Modeling total dissolved gas (TDG) in the Columbia and Snake Rivers.

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There is a need for a predictive model of total dissolved gas (TDG) in the Columbia and Snake Rivers. Ideally, it will require only spill and flow as inputs and be sensitive to high TDG levels. Special attention is given to applications within the COMPASS salmon migration model.

A data exploration of historic gas levels reveals that TDG generation varies in location specific ways. (Figure 1).

- Dams that generate TDG at low spills but reach peak production very quickly, e.g. BON, JDA. Here, observed gas levels reach an asymptote regardless of spill volume. There are operational actions that constrain gas levels to be beneath a "gas cap".
- Dams that generate a little extra TDG with spill, but mostly just pass TDG downstream from the forebay. E.g. at PRD, observed gas is ~5% points higher than upstream for a wide range of spills.
- Dams where TDG is conspicuously generated by spill such as at "headwater" dams where the upstream TDG levels are usually low and spill generates the extra observed TDG measured at the tailrace monitor, e.g. LWG.
- Dams that have a hybrid response, passing TDG from upstream and generating gas, e.g. WAN which has some of the highest observed TDG concentrations in this study.

The system of monitoring equipment (and hence data) is slightly different than the modeled configuration of the process. For each dam/pool system, there may be multiple measures tracked by a model such as COMPASS, where conditions on the left and right banks are separately modelled in the pools, passing the dams and exiting the tailrace. In contrast, there are only 2 data values: a forebay measurement and a tailrace measurement. Figure 2 illustrates these for a dam where the TDG monitoring site is on the same side as the spillway. This is common (e.g. JDA, IHR, and LGS), although there are various other configurations in the system.

A very influential process occurs when powerhouse-side water is "entrained" in the spill waters and gassed to the same level as the spill-side water so $G_{phouse} > G_{FB}$ (ACOE 2009). There is no mechanism for this at BON or TDA where the spillways are physically removed from the powerhouses, but at other locations, powerhouse water moves beneath the spillway and becomes supersaturated with the spill water. In the case of Wells dam, the spillway is over the powerhouse so entrainment is much more likely. Ignoring this phenomena results in over-generating TDG in the spill waters when in fact it is the

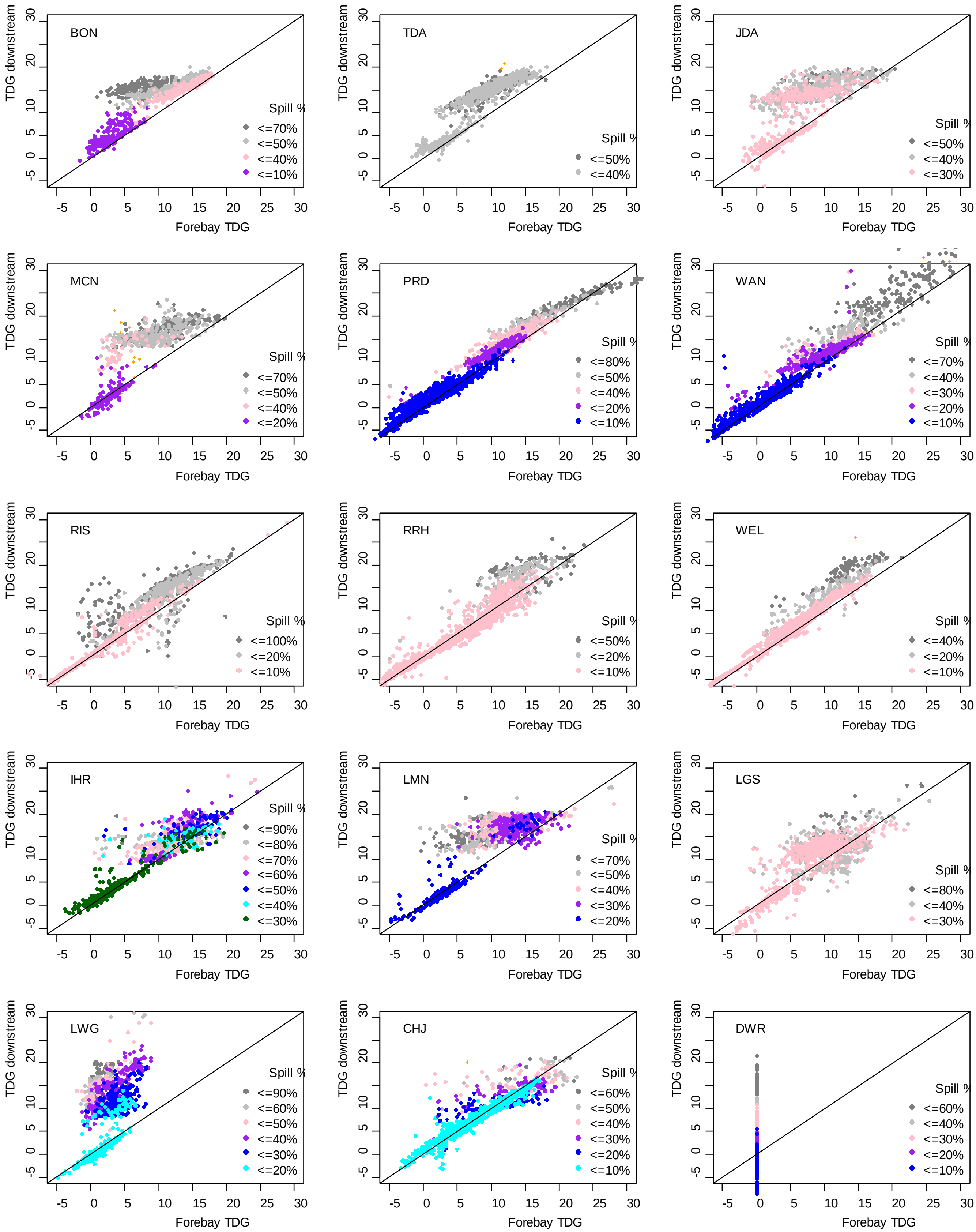

Figure 1 Relationship of observed forebay TDG to observed tailrace TDG. There are no data for DWR forebay.

volume of water being gassed that is important. When the spillway and powerhouse are physically isolated, the entrain_factor = 0.

When spillway and powerhouse are adjacent, entrain_factor > 0, based on specific studies. The ACOE (2009) reports that entrainment at LGS and LWG is proportional to the spill volume, and at other sites is present but poorly quantified (perhaps a volume rather than a fraction) in which case representative spills were used to compute a fraction for use in TDG model calibration.

Site	Entrainment factor	Other entrainment	Optionally enforced *k*	Comment
BON	0			Separation of powerhouse and spill
TDA	0			Separation of powerhouse and spill
JDA		35 KCFS*	0.3	April – June spill is on order of 50- 100 KCFS and entrainment varies with spill (ACOE 2011a)
MCN		35 KCFS*	0.25	April – June spill is on order of 100 to 150 KCFS
IHR		30 KCFS*	0.6	April – June spill is highly variable at least 20 KCFS but often over 80 KCFS. Assuming 50 KCFS of spill
LMN		30 KCFS*	1.0	LMN spill is targeted at 30 KCFS
LGS	2.0**			ACOE 2009
LWG	1.75			ACOE 2009
CHJ	0			ACOE 2011b
PRD, WAN			0	Assigned, due to separation
RRH, RIS, WEL			1	Assigned due to proximity

* Quasi constant or variable due to operations, but not proportional to spill (ACOE 2009).

**Reduced to 1 during fitting process.

The mathematics of the mixing process are developed here to enable simultaneous fitting of spill-generated gas parameters and tailrace mixing. The strength of this method is to specifically and explicitly isolate and parameterize the TDG generating processes.

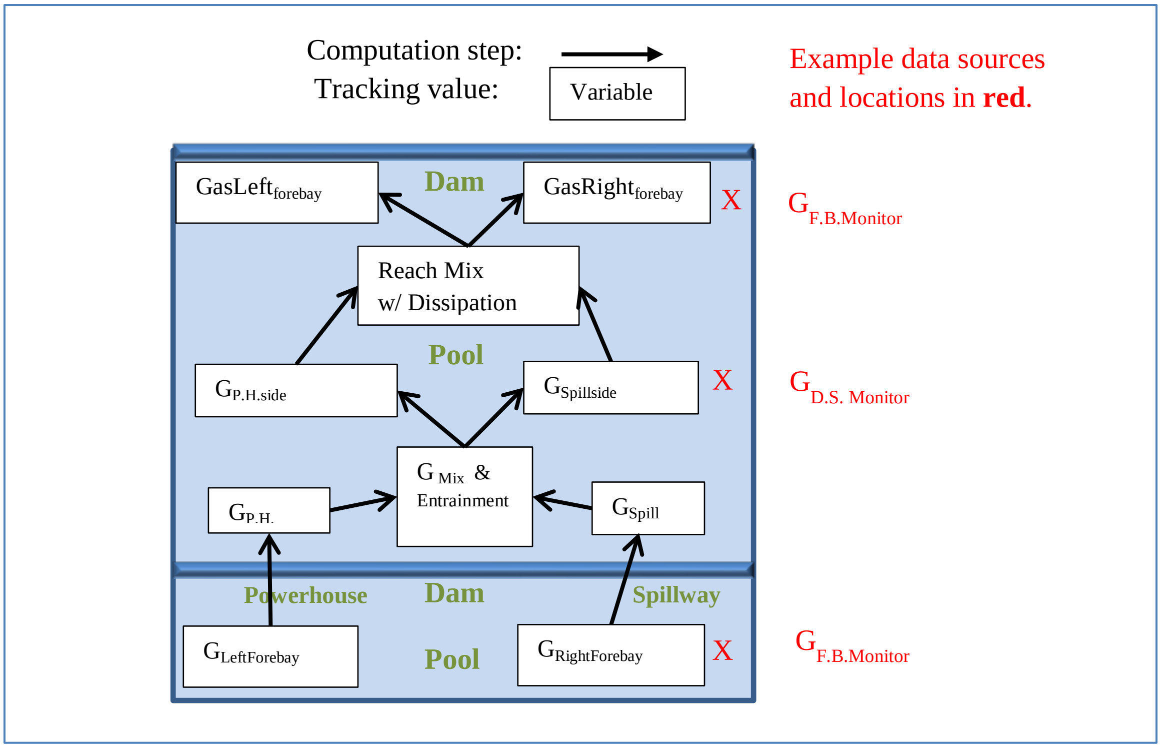

Figure 2 Schematic of one possible layout of the TDG monitoring / generation environment with computational flow and data sources identified.

Ultimately, $G_{D.S.}$ measures TDG in a mixture of water that passed through the powerhouse, or was generated by spill. Conceptually, perfectly mixed water has this level of TDG:

$$G_{Mix} = G_{Spill} f + G_{Phouse}(1 - f)$$

where *f* is the fraction of total flow that is spilled. However, the monitoring value, $G_{D.S.}$, may be measuring incompletely mixed waters with a value somewhere between G_{spill} and G_{Phouse}. It is mathematically convenient to represent the mixture in terms of its *separation*. Let α represent the separation and define: $G_{dif} = G_{spill} - G_{Phouse}$. When α =0 there is complete mixing, and when α =1 it is completely separated. In the absence of other source of TDG, the waters on either side of the river downstream are:

$$\begin{aligned} G_{Spillside} &= G_{Mix} + G_{dif}(1 - f)\alpha \\ &= G_{Mix} + (G_{spill} - G_{Phouse})(1 - f)\alpha \end{aligned}$$

$$\begin{aligned} G_{Phouseside} &= G_{Mix} - G_{dif} f \alpha \\ &= G_{Mix} - (G_{spill} - G_{Phouse}) f \alpha \end{aligned}$$

The powerhouse itself does not generate additional TDG, so in a simple case of spillway and powerhouse separation, water exiting the turbines has the same level of TDG as the forebay and ultimately serves to dilute the level of TDG from the spillside water in the mixed waters. However, given entrainment, then the water exiting on the powerhouse side is a mixture itself of entrained and ordinary flows. G_{Phouse} is computed in terms of the G_{FB} and the volume of water being entrained. Allowing it to be proportional to spill at any site, the entrained flow, $Q_E = k \cdot Q_{Spill} = k \cdot f \cdot Q$, and un-entrained flow, $Q_{notE} = Q_{Phouse} - Q_E = (1-f) \cdot Q - kfQ$ then gives:

$$G_{Phouse} = \left(\frac{Q_{Phouse} - Q_E}{Q_{Phouse}} \right) G_{FB} + \frac{Q_E}{Q_{Phouse}} G_{Spill}$$

$$G_{Phouse} = (1 - \frac{fk}{1-f}) G_{FB} + \frac{fk}{1-f} G_{Spill}$$

With further substitution and algebra, we can rewrite the G_{Mix} in terms of *f*, *k,* G_{Spill} and G_{FB}:

$$G_{Mix} = G_{Spill} f + \left((1 - \frac{fk}{1-f}) G_{FB} + \frac{fk}{1-f} G_{Spill} \right) (1-f)$$

$$G_{Mix} = G_{Spill} f (1+k) + G_{FB} \left(1 - f - fk\right)$$

This has an important constraint : $k \leq \frac{1}{f} - 1$ because it is impossible to entrain more water than the powerhouse flow.

The calibration data is from the downstream monitoring site and the elvel of TDG measured there is $G_{DS.}$ This monitoring value can be on either side of the river and thus are identified as $G_{Spillside}$ or $G_{Phouseside}$. There is an additional possibility that the downstream monitor is in the middle of the river. In that case, mixing is assumed to be complete, ie. α =0 and either $G_{spillside}$ or $G_{Phouseside}$ can be compared to $G_{D.S.}$ assigning α =0.

Assuming that the downstream monitor is on the spill side then:

$$G_{Spillside} = G_{Spill} f + G_{Phouse}(1-f) + \left(G_{spill} - G_{Phouse}\right)(1-f)\alpha$$

substituting G_{Phouse} and performing some algebra yields:

$$G_{Spillside} = G_{Spill}(f(1+k) + \alpha(1-f) - \alpha fk) + G_{FB}(1 - f(1+k) - \alpha(1-f) + \alpha fk)$$

Similarly:

$$G_{Phouseside} = G_{Spill}\left(f(1+k) - f\alpha\left(1 - \frac{kf}{1-f}\right)\right) + G_{FB}\left(1 - f(1+k) + f\alpha\left(1 - \frac{kf}{1-f}\right)\right)$$

Depending on the side of the river where the TDG monitoring station is located, we can use one of these two final equations for G_{DS}, and inputs including f, G_{FB} and G_{DS} data can be used to calibrate a model for

G_{Spill} . Two types of equations are considered. The first is a bounded exponential model because of historic precedence as used in the CRiSP model (CBR, 2000), consistency with ACOE methods, and its curvi-linear properties. The second is a linear model because many sites have a simple relationship of G_{spill} to Q_{spill} as shown in Figure 1.

$$G_{Spill} = P_0 + P_1 e^{P_2 Q_{Spill}}$$

$$G_{Spill} = P_0 + P_1 Q_{Spill}$$

The linear model is effective at any site, and some sites can be fit with the exponential model. At each site, each record, *i*, was weighted according to $w_i = \frac{TDG_{obs,i}}{\sum_i TDG_{obs,i}}$ because of the need to accurately forecast at higher (more dangerous) TDG levels, constrained to be in the months April – June and over the years 2009 – 2014.

Data

Forebay TDG, tailrace TDG, spill volume, and flow volume data were obtained from the DART data site (CBR 2014). Spill fraction was computed as spill / flow.

Results

Equations for $G_{spillside}$ or $G_{Phouseside}$ were fitted with data in order to obtain TDG parameters (Table 1) and included in a COMPASS run for each year from 1999 through 2014. Modelled TDG was then compared directly to the observations.

A measure of the success of the model is the Mean Absolute Deviation (MAD) between the model and the observations. Figure 3 shows MAD (for all observations) and MAD110 for observations > 110% at each site, in each year during the months of April, May and June (days 91-181). MAD is computed as: $MAD = mean(abs(TDG_{obs} - TDG_{model}))$ over the days of interest (April- June) and MAD110 only applies this computation to days when the observed TDG was over 110%.

Additional Notes for Figure 3 : The red box depicts the years which were included in the calibration. The darkest green values are the lowest. In many years there are no observations of TDG > 110 at LWG forebay. Single spurious values or missing values are often due to data problems (e.g. CHJ 2014 downstream and MCN 2014 upstream). In 2001, spill was nearly non-existent.

In Figure 4 each downstream site is shown in each year over the days of interest. The closer the red and orange lines, the better.

Discussion

Overall model fit is good. In general, there is more variability in observations than in the model predictions. The following are known processes that are ignored or simplified due to data limitations and forecasting scope:

1) Regression models are used, so extra variability is seens as error.
2) TDG monitoring site missing or erroneous observations.
3) Side-to-side mixing in the reservoirs is a fixed function of distance (gas_theta).
4) Entrainment and gassing of powerhouse water is assumed to happen at a fixed proportion of spill (within constraint above).
5) Mixing of powerhouse and spill waters is assumed to be constant regardless of flow.
6) The gas dissipation constant is based on water temperatures near 25°C although varies with temperature.
7) Physical gas dissipation and mixing processes are a function of physical geometry of the river and not our idealized geometric shapes.
8) The gas dissipation process is a function of wind speed due to its effect on the reservoir surface.
9) Data on historical tailwater depth and spill gate configuration, which impact TDG generation, are incomplete and are not known reliably in a forecasting scenario.
10) Forebay TDG levels at headwater dams (DWR, CHJ, and LWG) are not modelled because there is no upstream source for them in COMPASS. The 10-year daily average observations are used as inputs at LWG and CHJ. DWR has no monitor.

For running COMPASS with modelled TDG, the following steps are recommended:

1. Set output_gas Off at reaches and dams.
2. Include a file with formatted nsat_day_equation, nsat_night_equation, and backup_nsat_equation for 15 dams. Note that nsat equation 62 can have additional parameters which should be zero and nsat equation 30 needs to have bounds (KCFS spill lower and upper levels, between which the equation applies).
3. Set output_gas On for LWG and CHJ and include 10 year average daily TDG forebay observations for these two sites (one is a reach and the other a headwater). These can be obtained from DART (CBR 2014).
4. Adjust output_settings to include TDG at sites of interest. The output flag is “32” which can be incorporated with other flags.

References

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Additional Tables and Figures below

Table 1 COMPASS-ready parameter set. NOTE: COMPASS expects gas_theta for legacy reasons. The mix fraction α = 1-exp(-Gas_theta) can be used for direct computations.

Dam	COMPASS Eqn #	Gas_theta	α	entrain_factor	P_0	P_1	P_2
BON	62	0	0	0	16.16	0.02983	0
TDA	62	0	0	0	21.9	0.02109	0
JDA	62	0.232	0.207054	0.3	11.04	0.05969	0
MCN	62	0.194	0.176342	0.25	12.38	0.04007	0
PRD	30	20	1	0	34.9	-16.23	-0.002783
WAN	62	20	1	0	17.63	0.08495	0
RIS	62	3.307	0.963374	1	21.6	0.007694	0
RRH	30	20	1	1	24.47	-47.83	-0.2692
WEL	62	20	1	1	20.56	0.05935	0
IHR	62	0	0	0.6	11.15	0.1009	0
LMN	30	0	0	1	22.12	-11.4	-0.03437
LGS	62	0.399	0.329009	1	9.304	0.1675	0
LWG	62	0.114	0.107742	1.75	7.007	0.2261	0
CHJ	30	0.269	0.235857	0	20.92	-14.74	-0.01815
DWR	30	20	1	0	36.65	-40.22	-0.3211

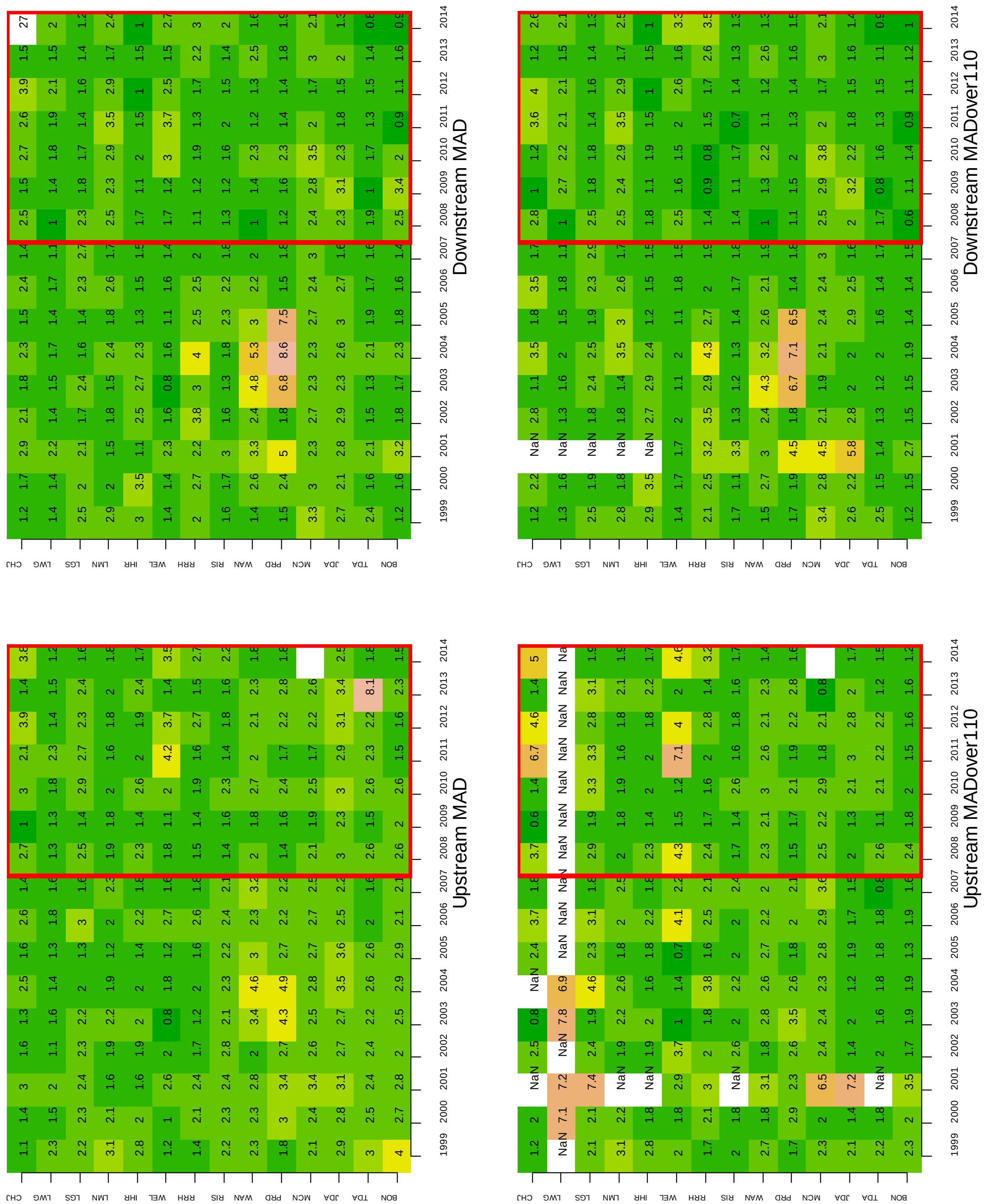
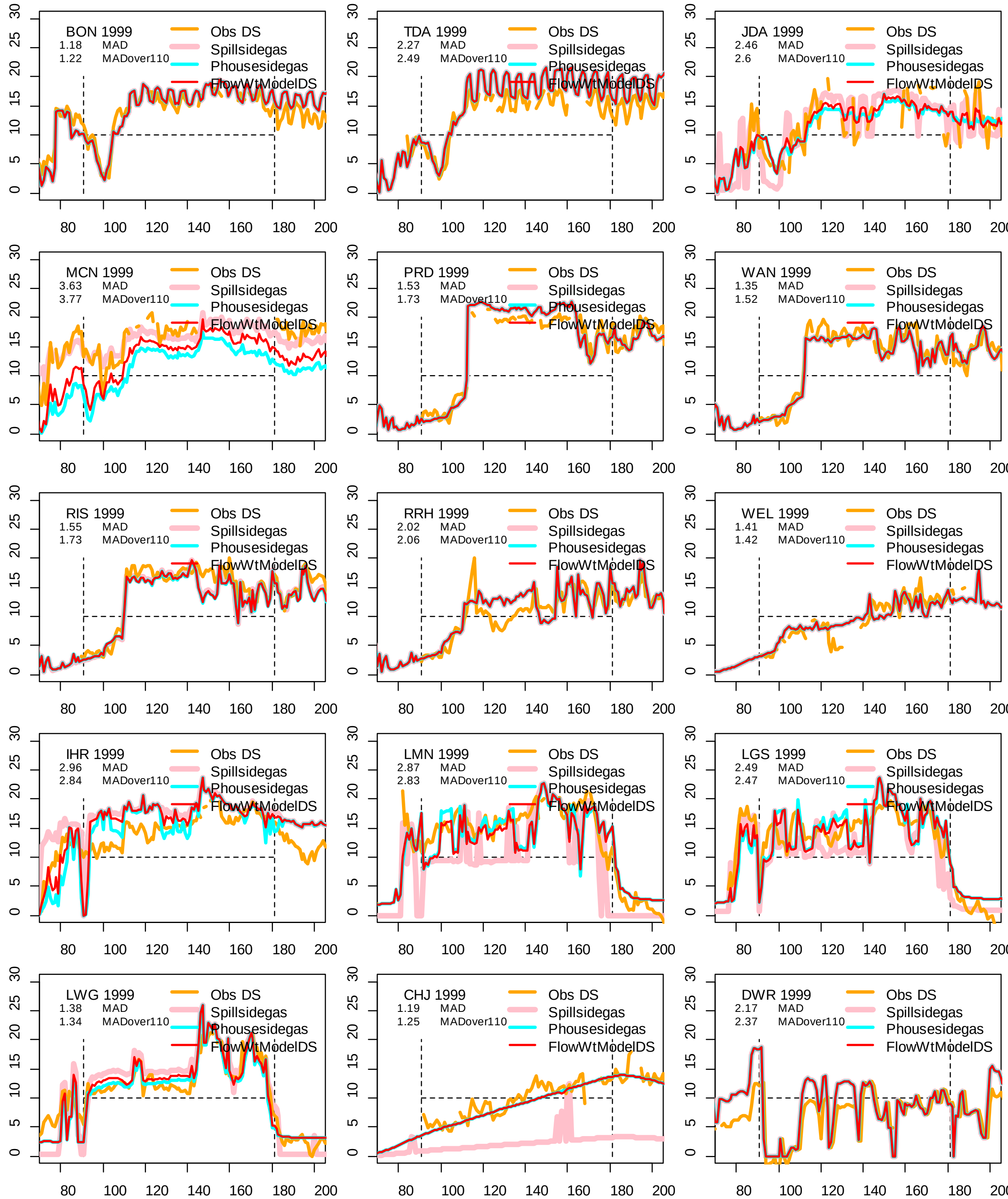
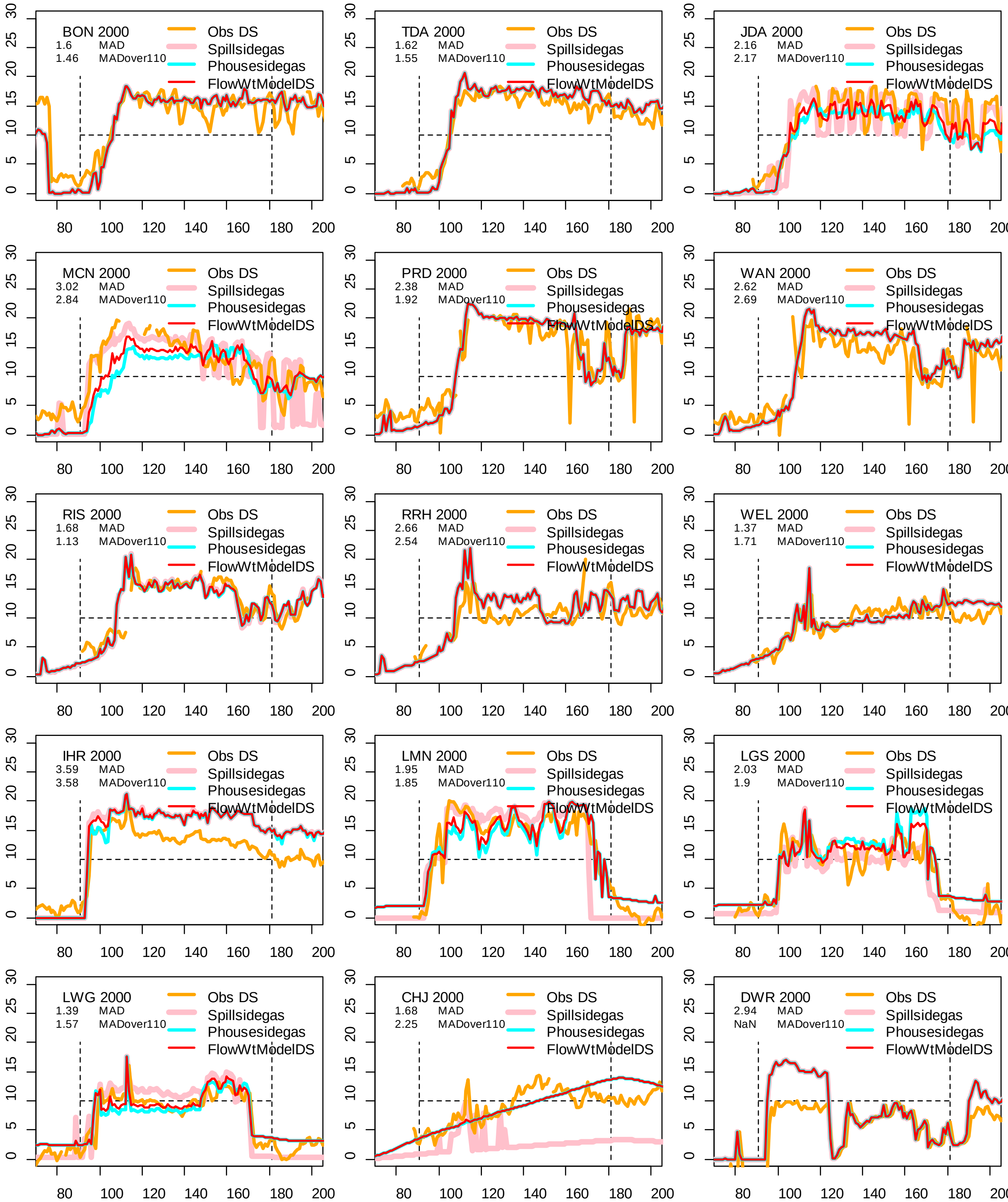


Figure 3 Mean Absolute Deviation during period of interest (April – June). See "Results".

Figure 4 Observed TDG in tailrace and COMPASS outputs.

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MCN 2000
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PRD 2000
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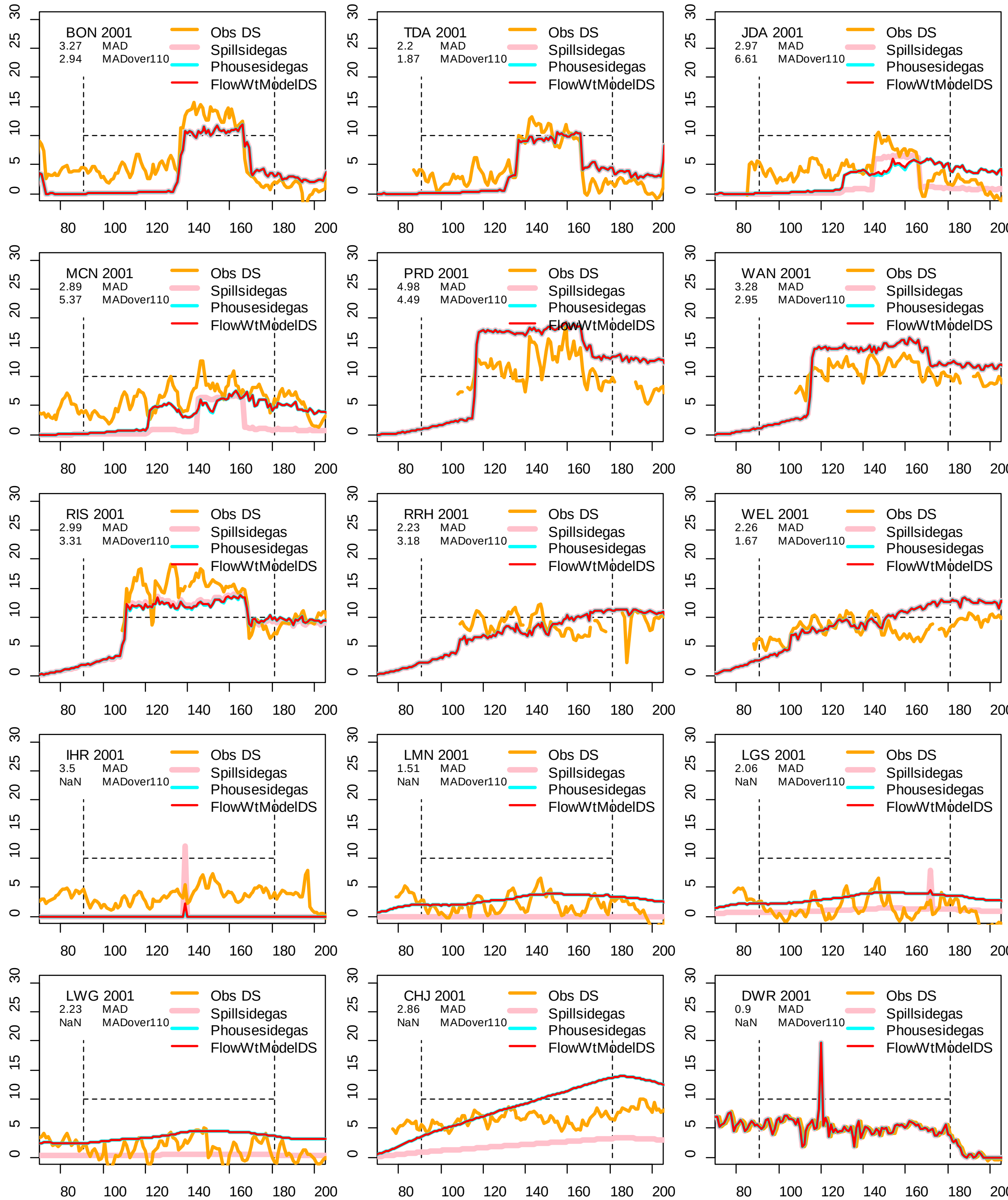
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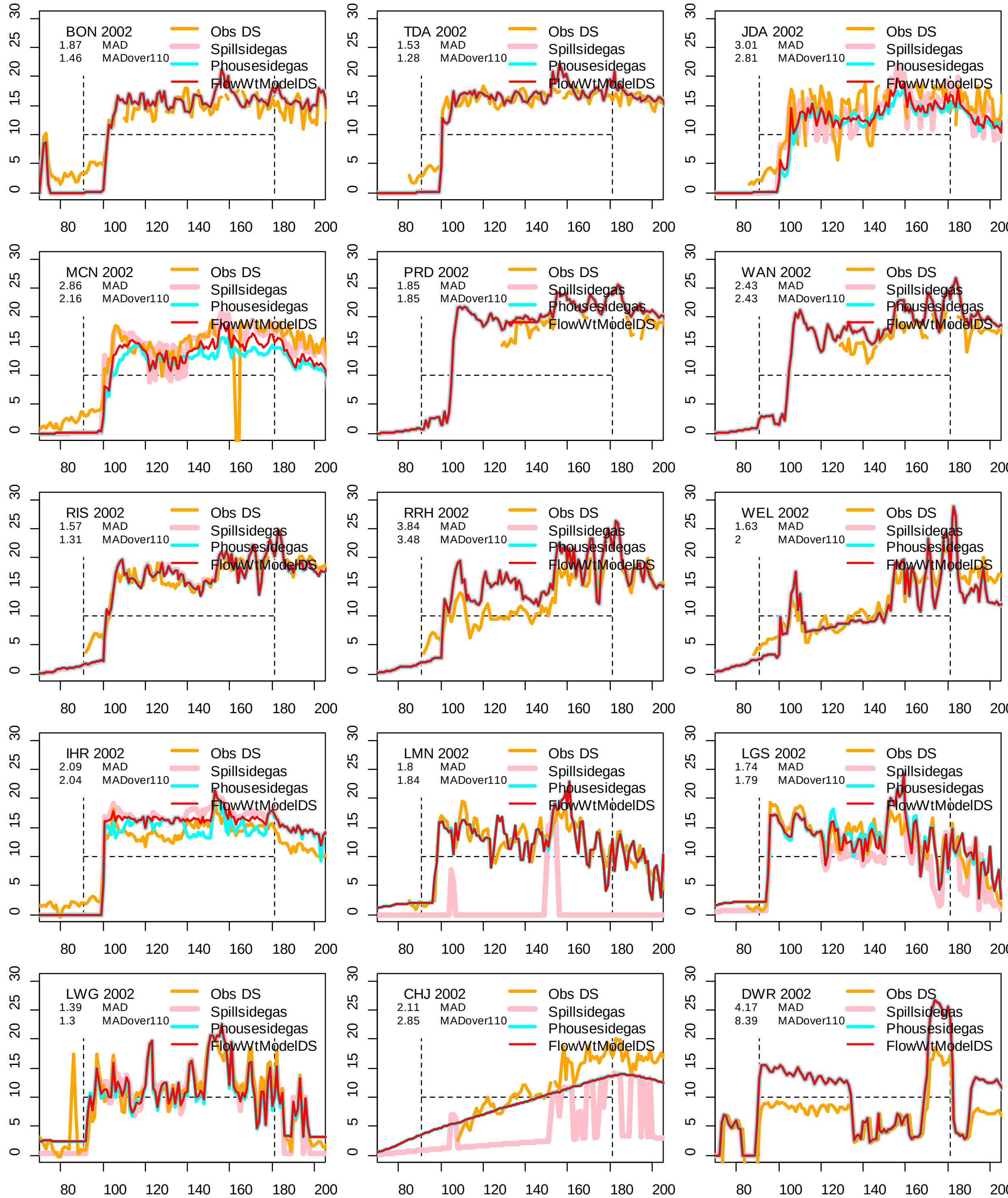
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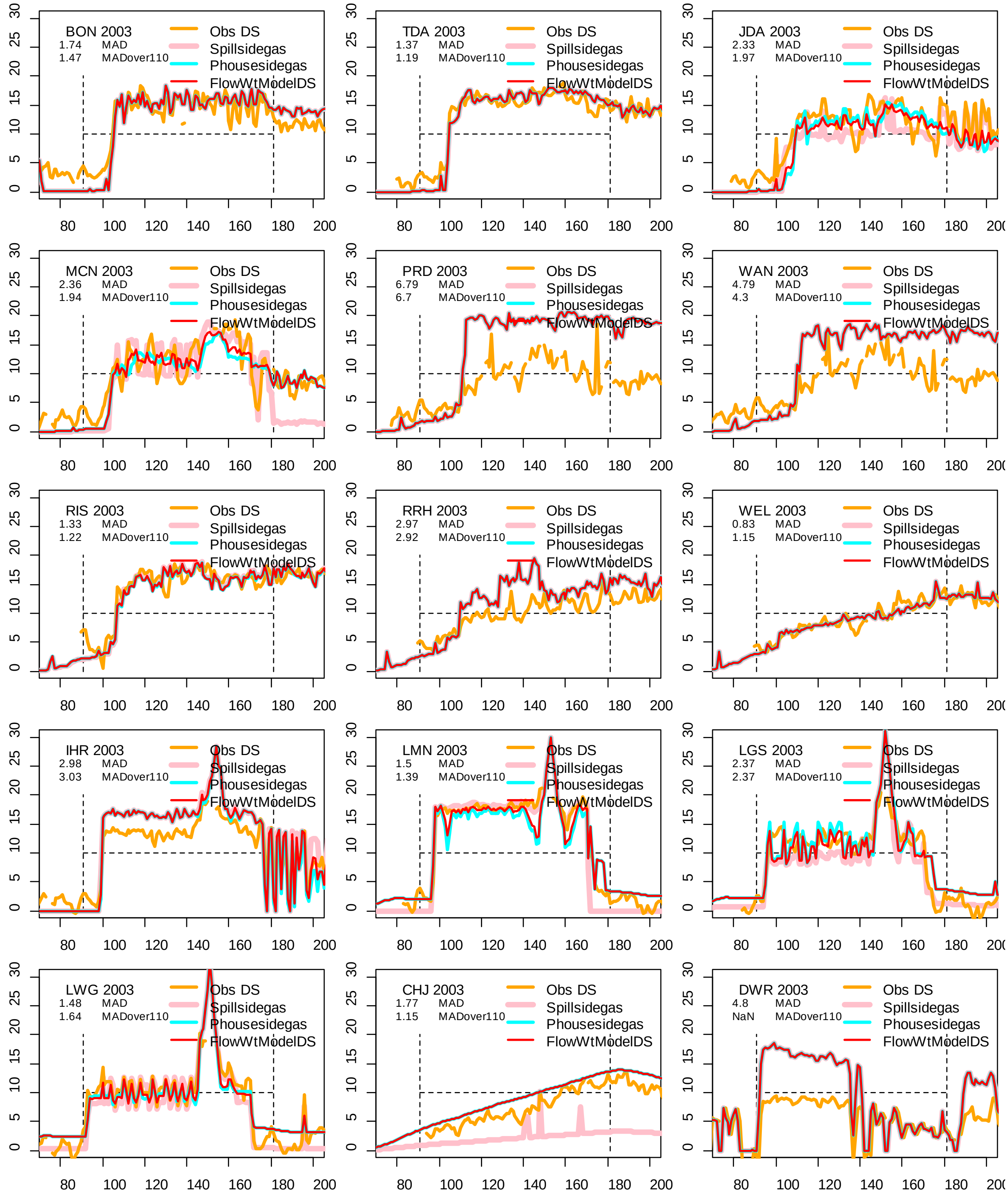
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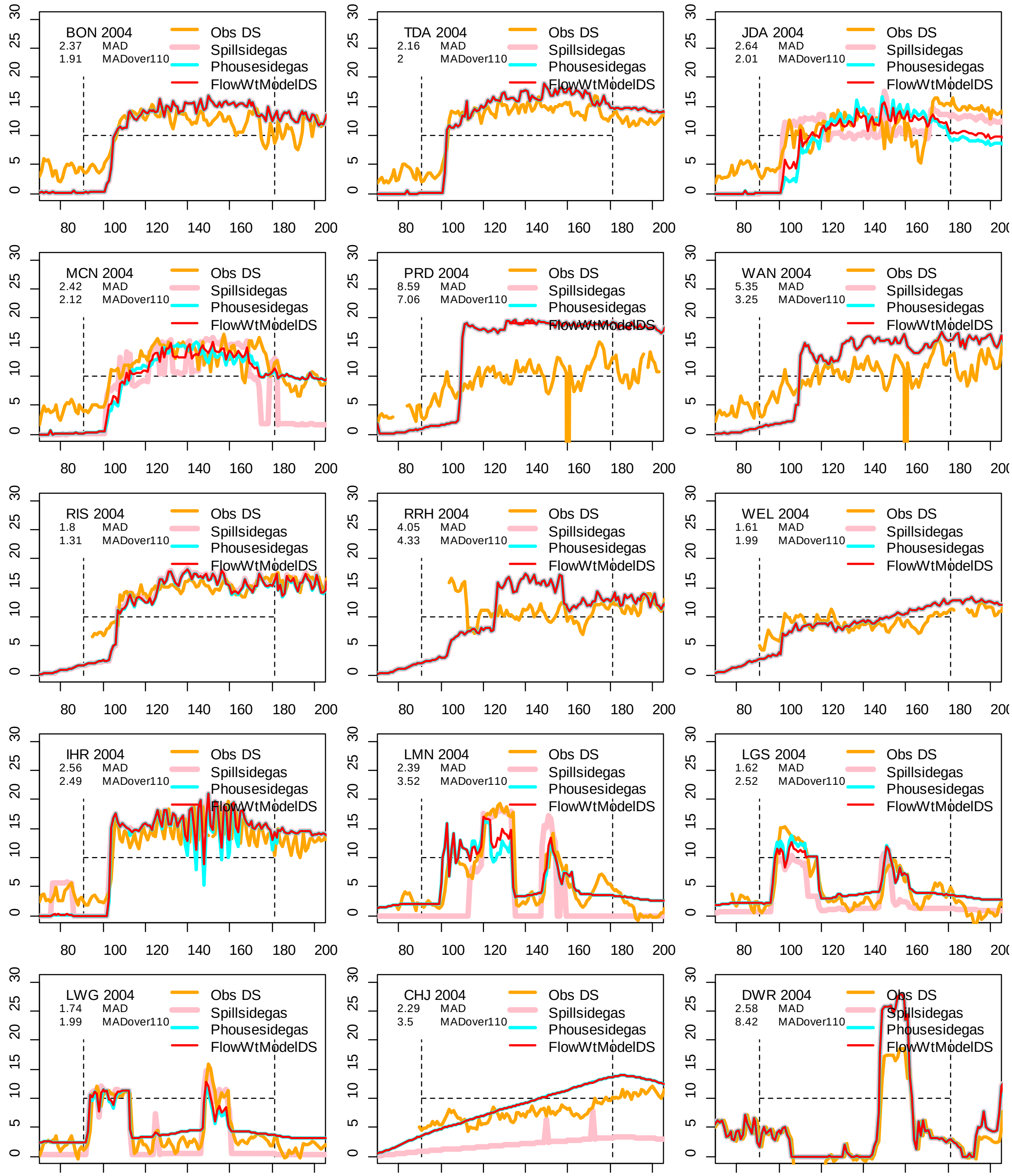
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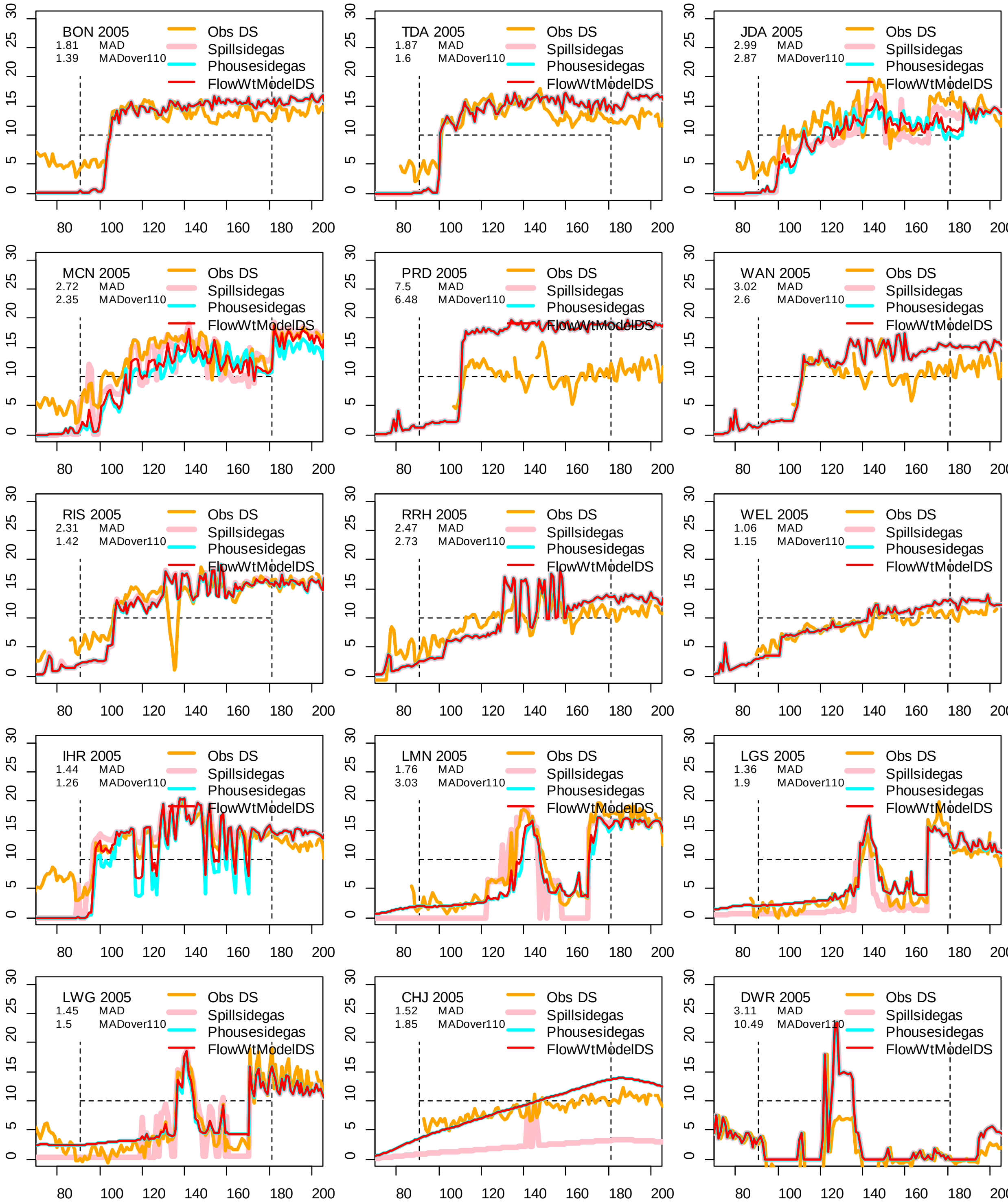
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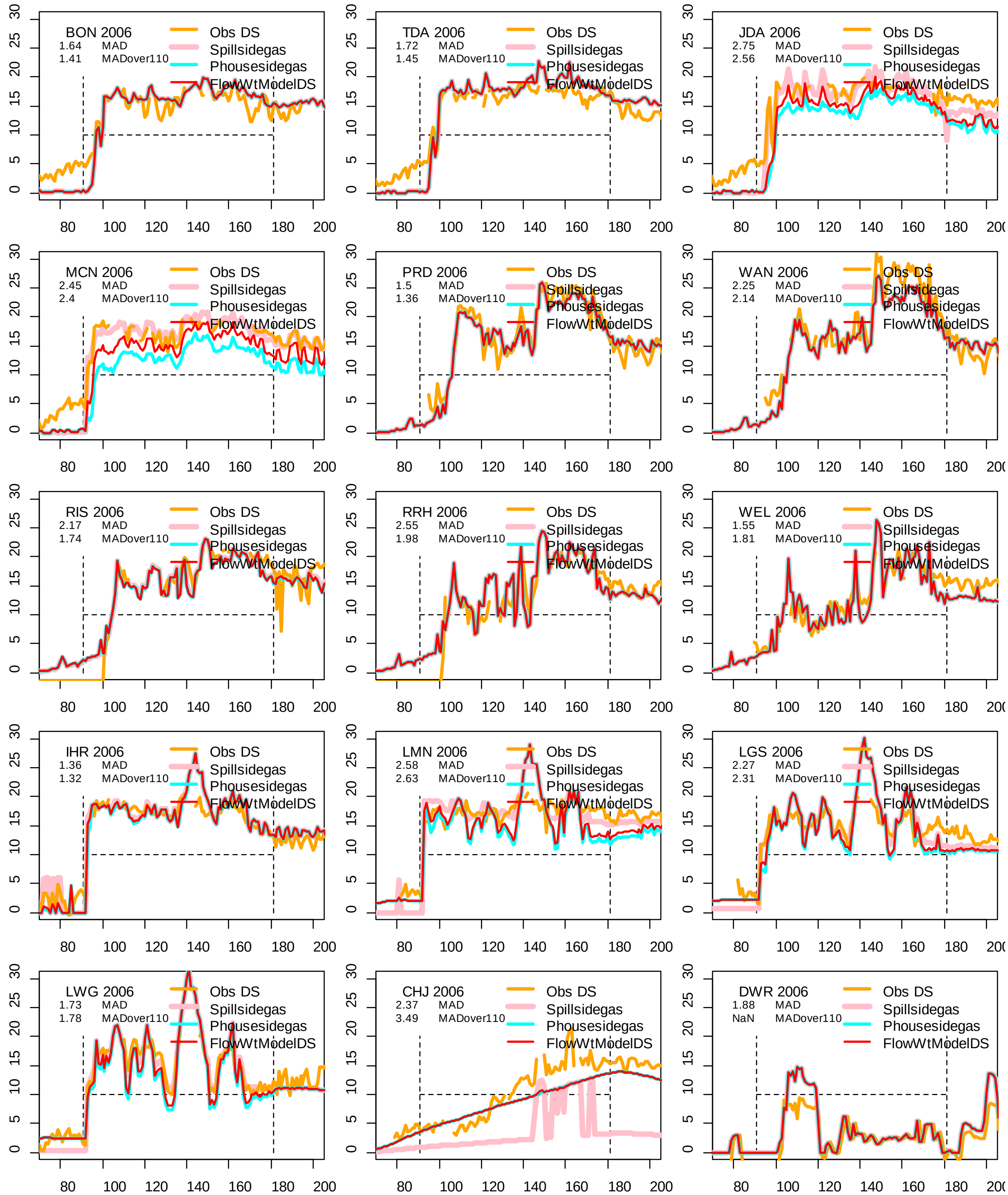
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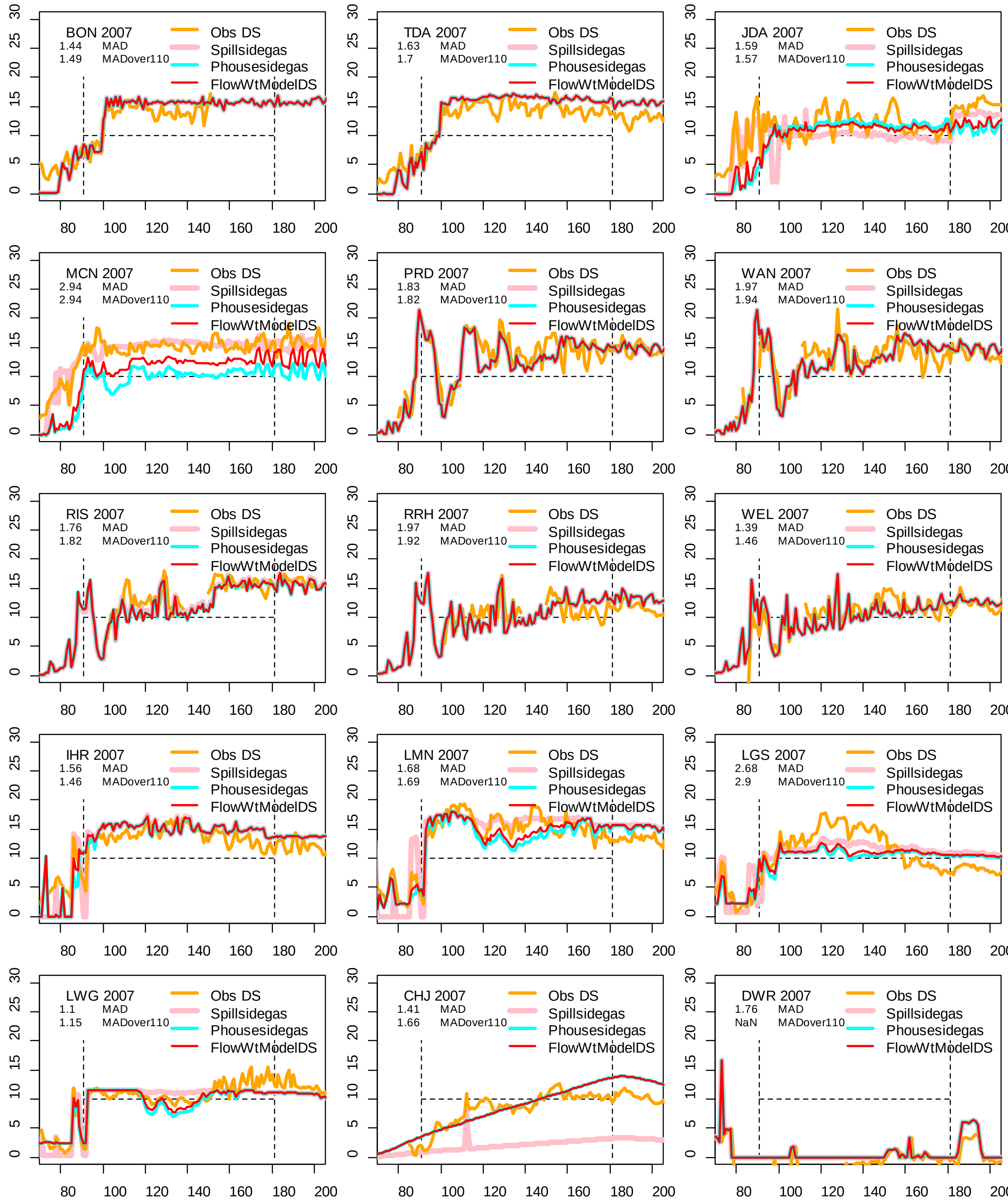
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1.68 MAD
1.69 MADover110
LGS 2007
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2.9 MADover110
LWG 2007
1.1 MAD
1.15 MADover110
CHJ 2007
1.41 MAD
1.66 MADover110
DWR 2007
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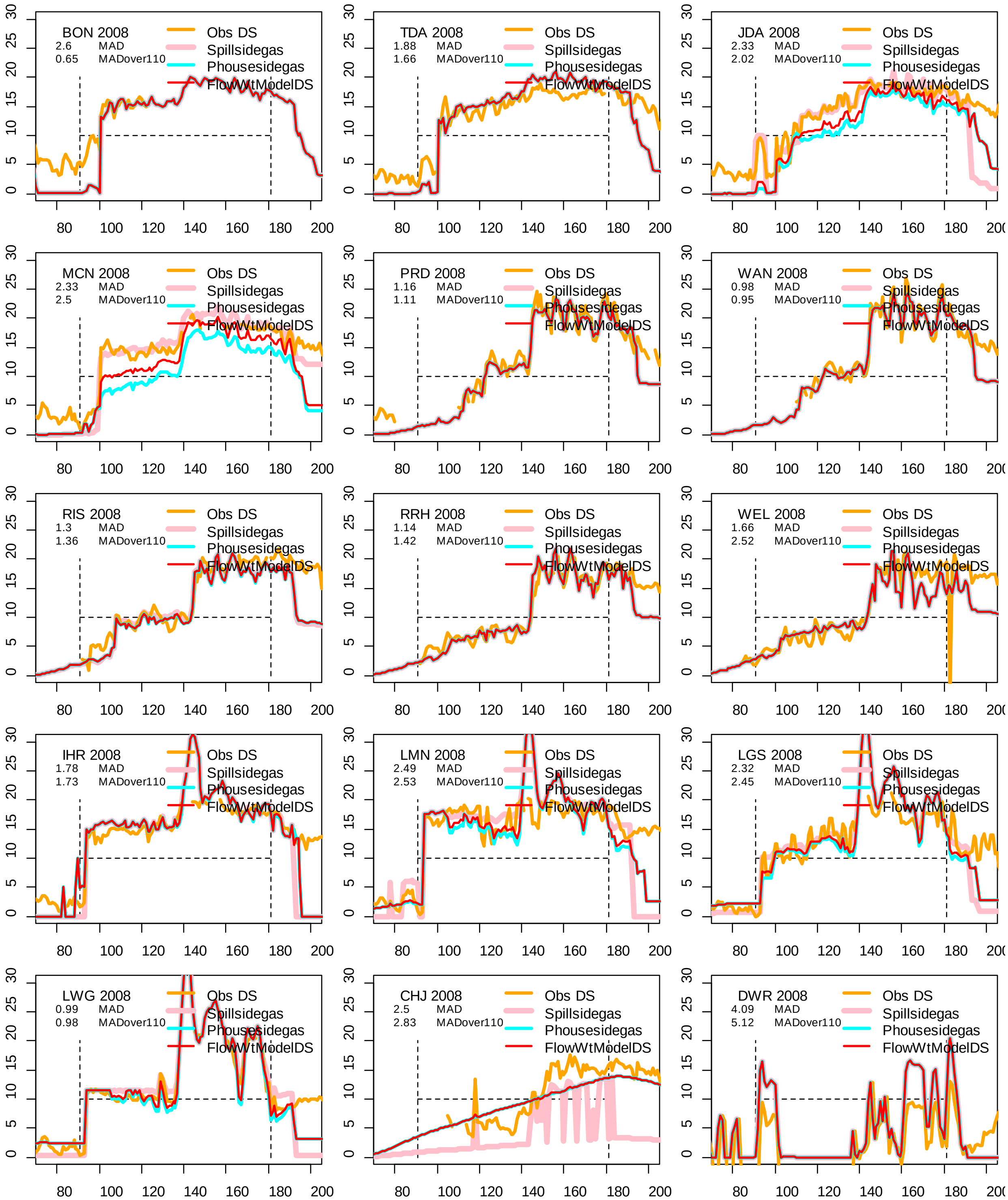
NaN MADover110
Obs DS
Spillsidegas
Phousesidegas
FlowWtModelDS
0 5 10 15 20 25 30
80 100 120 140 160 180 200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MCN 2008
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2.5 MADover110
PRD 2008
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1.11 MADover110
WAN 2008
0.98 MAD
0.95 MADover110
RIS 2008
1.3 MAD
1.36 MADover110
RRH 2008
1.14 MAD
1.42 MADover110
WEL 2008
1.66 MAD
2.52 MADover110
IHR 2008
1.78 MAD
1.73 MADover110
LMN 2008
2.49 MAD
2.53 MADover110
LGS 2008
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2.45 MADover110
LWG 2008
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CHJ 2008
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DWR 2008
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Obs DS
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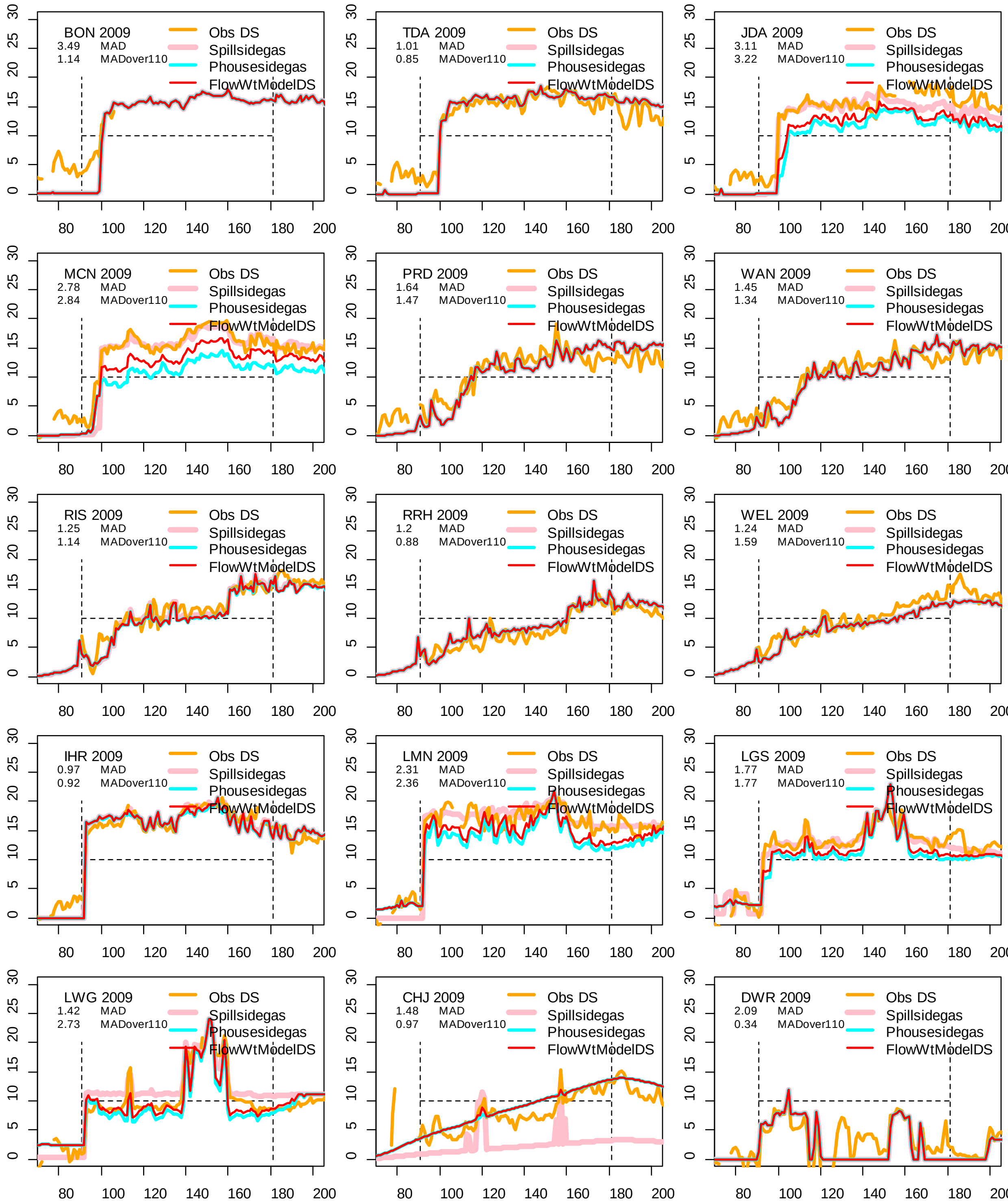
Phousesidegas
FlowWtModelDS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JDA 2009
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MCN 2009
2.78 MAD
2.84 MADover110
PRD 2009
1.64 MAD
1.47 MADover110
WAN 2009
1.45 MAD
1.34 MADover110
RIS 2009
1.25 MAD
1.14 MADover110
RRH 2009
1.2 MAD
0.88 MADover110
WEL 2009
1.24 MAD
1.59 MADover110
IHR 2009
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0.92 MADover110
LMN 2009
2.31 MAD
2.36 MADover110
LGS 2009
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1.77 MADover110
LWG 2009
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2.73 MADover110
CHJ 2009
1.48 MAD
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DWR 2009
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Spillsidegas
Phousesidegas
FlowWtModelDS
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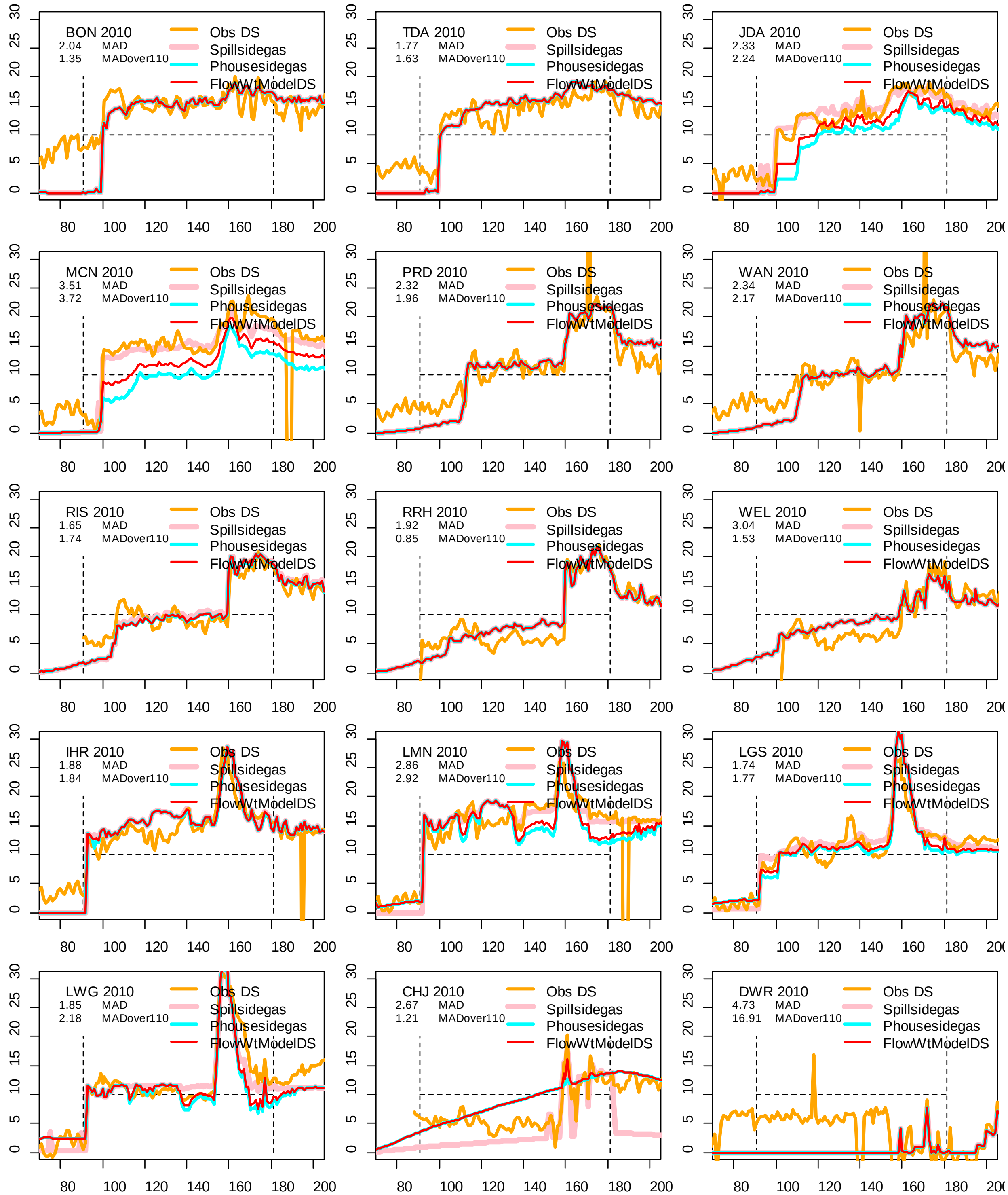
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MCN 2010
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3.72 MADover110
PRD 2010
2.32 MAD
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WAN 2010
2.34 MAD
2.17 MADover110
RIS 2010
1.65 MAD
1.74 MADover110
RRH 2010
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0.85 MADover110
WEL 2010
3.04 MAD
1.53 MADover110
IHR 2010
1.88 MAD
1.84 MADover110
LMN 2010
2.86 MAD
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LGS 2010
1.74 MAD
1.77 MADover110
LWG 2010
1.85 MAD
2.18 MADover110
CHJ 2010
2.67 MAD
1.21 MADover110
DWR 2010
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Obs DS
Spillsidegas
Phousesidegas
FlowWtModelDS
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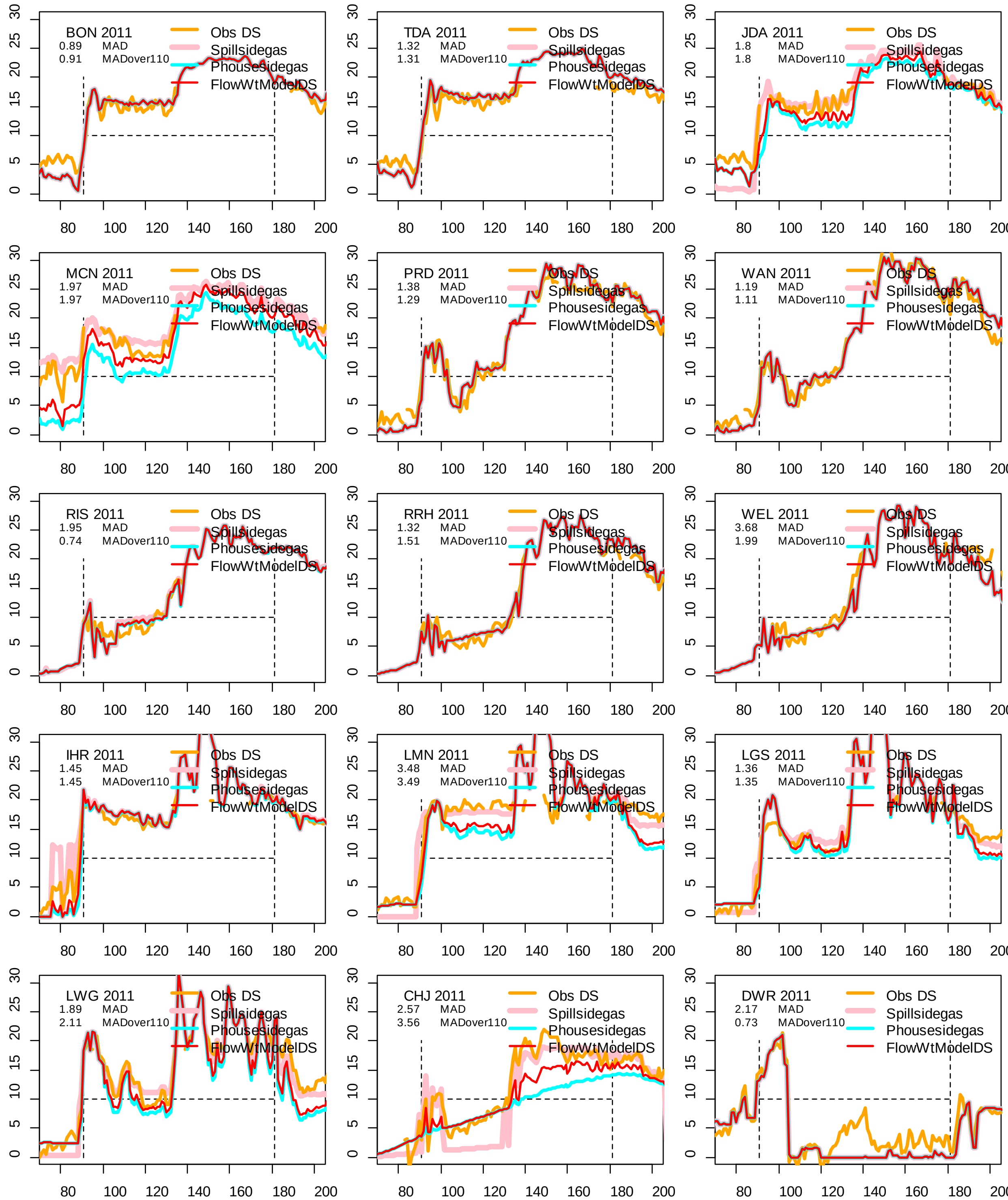
80 100 120 140 160 180 200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JDA 2011
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1.8 MADover110
MCN 2011
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1.97 MADover110
PRD 2011
1.38 MAD
1.29 MADover110
WAN 2011
1.19 MAD
1.11 MADover110
RIS 2011
1.95 MAD
0.74 MADover110
RRH 2011
1.32 MAD
1.51 MADover110
WEL 2011
3.68 MAD
1.99 MADover110
IHR 2011
1.45 MAD
1.45 MADover110
LMN 2011
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LGS 2011
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LWG 2011
1.89 MAD
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CHJ 2011
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DWR 2011
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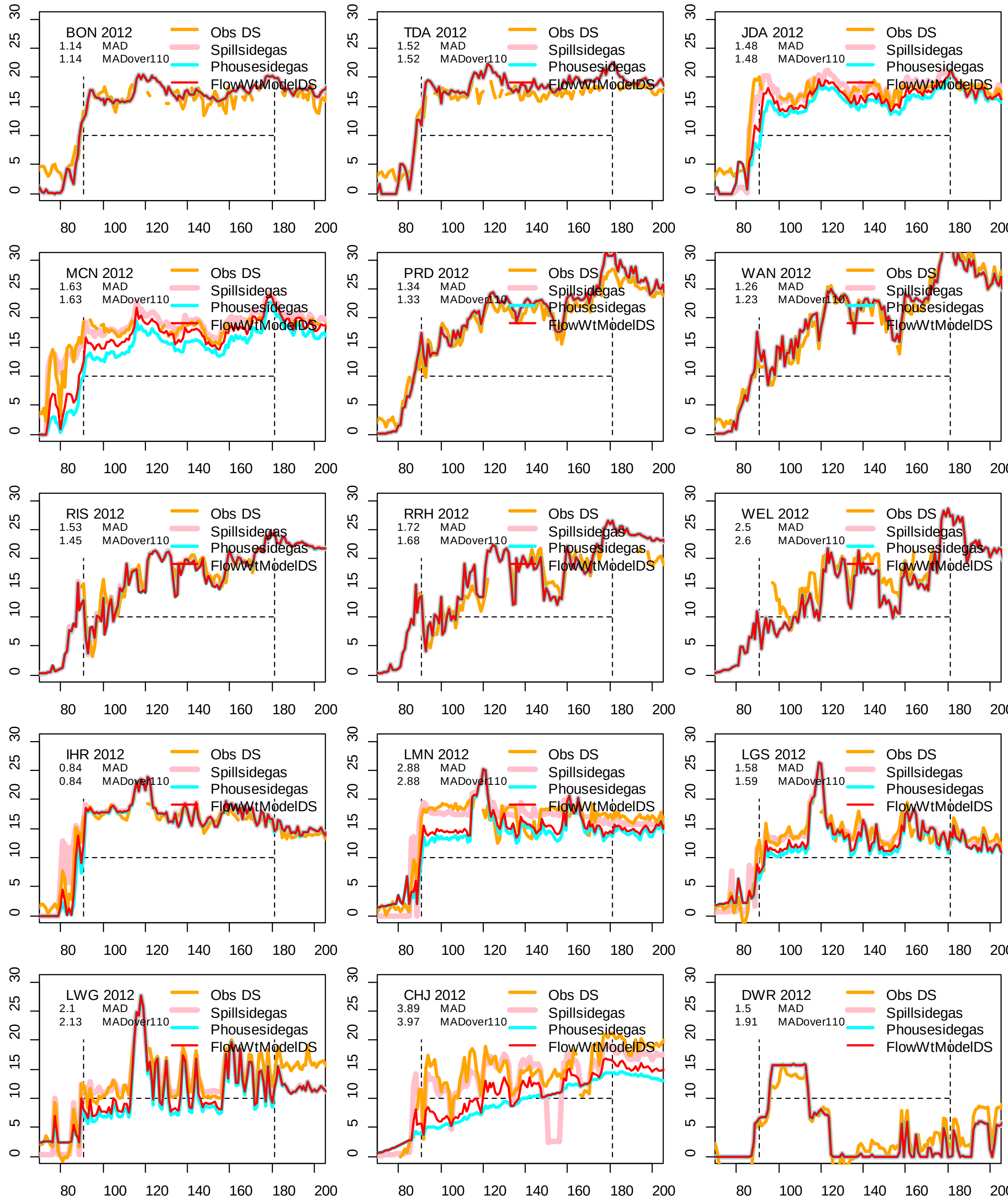
Obs DS
Spillsidegas
Phousesidegas
FlowWtModelDS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MCN 2012
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PRD 2012
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WAN 2012
1.26 MAD
1.23 MADover110
RIS 2012
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RRH 2012
1.72 MAD
1.68 MADover110
WEL 2012
2.5 MAD
2.6 MADover110
IHR 2012
0.84 MAD
0.84 MADover110
LMN 2012
2.88 MAD
2.88 MADover110
LGS 2012
1.58 MAD
1.59 MADover110
LWG 2012
2.1 MAD
2.13 MADover110
CHJ 2012
3.89 MAD
3.97 MADover110
DWR 2012
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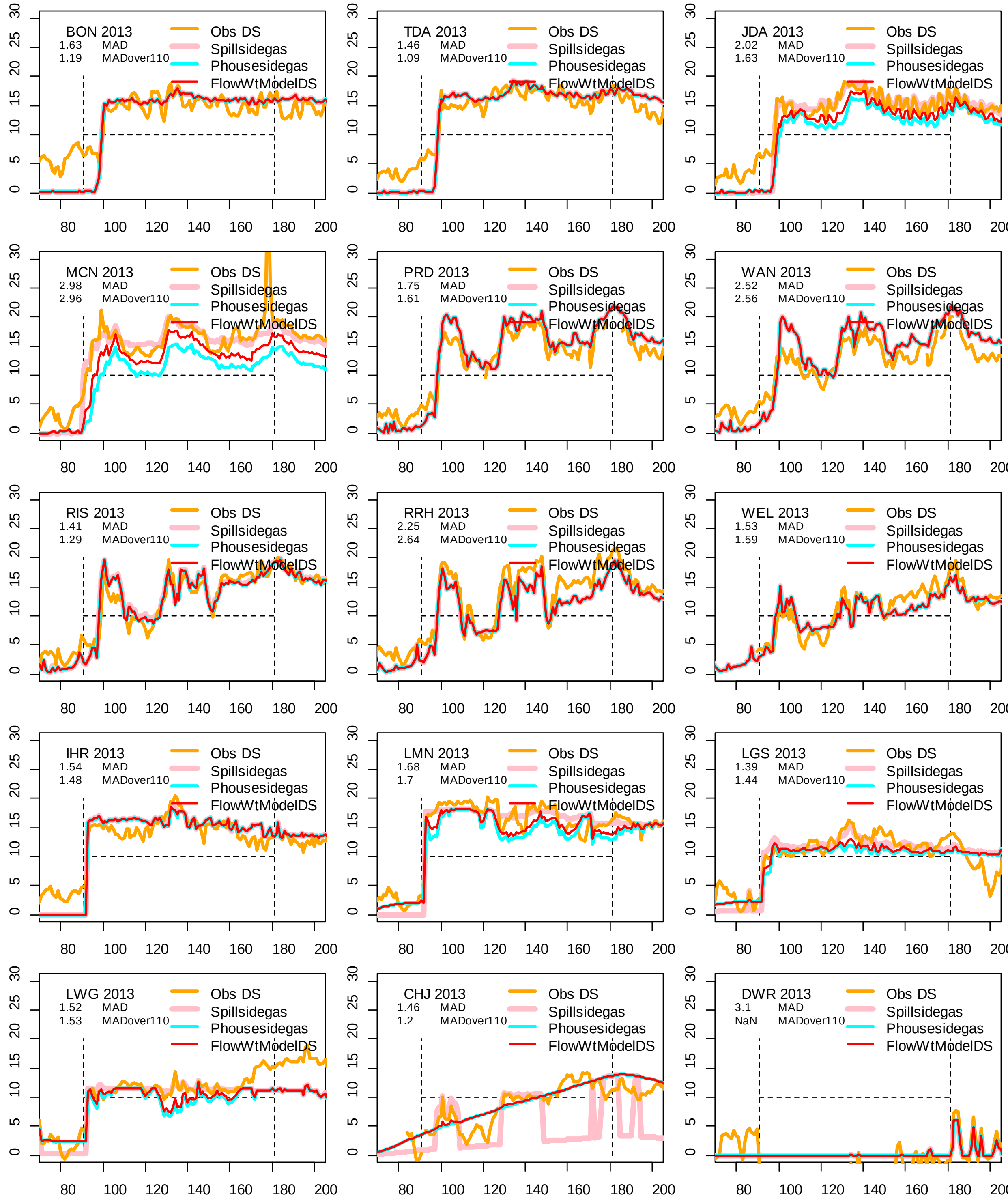
1.91 MADover110
Obs DS
Spillsidegas
Phousesidegas
FlowWtModelDS
0 5 10 15 20 25 30
80 100 120 140 160 180 200



BON 2013
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TDA 2013
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JDA 2013
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1.63 MADover110
MCN 2013
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2.96 MADover110
PRD 2013
1.75 MAD
1.61 MADover110
WAN 2013
2.52 MAD
2.56 MADover110
RIS 2013
1.41 MAD
1.29 MADover110
RRH 2013
2.25 MAD
2.64 MADover110
WEL 2013
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1.59 MADover110
IHR 2013
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LMN 2013
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LGS 2013
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LWG 2013
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1.53 MADover110
CHJ 2013
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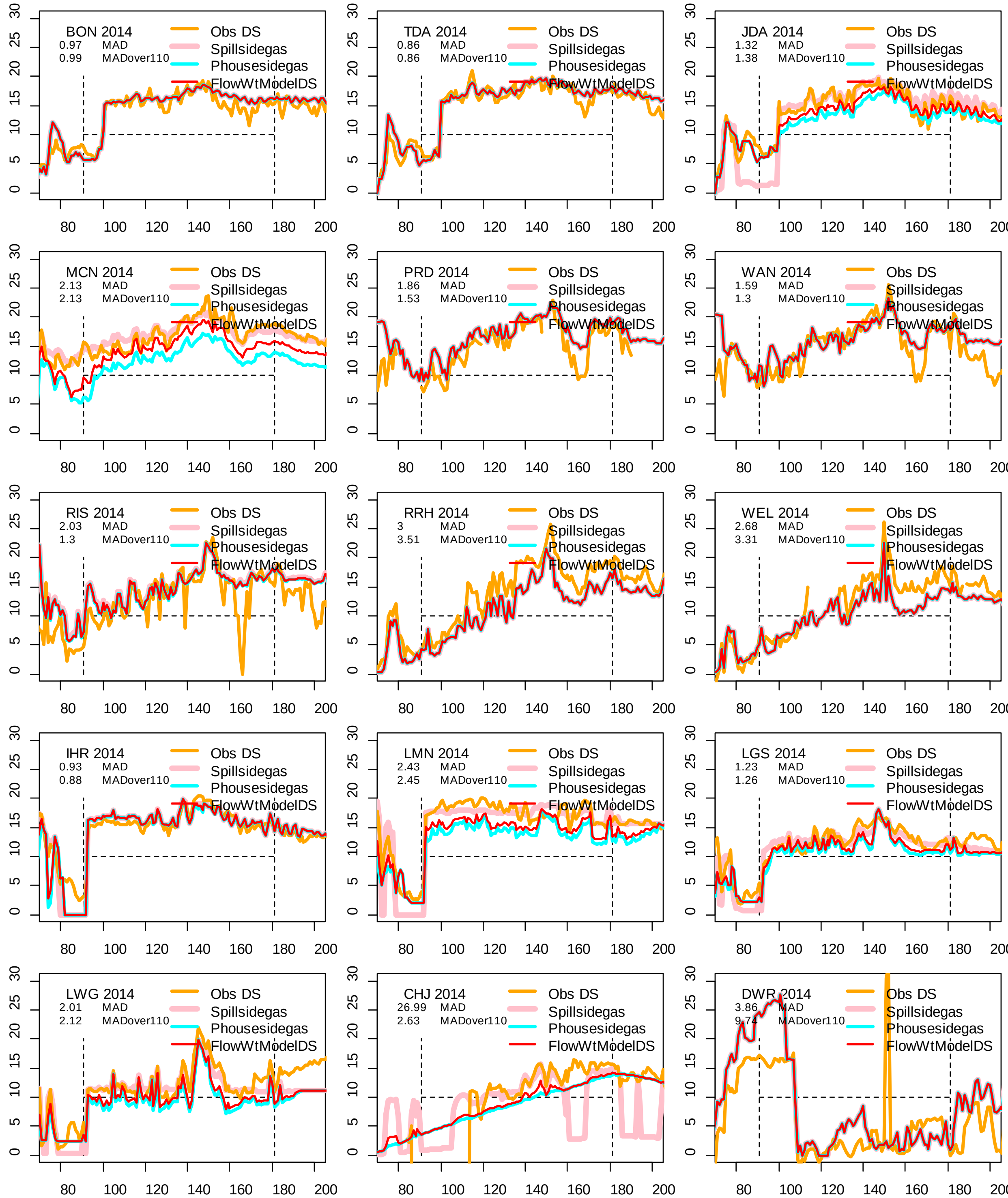
DWR 2013
3.1 MAD
NaN MADover110
Obs DS
Spillsidegas
Phousesidegas
FlowWtModelDS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JDA 2014
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MCN 2014
2.13 MAD
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PRD 2014
1.86 MAD
1.53 MADover110
WAN 2014
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RIS 2014
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RRH 2014
3 MAD
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WEL 2014
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IHR 2014
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LMN 2014
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LGS 2014
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1.26 MADover110
LWG 2014
2.01 MAD
2.12 MADover110
CHJ 2014
26.99 MAD
2.63 MADover110
DWR 2014
3.86 MAD
9.74 MADover110
Obs DS
Spillsidegas
Phousesidegas
FlowWtModelDS