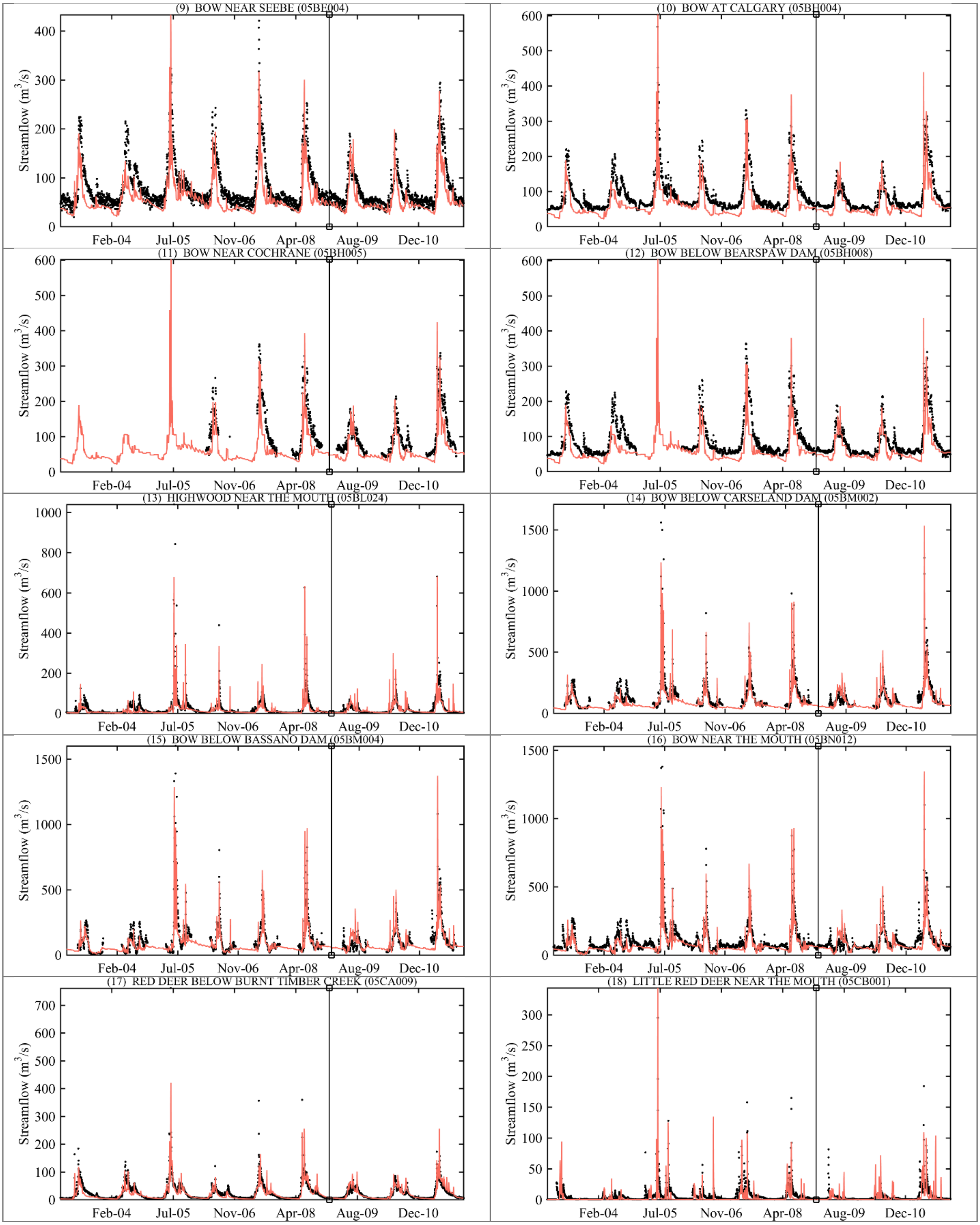
	Station	Station Name	Province	Latitude	Longitude	Drainage Area	Regulated	Subbasin	Operation Schedule
1	05AA023	Oldman River near Waldrons Corner	AB	49.81	-114.18	1446	False	A	Continuous
2	05AA024	Oldman River near Brocket	AB	49.55	-113.82	4400	True	A	Continuous
3	05AB046	Willow Creek at Highway NO. 811	AB	49.75	-113.40	2510	False	A	Seasonal
4	05AD007	Oldman River near Lethbridge	AB	49.71	-112.86	17 000	True	A	Continuous
5	05AE006	St. Mary River near Lethbridge	AB	49.57	-112.84	3530	True	A	Continuous
6	05AG006	Oldman River near the Mouth	AB	49.91	-111.80	27 500	True	A	Continuous
7	05AJ001	South Saskatchewan River at Medicine Hat	AB	50.04	-110.67	56 400	True	A	Continuous
8	05BB001	Bow River at Banff	AB	51.17	-115.57	2210	False	B	Continuous
9	05BE004	Bow River near Seebe	AB	51.12	-115.00	5170	True	B	Continuous
10	05BH004	Bow River at Calgary	AB	51.05	-114.05	7870	True	B	Continuous
11	05BH005	Bow River near Cochrane	AB	51.17	-114.46	7410	True	B	Seasonal
12	05BH008	Bow River Blow Bearspaw Dam	AB	51.09	-114.22	7770	True	B	Continuous
13	05BL024	Highwood River near the Mouth	AB	50.78	-113.82	3950	True	B	Continuous
14	05BM002	Bow River Below Carseland Dam	AB	50.82	-113.44	15 700	True	B	Seasonal
15	05BM004	Bow River Below Bassano Dam	AB	50.75	-112.54	20 300	True	B	Seasonal
16	05BN012	Bow River near the Mouth	AB	50.04	-111.59	25 300	True	B	Continuous
17	05CA009	Red Deer River below Burnt Timber Creek	AB	51.64	-115.01	2250	False	C	Continuous
18	05CB001	Little Red Deer River near the Mouth	AB	52.02	-114.14	2580	False	C	Continuous
19	05CC002	Red Deer River at Red Deer	AB	52.27	-113.81	11 600	True	C	Continuous
20	05CE001	Red Deer River at Drumheller	AB	51.46	-112.71	24 900	True	C	Continuous
21	05CK004	Red Deer River near Bindloss	AB	50.90	-110.29	47 800	True	C	Continuous
22	05DB006	Clearwater River near Dovercourt	AB	52.25	-114.85	2250	False	D	Continuous
23	05DC001	North Saskatchewan River near Rocky Mountain House	AB	52.37	-114.94	11 000	True	D	Continuous
24	05DD005	Brazeau River Below Brazeau Plant	AB	52.91	-115.36	5660	True	D	Continuous
25	05DD007	Brazeau River Below Cardinal River	AB	52.88	-116.55	2600	False	D	Seasonal
26	05DF001	North Saskatchewan River at Edmonton	AB	53.53	-113.48	28 100	True	D	Continuous
27	05EE007	Vermilion River near Marwayne	AB	53.49	-110.39	7260	True	E	Seasonal
28	05EF001	North Saskatchewan River near Deer Creek	SK	53.52	-109.61	57 200	True	E	Continuous
29	05FA011	Battle River at Duhamel	AB	52.94	-112.96	5010	False	F	Continuous
30	05FC001	Battle River Near Forestburg	AB	52.57	-112.34	7680	True	F	Seasonal
31	05FC008	Battle River At Highway No. 872	AB	52.40	-111.41	11 700	True	F	Seasonal
32	05FE004	Battle River near the Saskatchewan Boundary	AB	52.85	-110.01	25 100	True	F	Continuous
33	05GG001	North Saskatchewan River at Prince Albert	SK	53.20	-105.77	131 000	True	G	Continuous
34	05HD039	Swift Current Creek near Leinan	SK	50.49	-107.65	3730	True	H	Continuous
35	05HG001	South Saskatchewan River at Saskatoon	SK	52.14	-106.64	141 000	True	H	Continuous
36	05KD003	Saskatchewan River below Tobin Lake	SK	53.70	-103.29	289 000	True	K	Continuous
37	05KJ001	Saskatchewan River at the Pas	MB	53.83	-101.20	389 000	True	K	Continuous

Table S4: Climate stations with Adjusted and Homogenized Canadian Climate Data (AHCCD)

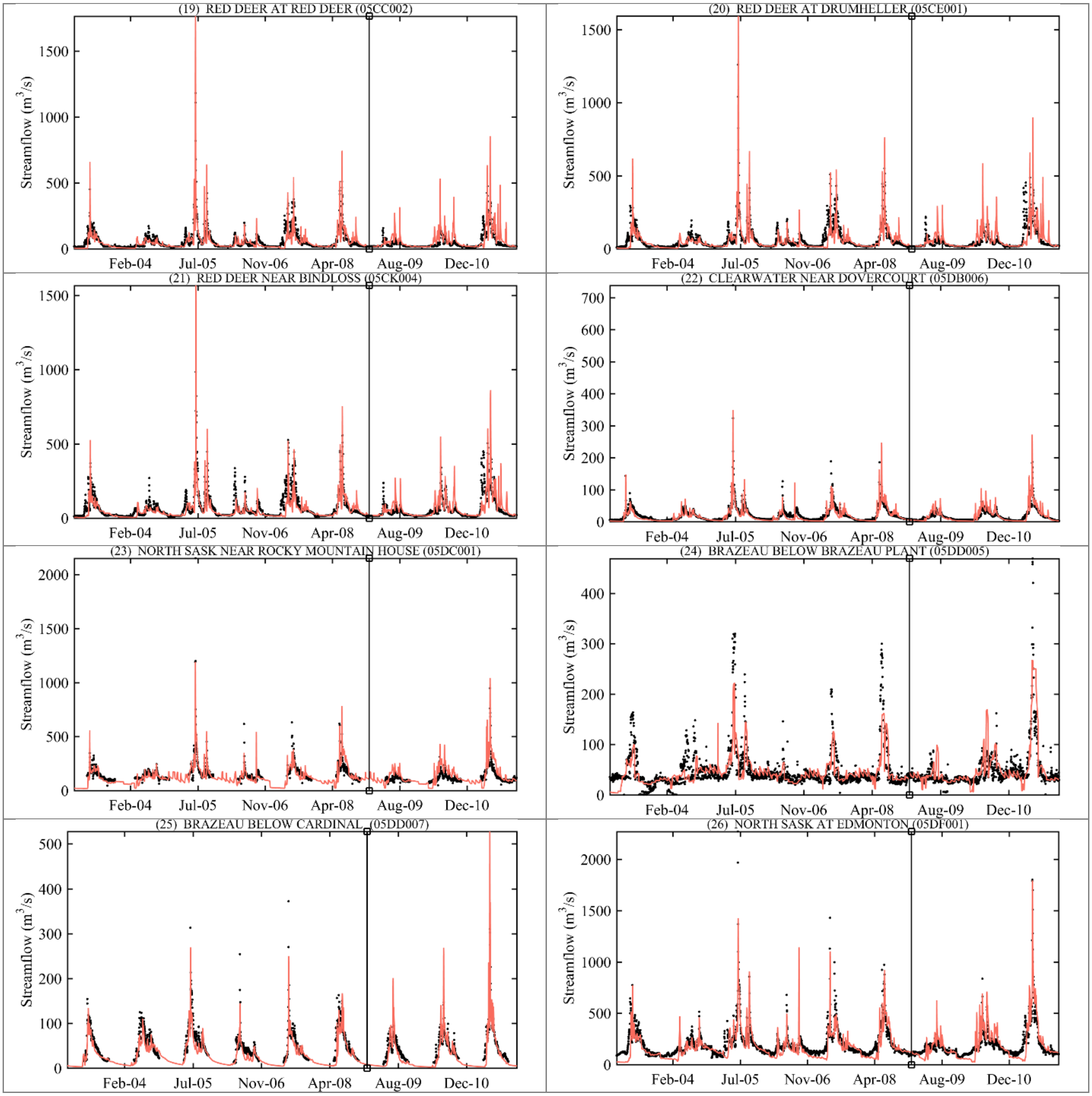
No	Station Name	Station ID	Prov	Long (°)	Lat (°)	Elev (m)	Start year-mon	End year-mon
I	Beaver Mines	3050600	AB	-114.200	49.500	1257	1913-1	2012-3
II	Calgary	3031093	AB	-114.000	51.100	1084	1885-1	2012-7
III	Calmar	3011120	AB	-113.900	53.300	720	1915-1	2016-12
IV	Carway	3031400	AB	-113.400	49.000	1354	1915-1	2011-11
V	Edmonton	3012205	AB	-113.600	53.300	723	1883-1	2012-4
VI	Highwood Au	3053250	AB	-114.400	50.600	1580	1903-1	2011-9
VII	Olds	3024920	AB	-114.100	51.800	1040	1914-1	2015-6
VIII	Ranfurly 2NW	3015405	AB	-111.700	53.400	673	1905-1	2014-11
IX	High Point	4023240	SK	-107.900	51.000	645	1929-1	2017-7
X	Kindersley	4043900	SK	-109.200	51.500	694	1942-1	2013-11
XI	Prince Albert	4056240	SK	-105.700	53.200	428	1889-1	2013-11
XII	Waseca	4048520	SK	-109.400	53.100	638	1908-1	2014-12
XIII	Flin Flon	5050920	MB	-101.900	54.800	320	1927-1	2017-12
XIV	Grand Rapids Hydro	5031111	MB	-99.300	53.200	223	1962-1	2017-12
XV	The Pas	5052880	MB	-101.100	54.000	270	1910-1	2014-11

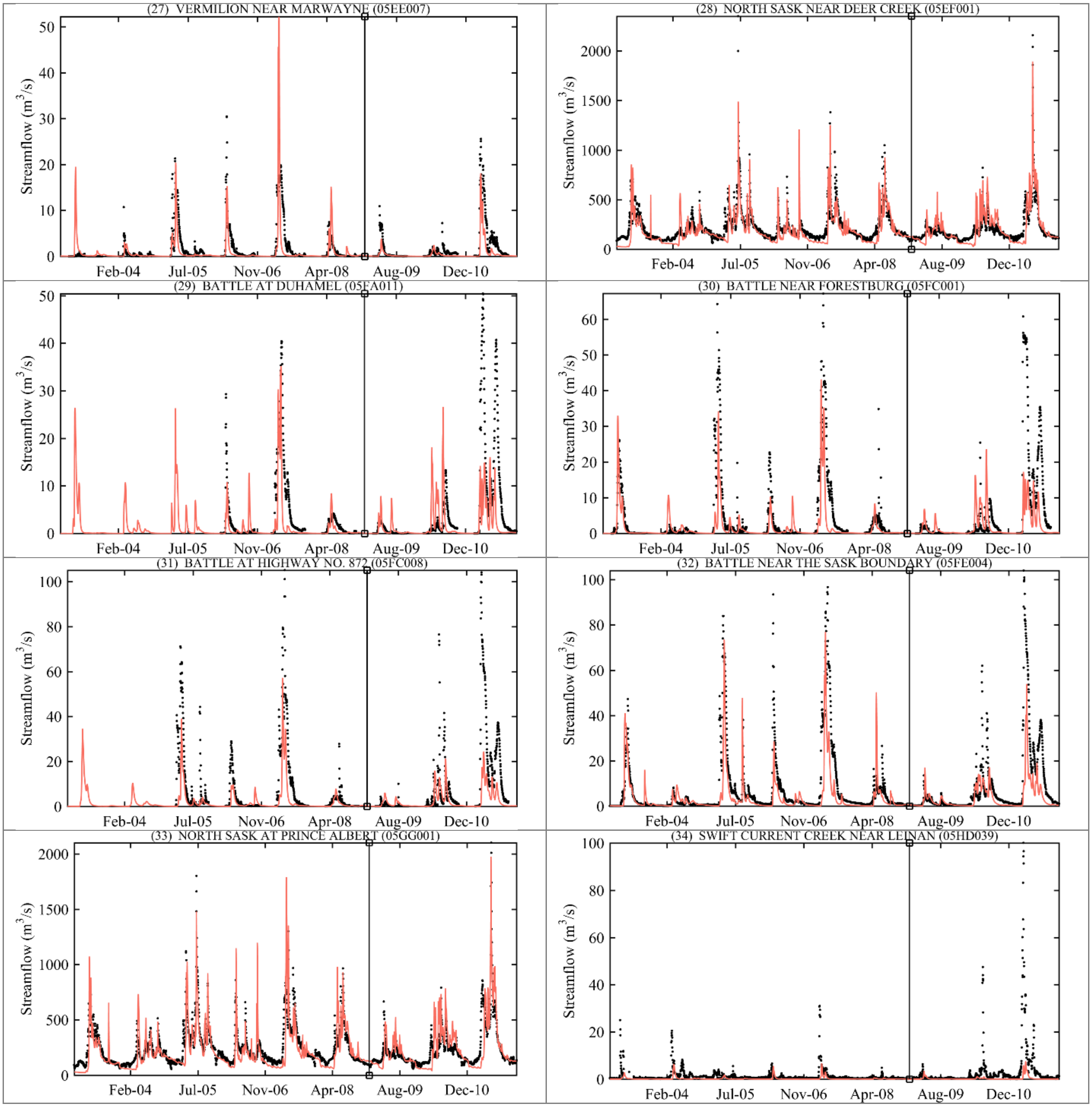
Figure S1: Simulated (light red) and observed (black) streamflow of selected stations in SaskRB. The calibration and validation period is separated by a vertical line at the end of 2008.

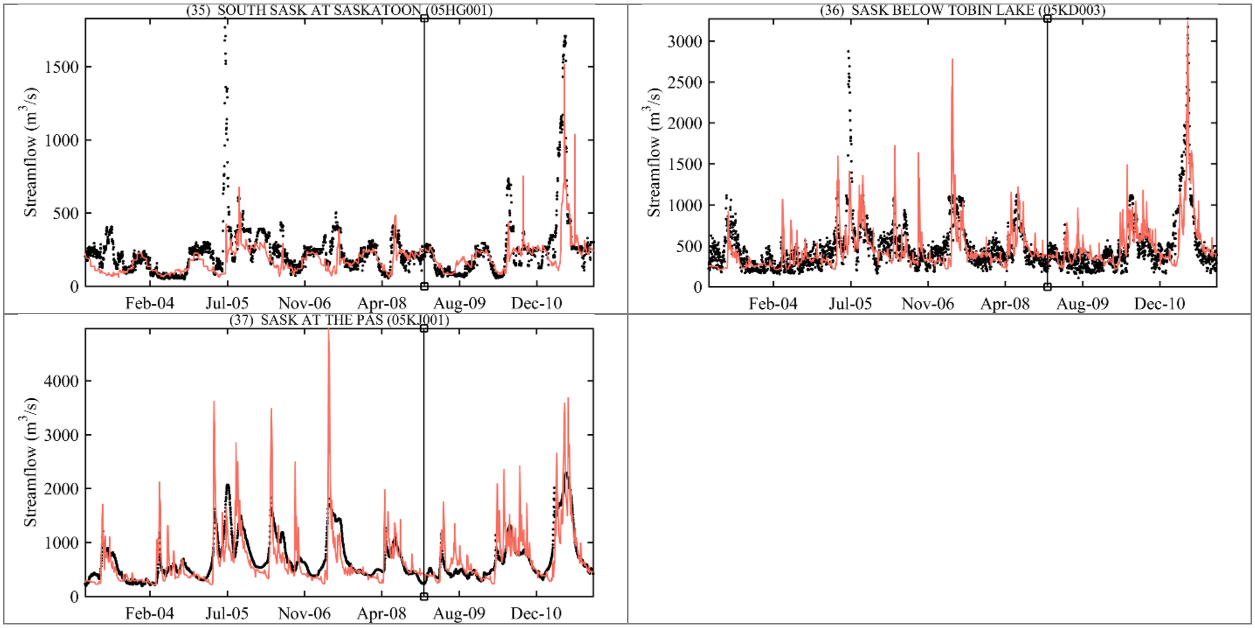




(9) BOW NEAR SEEBE (05BE004)
(10) BOW AT CALGARY (05BH004)
(11) BOW NEAR COCHRANE (05BH005)
(12) BOW BELOW BEARSPAW DAM (05BH008)
(13) HIGHWOOD NEAR THE MOUTH (05BL024)
(14) BOW BELOW CARSELAND DAM (05BM002)
(15) BOW BELOW BASSANO DAM (05BM004)
(16) BOW NEAR THE MOUTH (05BN012)
(17) RED DEER BELOW BURNT TIMBER CREEK (05CA009)
(18) LITTLE RED DEER NEAR THE MOUTH (05CB001)
Streamflow (m^3/s)
Feb-04
Jul-05
Nov-06
Apr-08
Aug-09
Dec-10


(19) RED DEER AT RED DEER (05CC002)
(20) RED DEER AT DRUMHELLER (05CE001)
(21) RED DEER NEAR BINDLOSS (05CK004)
(22) CLEARWATER NEAR DOVERCOURT (05DB006)
(23) NORTH SASK NEAR ROCKY MOUNTAIN HOUSE (05DC001)
(24) BRAZEAU BELOW BRAZEAU PLANT (05DD005)
(25) BRAZEAU BELOW CARDINAL (05DD007)
(26) NORTH SASK AT EDMONTON (05DF001)
Streamflow (m3/s)
Feb-04
Jul-05
Nov-06
Apr-08
Aug-09
Dec-10


(27) VERMILION NEAR MARWAYNE (05EE007)
(28) NORTH SASK NEAR DEER CREEK (05EF001)
(29) BATTLE AT DUHAMEL (05FA011)
(30) BATTLE NEAR FORESTBURG (05FC001)
(31) BATTLE AT HIGHWAY NO. 872 (05FC008)
(32) BATTLE NEAR THE SASK BOUNDARY (05FE004)
(33) NORTH SASK AT PRINCE ALBERT (05GG001)
(34) SWIFT CURRENT CREEK NEAR LEINAN (05HD039)
Streamflow (m3/s)
Feb-04
Jul-05
Nov-06
Apr-08
Aug-09
Dec-10


(35) SOUTH SASK AT SASKATOON (05HG001)
Streamflow (m3/s)
0
500
1000
1500
Feb-04
Jul-05
Nov-06
Apr-08
Aug-09
Dec-10
(36) SASK BELOW TOBIN LAKE (05KD003)
Streamflow (m3/s)
0
500
1000
1500
2000
2500
3000
Feb-04
Jul-05
Nov-06
Apr-08
Aug-09
Dec-10
(37) SASK AT THE PAS (05KJ001)
Streamflow (m3/s)
0
1000
2000
3000
4000
Feb-04
Jul-05
Nov-06
Apr-08
Aug-09
Dec-10

References

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