Better Precipitation Product over the Red River Basin

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Abstract

Hydrological model WATFLOOD^{TM} was setup on the Red River Basin for Manitoba Hydro to study the future climate impact on the existing facility. Spatial gaps in station data motivated the searching for a better precipitation product over the red river basin in order to improve model results. North American Regional Reanalysis (NARR) data was chosen to be tested. Anomalies were identified within NARR data during data assessment. Distinct temporal and spatial anomalies were found through the anomaly analysis. A discussion was carried out about the sources of the anomalies. A hybrid approach was used to eliminate the spatial and temporal anomalies, and the hybrid data (HYBD) was then assessed using hydrological model WATFLOOD^{TM}. The results of WATFLOOD^{TM} using HYBD showed that the hybrid precipitation product was able to improve the model results successfully and eliminate the anomalies within NARR precipitation. Few recommendations were made to Manitoba Hydro at the end of this paper regarding using NARR data for hydrological modeling purpose.

Acknowledgements

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I would also like to thank Dr. Nick Kouwen, Mr. Mark, Gervais M.Sc., and Mr. Phil Slota for their help on the model setup and calibration and NARR data extraction

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Chapter1 Introduction

1.1 Hydrological Model and Gridded Climate Data

A hydrological model is a simplified characterization of the real world system, and they are created for different purposes Different model also have different types of modeling approaches (Moradkhani and Sorooshian, 2009). Two of the most distinctive approaches are the lumped model and the distributed models. The main difference between these two is that the lumped model generates the output flow from precipitation without considering spatial difference while the distributed model took spatial variability of the input data into account to generate the output flow. (Beven, 1985; Refsgaard, 1996; Smith et al., 2004).

No matter what type of model is being used, Precipitation is always a major forcing variable to the land surface hydrological process(Hsu and Sorooshian, 2009)and a complete coverage of forcing data is especially important to hydrological modeling on larger watersheds. The traditional source of obtaining the precipitation information is from gauge records. However, lack of gauges had always been an issue for hydrological modeling (Grimes, 2009).

The well known Thiessen Polygon Method (Thiessen, 1911) was one of the few earlier attempts to interpolating precipitation between climate stations. With the development of computer algorithm, more advanced interpolation methods were introduced including the methods used to interpolate the climate data onto a gridded base map which was called the Gridded Climate Data. The original focus of the gridded data is to estimate the precipitation at the area where the gauge are spars or not available. With the improvements of GIS technology, some more advanced interpolation methods allows elevation as an independent variable in the interpolation method to reflect the physical terrain influence. (Price et al., 1999).

Besides interpolating station precipitation records to get historical data on gridded base, development had also been done on prediction of future weather or climate pattern by using atmospheric climate models. In these models, precipitation is generated as a model output from other atmospheric parameters, for example the general circulation models (GCMs) and Regional Climate Models (RCMs) (Boer et al., 1992; Caya et al., 1995). Due to its courser resolution, applying these climate model data usually requires an unbiased method for interpolation to the scale of operation (Price, et al., 1999)

1.2 Problem Statement

The Red River, also known as the Red River of the North, Originates from the browns Valley, South Dakota. It flows north to Winnipeg, Canada, and into the Lake of Winnipeg, joins the larger Churchill-Nelson River Basin which is a major hydro power resource for Manitoba Hydro. As Manitoba hydro started adapting climate change policy into its operation; study was initiated to investigate the impact of climate change on existing hydro facilities. To understand the impact of climate change on future flow, hydrological model over Manitoba Hydro's major basins needs to be established. Hydrological Model WATFLOOD^{TM} was setup for the Red River Basin in the summer of 2010 and was initially calibrated with station data.

Hydrological modeling on larger watersheds like the Red River basin requires reliable daily forcing data, which includes precipitation. The current available stations data free to public presents significant spatial data gaps in the American side of the basin. Sub basins that suffered from insufficient data coverage experienced difficulty in achieving decent hydrographs because of both volume and timing errors. North American Regional Reanalysis (NARR) data was used to fill in the spatial data gaps as a first attempt among the searching of a better precipitation product for hydrological modeling on the Red River Basin.

However, NARR appears to have numerous issues in its precipitation field. Discontinuity of precipitation across the border had been observed (Mo et al., 2005). Therefore, an assessment on the NARR data had to be done before applying it to a hydrological model and correction are needed if necessary.

1.3Research Objective

The objective of the research is to evaluate the NARR's temporal and spatial anomalies with respect to the distributed station data and point station data. By comparing hydrographs and analyzing the anomaly, a proposed solution for correcting these anomalies will be established. The Corrected NARR data will be then applied to Hydrological Model WATFLOOD^{TM} without changing any parameters for validation of the applied corrections.

Chapter2 Literature Review

2.1 North American Regional Reanalysis (NARR) Data

NARR data was developed by National Centers for Environmental Prediction (NCEP). It is a long-term, dynamically consistent, high-resolution, high-frequency, atmospheric and land surface hydrology dataset for the North American domain (Mesinger et al., 2006,). The major components of the model includes: the lateral boundaries from and the data used for the NCEP–DOE Global Reanalysis, the NCEP Eta Model and its Data Assimilation System, a recent version of the Noah land-surface model, and the use of numerous datasets additional for improving results.(Mesinger et al., 2006,)

Precipitation was first generated within NARR model itself as a first guess, the generated first guess was later on corrected against assimilated observed precipitation data to ensure the model precipitation during assimilation is close to the observed data (Mesinger et al., 2004). The observed precipitation was assimilated as latent heat and being used to generate corrected precipitation indirectly. (Lin et al. 1999)

Becker (Becker, et al 2009) examined the precipitation characteristic in NARR and compared it with the observed station data in the USA. NARR data's annual precipitation was found to be close to the observed precipitation with a slightly underestimation during summer time across USA (Becker, et al 2009).

Choi (Choi, et al 2009) examined the NARR data using hydrological model SLURP, and compared it with NNGR data within the northern Manitoba area. Choi concluded that the NARR generated hydrograph is in much better agreement with observations than NNGR data set. (Choi, et al 2009)

2.2 Hydrological Model WATFLOOD™

WATFLOOD™ is a fully distributed physical based model of the hydrological budget of a watershed.(Kowen,2009) Its unique Group Response Unites systems allows fully distributed hydrological process computation and capturing the spatial variability of forcing data without losing computational efficiency. The processes includes interception, infiltration, evaporation, snow accumulation and ablation, interflow, recharge, base flow, and overland and channel routing.(Kouwen, 2009) Its emphasis on the physical hydrological cycle processes allows internal processes validation using isotope tracing method(Stadnyk et al, 2004).

Several climate change impact studies had been done by using WATFLOOD™,. Phol, S. (Phol, et al, 2006) used WATFLOOD™ with GCM data to assess the impact of climate change on runoff and annual water balance over Canadian Arctic basin. Kouwen (Kouwen et al, 2006) used WATFLOOD™ coupled with hydrodynamic model, ONE-D to assess the impact of climate change on Athabasca, Claire, and Mamawi lakes and the Peace and Athabasca rivers in the Peace-Athabasca Delta. Another earlier study over the Peace and Athabasca River done by Brenda (Brenda et al, 2006) used WATFLOOD™ to asses the impact of climate change impacts by feeding future climate model data. WATFLOOD™ simulated flow showed generally good agreement for volume and timing of flow with measured flow (Brenda et al, 2006)

Kouwen (Kouwen et al, 2010) also proved the WATFLOOD™'s capability in terms of flood simulation. It is important for the Red River Basin as flood is also one of its main issues that are under concern.

Charpter3 Study Area and Data

3.1 Study Area

The Red River Basin lies across the center of southern Manitoba and northern USA. It originates in South Dakota and flows north. Assiniboine River joins it in the heart of Winnipeg city although the Assiniboine River was excluded in the WATFLOOD^{TM} model. The natural outlet of the watershed is at the Lake Winnipeg.

Red River drains north into the Nelson-Churchill River system. Nelson-Churchill River system is one of the major resources for power generation. A good understanding of the amount of the flow through the river is needed to better estimate the power generation potential for the down stream hydro power plants.

Red River is known for its flood issues. The frequent flood had caused severe damages to the major cities along the river. A basin Scale model is need for a better estimation of the flood amount in order to mitigate the flood damage.

Water Quality is also one of the major concerns over the Red River Basin. A basin scale hydrological model would be able to estimate a base point for the water quality analysis.

Last but not the least, the Red River's frequently created its fertile land for agricultural activities. The recent tile drainage system is cheap and easy to install but created unknown impact on the River's flow. For better watershed management and flow regulation, a watershed scale hydrological model is needed to study the impact of the new drainage system on flow and develop a proper management and regulation strategies.

3.2 Data

Data related to this undergraduate thesis contained three sets of point station data which are NOAA's Global Daily Summary, United States Historical Climatology Network (USHCN), Environment Canada stations dataset, and one set of gridded climate data NARR. These data sets cover the entire Red River Basin, but only the precipitation data was studied.

The three sets station data contains 137 stations and were distributed onto a grid based precipitation field using inverse distance weighting method. This precipitation field is applied directly to WATFLOOD^{TM}. Point station data before distribution is referred to as PTSTA and DSSTA referred to the distributed station data precipitation field

NARR data is obtained from the NOAA Earth System Research Laboratory, Physical Science Division's ftp website: ftp://ftp.cdc.noaa.gov/Datasets/NARR/. Data was obtained in Net CDF file format, Several MatLAB scrip developed by Phil, Slota and Sung Joon, Kim was used to convert NARR precipitation field at 32 km resolution to point tb0 format files. The time span of these forcing data is six years from 1994 to 1999.

Besides forcing data, WATFLOOD^{TM} model also requires DEM and land cover data as topographic and land use information inputs, it also needs recorded flow to compare with simulated flow. DEM data was obtained from SRTM with 90 meter resolution, and land cover was obtained from US National Land Cover Database and Manitoba Land Initiative. Flow gauge data was obtained from USGS national hydro-net work and Water Survey Canada HYDAT records.

Chapter 4 Methodology

4.1 Anomaly Identification

4.1.1 Hydrograph Anomaly Identification

Essentially, each NARR grid point fall within the area of interest was treated as a point station and being stored in tb0 file format. In order to make the NARR data work with 11km resolution grids in WATFLOOD^{TM}, NARR is downscaled from its original 34km grid size to 11km using point station redistribution program RAGMET.exe which utilized the inverse distance weighting method to interpolate station data on to a precipitation field. The distributed NARR data is referred to as DSNAR.

After obtaining the redistributed NARR precipitation fields (DSNAR), it was fed into the initially calibrated WATFLOOD^{TM} Model to generate initial NARR run. Hydrographs were obtained from the initial simulation at each sub basin. The statistics of the hydrograph was then compared with the hydrograph generated by using distributed station data (DSSTA) while keeping the parameters in the model unchanged. The comparison was plotted as shown in the graphs below:

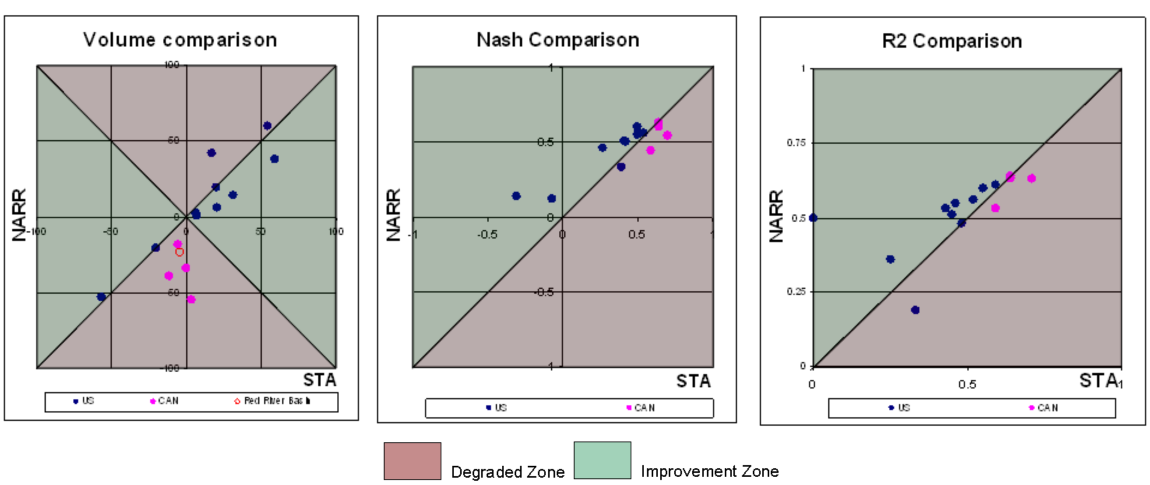

Figure 1: NARR Initial Run Results Comparison

Initial NARR simulation results comparison showed that majority of the US sub basins improved its results, in terms of all of the three statistics. However, all the Canadian sub basins showed degraded results after using NARR data. Since the parameter of the model is unchanged, the possible error within model calibration was eliminated, the difference of the model performance between US and Canadian area showed the spatial discrepancies within the DSNAR precipitation fields.

4.1.2 Precipitation Field Anomaly Identification

To further understand the spatial and temporal anomalies. We used the following anomaly mapping method.

First, the daily DSNAR and DSSTA precipitation fields were aggregated into cumulated monthly precipitation fields expanding from 1994 to 1999 made a total of 72 monthly fields.

The anomaly was calculated using the following equation:

$$A_{i,\,j,\,m} = (P_{i,\,j,\,m}^{\ DSNAR} - P_{i,\,j,\,m}^{\ DSSTA}) \,/\, P_{i,\,j,\,m}^{\ DSSTA}$$

In which "**A**" stand for Anomaly, "**P**" stands for Precipitation. "**i**" and "**j**" are spatial indicator indicating the row and column number of a specific grid on the precipitation map, while "**m**" is a temporal indicator indicating the month number.

Once the anomaly fields were extracted, they were inspected visually frame by frame to identify any spatial and temporal anomalies.

Through visual inspection, at least there types of anomalies occurred both spatially and temporally can be identified:

a). Area across 48.9 to 49 degree North, where it is close to the Canadian and American border, it appears to have a band of lower precipitation for DSNAR from May 1st to Oct 31st consistently through all the 6 years(1994 to 1999).

b). Area Above 49 Degree North appears to have a lower precipitation for DSNAR fields from May 1st to Oct 31st , but less in the magnitude of underestimating comparing to the border area

c). In the Area where we don't have any station data, DSNAR tends to have more spatial variations than the distributed station data during the winter time.

The different types of anomalies appeared in the DSNAR field showed significant spatial characteristics. Therefore, the anomaly field was divided spatially into five different sections for further analysis. The five sections were shown in the figure below:

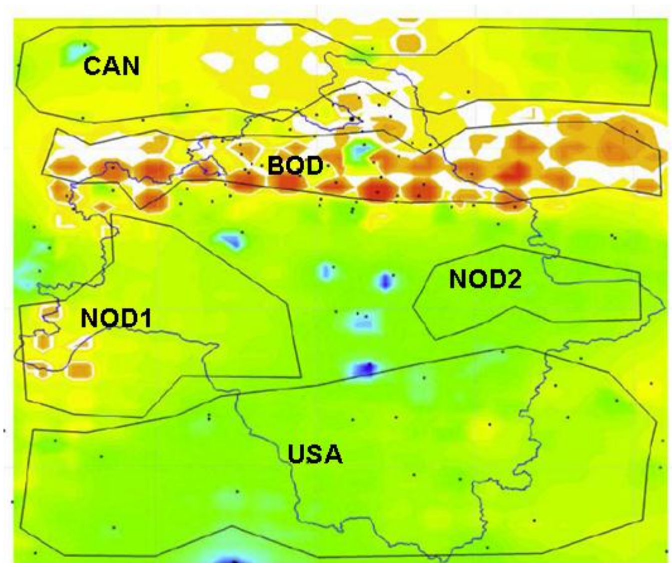

Figure 2: Five Spatial Anomaly Zones Extracted From Anomaly Map

In the above figure, the base layer is the averaged summer anomaly field calculated from May 1st to Oct 31st. According to the spatial characteristics of the anomaly, the map is divided into: Border area (BOD) where significant underestimating of precipitation occurred, No data area1 (NOD1) and No data area2 (NOD2) where no station data existed while NARR appeared to have much more spatial variations. The rest of the map was divided into Canadian area (CAN), and USA area (USA)

4.2 Anomaly Analysis

4.2.1 DSNAR vs DSSTA

Once the anomalies were separated into these five zones, average and coefficient of variance (Cv) among all the points within each area for DSNAR and DSSTA were calculated. For each area, the ratio of the averages and CVs was calculated between DSNAR and DSSTA using the following equations:

$$R_m^{CAN} = (Ave_m^{\ DSNAR\text{-}CAN} / Ave_m^{\ DSSTA\text{-}CAN})$$
$$R_m^{CAN} = (Cv_m^{\ DSNAR\text{-}CAN} / Cv_m^{\ DSSTA\text{-}CAN})$$

In which “**R**” stands for statistic ratio “**Ave**” stands for Average calculated for either DSNAR or DSSTA over a specific area. And “**Cv**” stands for the coefficient of variance calculated for either DSNAR or DSSTA over a specific area. The above equation shows the ratio of average and Cv calculated for Canadian (CAN) area.

A cumulative density function curve was then calculated for all these ratios and they were compared to the ratio equal to one line to exam the relationship between DSNAR and DSSTA’s volume difference (average) and spatial variation difference (Cv). They were plotted for both summer (May. to Oct.) and winter (Nov. to Apr.) to distinguish the temporal effects

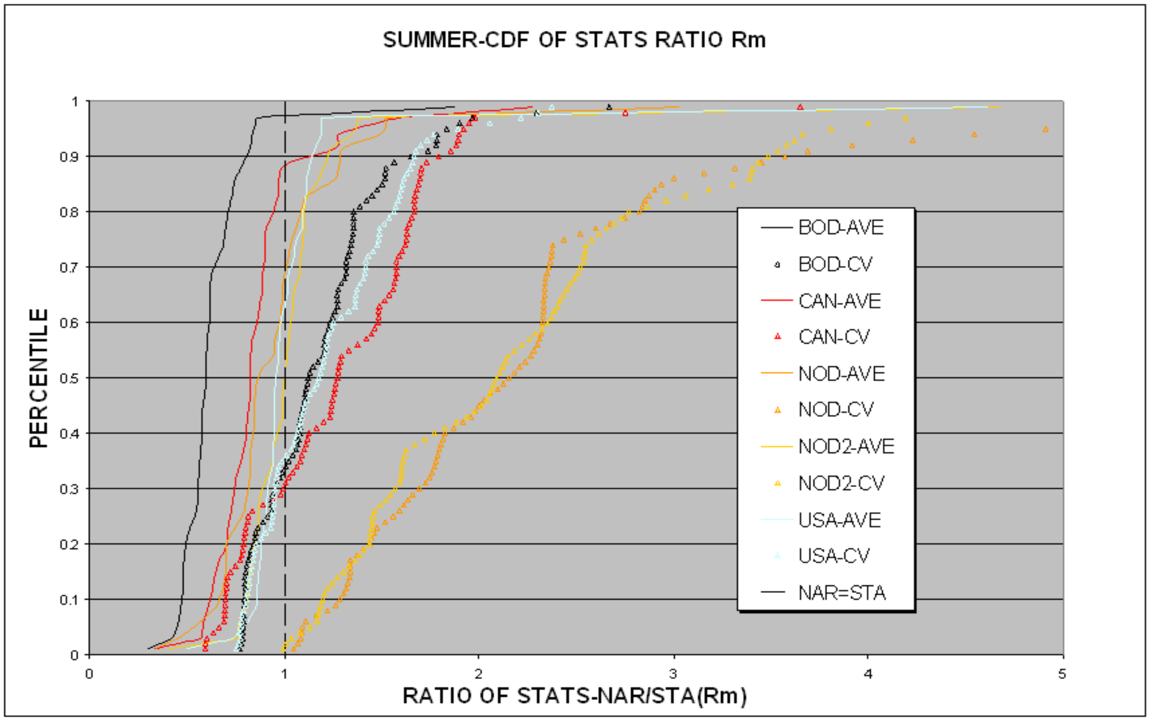

Figure 3: Cumulative Density Plot of Statistics Ratio during Summer

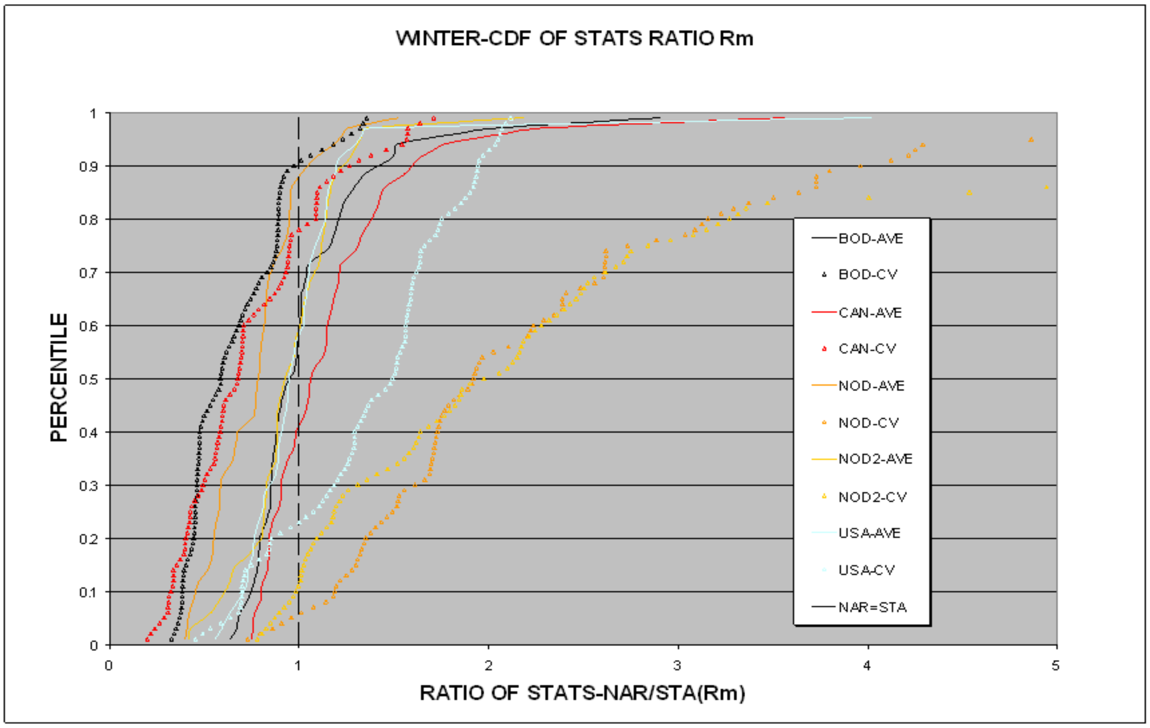

Figure 4: Cumulative Density Function of Statistics Ratio during Winter

From the above figures, it is clear to see that during the summer time, at the BOD and CAN areas, the precipitation in DSNAR is lower than precipitation in DSSTA. However, at the NOD1 and NOD2 areas, DSNAR's CV value is higher than the DSSTA's. Meanwhile, it is also clear to see that during the winter time, at the BOD and CAN areas, the volume difference had been reduced when compared to summer, while the spatial variation of DSNAR is less than DSSTA. Further more, over the NOD1 and NOD2 areas, the spatial variation of DSNAR is still larger than DSSAT.

From the study of the anomaly map and initial NARR run hydrograph results, we know the decreasing in the summer precipitation at the border area from DSNAR is unreasonable as it appeared to be an unnatural band, but more importantly, it is unreasonable as it produced much worse results on the unchanged WATFLOOD™ model. The fact that WATFLOOD™ was able to generate better results elsewhere using NARR and it also generated better results at the same location with only station data further demonstrate that the band is an error in NARR instead of natural occurrence nor model calibration errors

On the other hand, the more spatial variability at the NOD1 and 2 areas in DSNAR is quite reasonable as NARR used a more intensive climate station network in the US side. Using a successive scan method, the initial model generated precipitation was corrected against the assimilated station data. Therefore the NARR precipitation field in the US side, to some extend, preserved much of the information of the assimilated stations. It is more desirable from a hydrological modeling perspective that NARR has a higher spatial variation as it captured more events within that area.

4.2.2 DSSTA vs. PTSTA and DSNAR vs. PTSTA

The above DSNAR vs. DSSTA comparison is a comparison between the distributed data. The DSSTA is obtained by redistributing the PTSTA data onto a gridded precipitation field using the Inverse distance Weighting (IDW) method. The advantage of this comparison is that we can see the difference between the data sets that were directly applied to the WATFLOOD™ model and it will be more relevant to the hydrograph results comparison. However, for the purpose of examine DSNAR with the real record; the DSNAR will be compared directly with the PTSTA data. Meanwhile, the DSSTA fields were also compared with PTSTA data and used as a reference, and also served a purpose of examine the performance of the IDW method during redistribution of station data.

First, the daily precipitation fields from DSNAR and DSSTA were aggregated into 72 monthly cumulative fields lasting from 1994, Jan 1st to 1999 Dec31st. The average of cumulated monthly precipitation was then calculated among the six years and reduced the number of frames from72 cumulative monthly to 12 averaged cumulative monthly.

The average of cumulative monthly precipitation in PTSTA was calculated in the same manner for all the stations as well.

Time series of the 12 averaged monthly cumulative precipitation fields were extracted at the grids where point stations fell within. The relative error is then calculated between the time series of the grid point and the time series of the point station on that grid.

The following equations were used for calculating the relative error:

$$E_{n,\,ma}^{DSNAR} = (P_{n,\,ma}^{DSNAR} - P_{n,\,ma}^{PTSTA}) / P_{n,\,ma}^{PTSTA}$$

$$E_{n,\,ma}^{DSSTA} = (P_{n,\,ma}^{DSSTA} - P_{n,\,ma}^{PTSTA}) / P_{n,\,ma}^{PTSTA}$$

In the above equations, “**E**” stands for relative error and “**P**” stands for precipitation. “**n**” stands for point station number (station number 1 to number 119), “**ma**” stands for the 12 month numbers(Jan to Dec).

Meanwhile, the percentage of missing days within each point station was calculated. It is used as an indication of how valid the calculated relative errors are since it would be unreasonable to compare relative error at stations that had too many missing days. Once the relative error is calculated for each month at each station, the relative error and percentage missing days were averaged again to get Summer relative error(May to Oct.) and Winter relative error(Apr. to Nov.)

Moreover, the 119 stations were arranged into three groups: USA group, BORDER group, and CANADIAN group according to their latitude. They were then further rearranged in the order of increasing percentage missing days within each group as shown in the figure below:

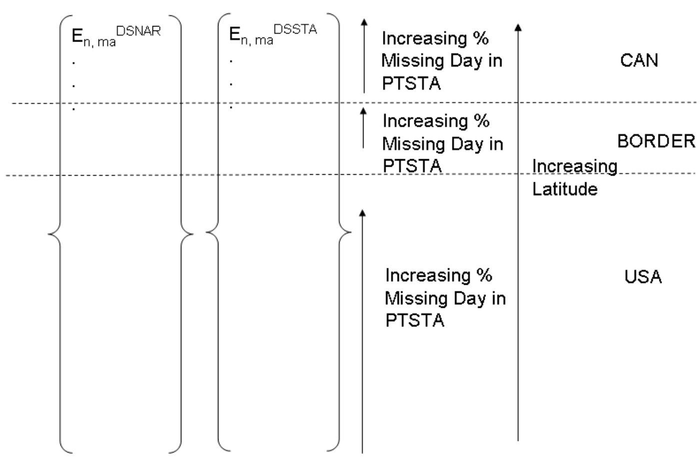

Figure 5: Steps Used for Sorting Relative Error Among 119 Stations

Finally the relative error was plotted for all the stations as shown in the figure below:

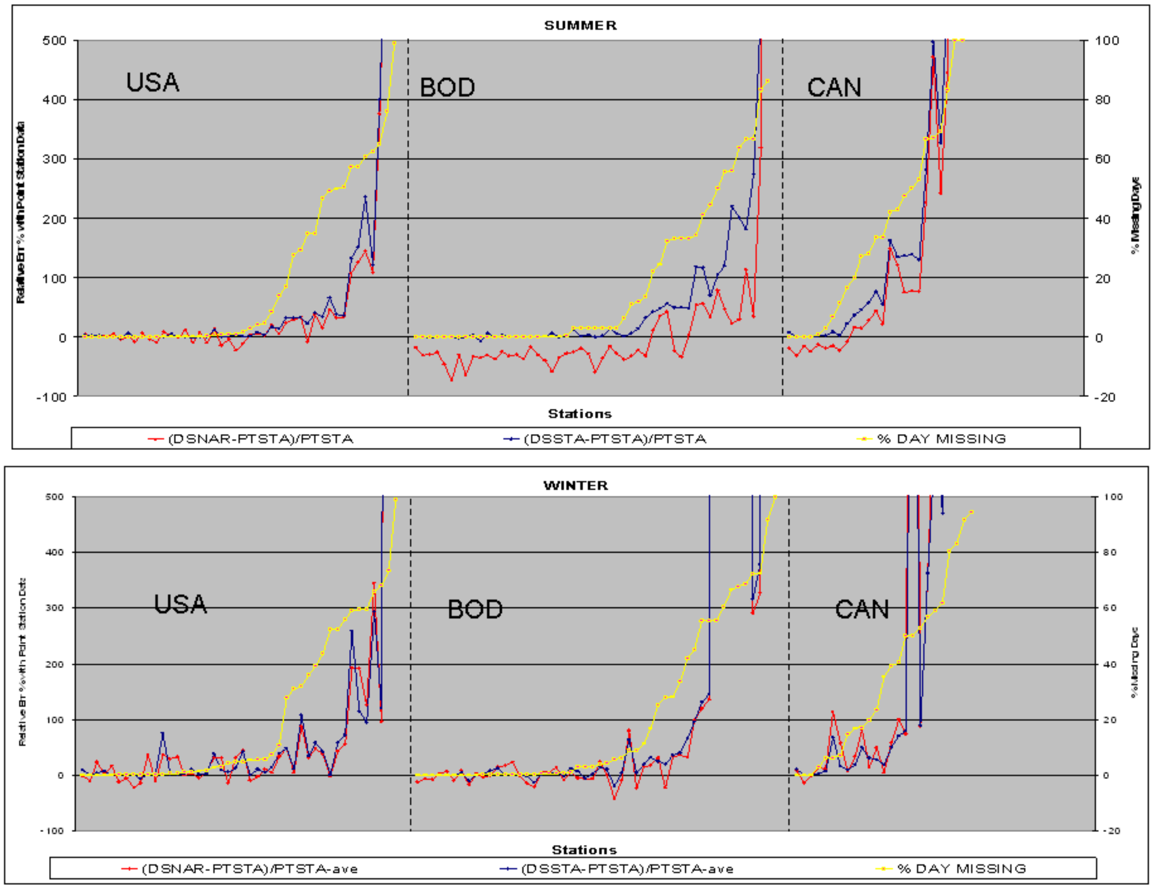

Figure 6: Relative Error Plot for Rearranged 119 Stations

From the above figures, it is very clear to see that the summer and winter relative error appears to have very distinctive difference between border and Canadian area.

For the border area in the summer time, DSNAR is underestimating about -25 to -30 percent relative to station data at the stations where we have complete record (percentage missing days <5%). However during the winter time, at the same area, this error trend does not occur. The relative error in the winter time at the border area appears to be evenly distributed along the zero percent line indicating a fair representation of the station data.

For the Canadian area in the summer time, DSNAR also understated the precipitation, but the magnitude is less, it varied from -15 to -20 percent relative to the station data at the stations where complete records existed. Meanwhile, the relative error in the winter time at the Canadian area is similar to that of the border area in winter; it varied closely alone zero percent line.

4.3 Anomaly Analysis Summary

Combining these findings through the DSNAR and DSSTA analysis in section 4.2.1 and the DSSTA vs. PTSTA and DSNAR vs. PTSTA analysis in section 4.2.2, it is certain to say that the NARR data at the Border and Canadian side is very poorly performed. It appears to have a band of extreme underestimation of precipitation across the border area and relatively less, yet significant underestimation over the Canadian area for the Red River Basin. It also failed to capture the spatial variation of the precipitation at border and Canadian area in the winter time as shown in section 4.2.1. Therefore it is not a fair representation of the actual weather pattern over these two areas. It also explained the degraded results in WATFLOOD™ for the initial NARR run found in section 4.1.1.

On the other hand, over the American side, both summer and winter precipitation showed a small relative error and discrepancy comparing DSNAR with PTSTA and DSSTA. Furthermore, section 4.2.1 showed that the NARR appears to have more spatial variation than DSSTA. Therefore, over the US area, NARR closely followed the station records, captured spatial variations and might reflected the characteristics of the actual weather pattern over the US area

4.4 Anomaly Correction

Consistent anomalies occurred within a climate model is easy to correct, however, through studies and several discussions about the source of the NARR anomaly; we found that the NARR anomalies presented here were not consistence model errors but event based anomalies. The details of the discussion about the source of NARR anomalies can be found in Charpter5 discussion section of this report. Based on the characteristics of the anomaly we decide to use a hybrid approach to correct the NARR anomalies.

A hybrid precipitation field was created by combining the American NARR grid points and all the 137 previously used point stations over entire Red River basin, they were then fed into the point station data redistribution program RAGMET.exe to generate the hybrid daily precipitation fields(HYBD).

Once the HYBD daily precipitation fields were obtained, they were then fed into WATFLOOD^{TM} to generate hydrographs. All the parameters in WATFLOOD^{TM} were kept the same as the initial NARR run to eliminate the calibration errors.

4.5 Correction Evaluation

Once we had obtained the results from the WATFLOOD^{TM} by using HYBD with parameters kept the same, hydrograph and statistics comparisons were undertaken to evaluate the HYBD precipitation fields.

For the purpose of demonstration, only two hydrographs were shown, one is from the US sub basin, Goose River Basin, and another one is from the Canadian sub basin, Rat River Basin.

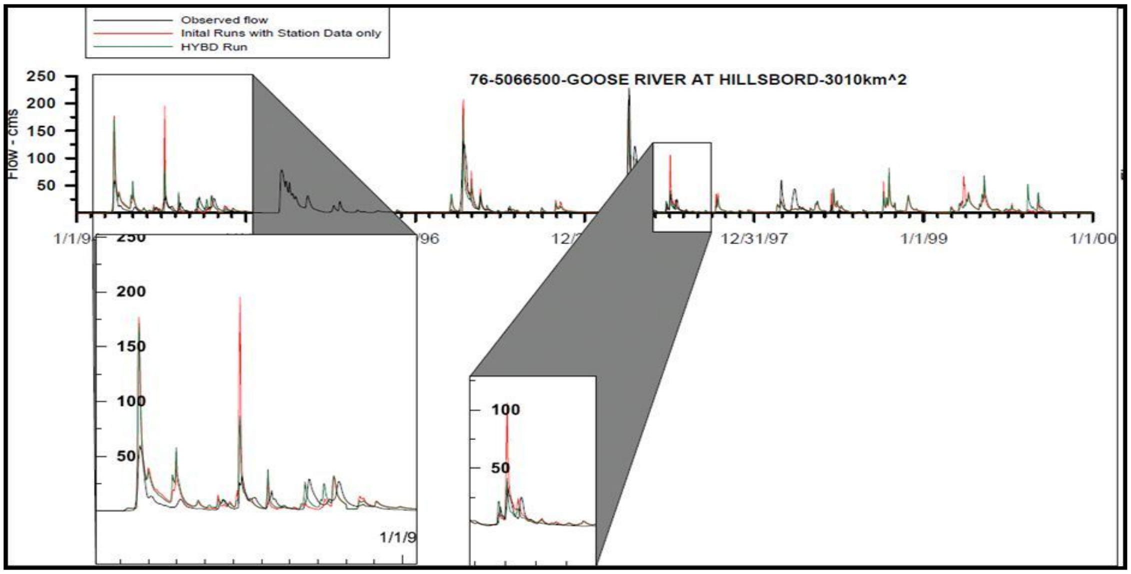

Figure 7: Comparison of Hydrograph at the Goose River Using Station Data only and using HYBD Precipitation

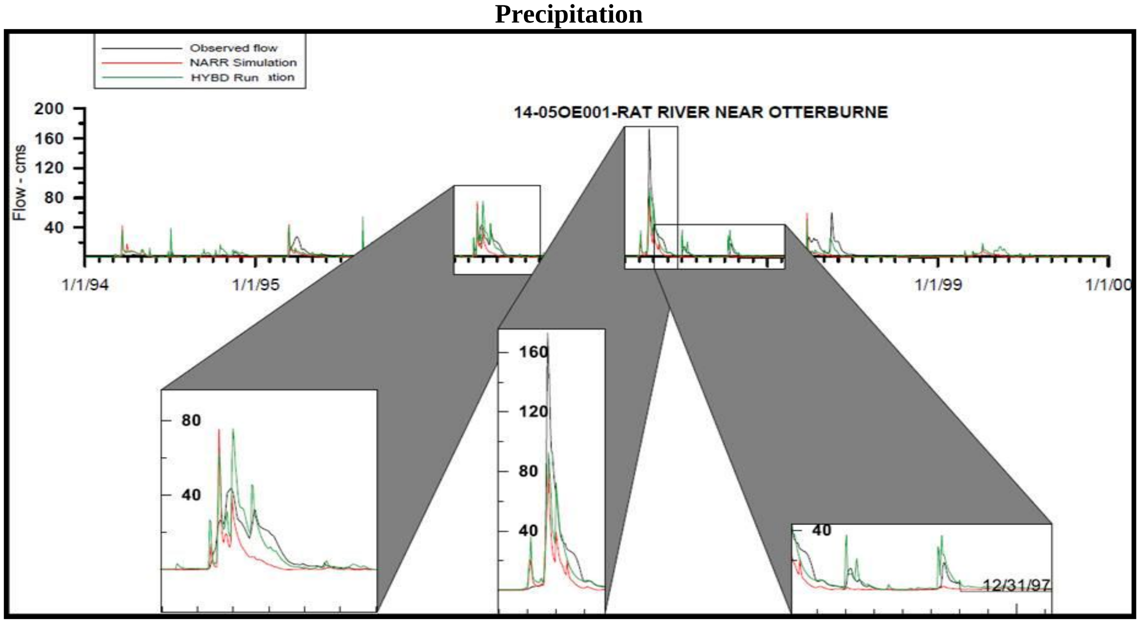

Figure 8: Comparison of Hydrograph at the Rat River Using NARR Precipitation and using HYBD Precipitation

The Goose River Sub basin in the first graph showed that by using HYBD data, the spiky extreme events were improved. The spiky extreme events were caused by over weighting the remote stations which is due to lack of climate stations over the basin area.

The Rat River Sub basin on the second graph showed that the HYBD data had improved the volume of the runoff during rainfall event; moreover, it captured the rainfall events that NARR data had failed to capture as we can see on the third subplot.

Further more, statistics for all the sub basins were calculated and their results were plotted on the comparison graph(top) and they were listed together with initial NARR run's results comparison graph (bottom) to demonstrate the improvement after changing from using NARR to using HYBD:

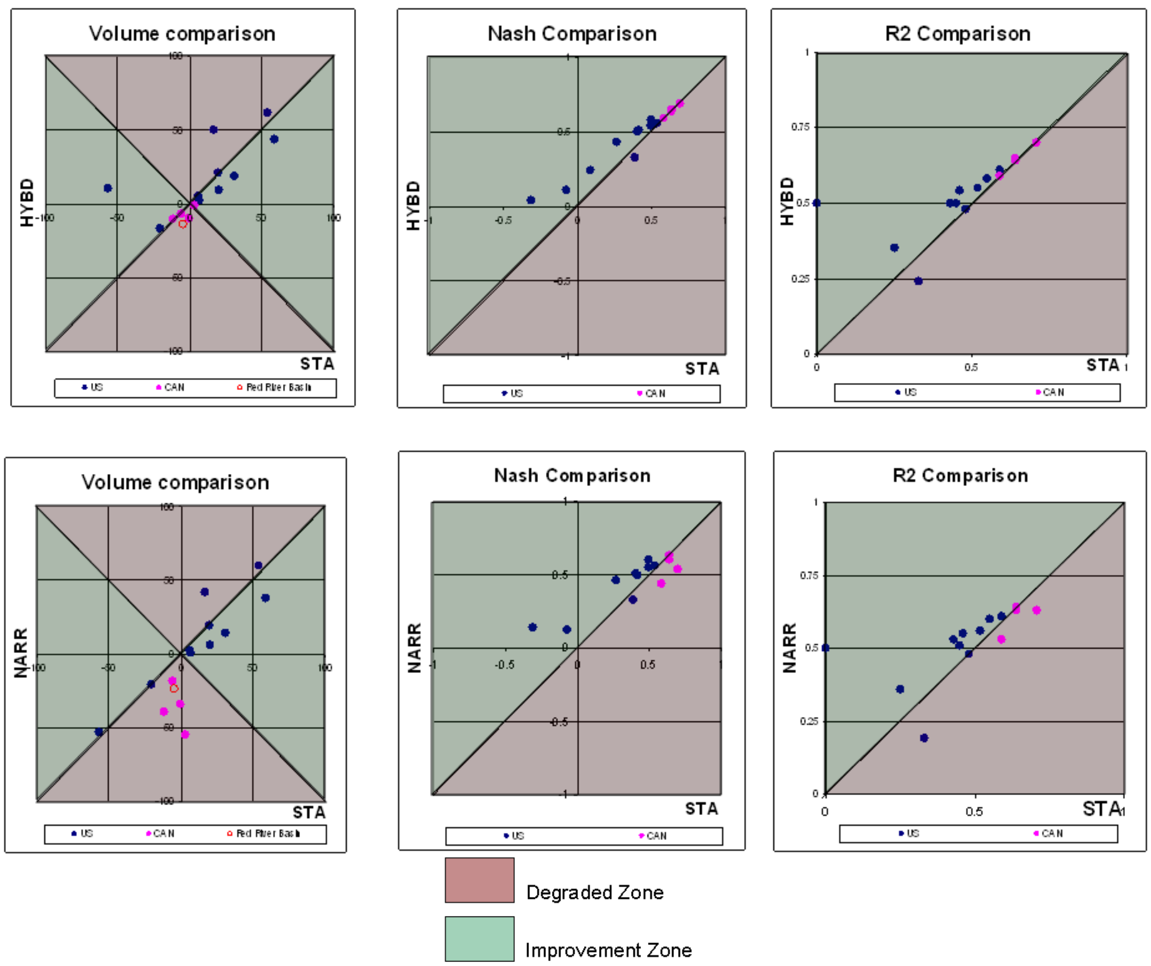

Figure 9: HYBD Run Results Comparison and NARR Run Results Comparison

By comparing the HYBD run results with he initial NARR run results, it is clear to see that by using HYBD precipitation fields, all the improvements in the American side had had been successfully kept and made further improvements on the Canadian sub basins. While keeping the WATFLOOD^{TM} parameters consistence, these improvements gave solid proof that HYBD is a valid precipitation product that eliminated the anomalies in NARR on the Canadian side while made the best use of the better section of the NARR data over the American side.

Chapter 5 Discussions

From the analysis, it is clear to see that the anomalies existed in the NARR data both temporally and spatially. Along the border area, there is a discontinuity of precipitation in the form of 25% to 30% under-estimation of precipitation in summer. Furthermore, along the Canadian side, a lesser underestimation of precipitation, about 15 to 20% comparing to station data existed.

The official Website of NARR's Q&A page addressed the border discontinuity issue. The NARR official website and Mo (Mo et al, 2005) suggested that the discontinuity occurred due to the different interpolation method used for the American and Canadian's assimilated precipitation data. However, it does not explain the poor precipitation quality within the Canadian area above the border.

Mesinger (Mesinger et al, 2004) used the following graphs to demonstrate comparison between the observed precipitation data that is assimilated into NARR model and the final NARR precipitation product.

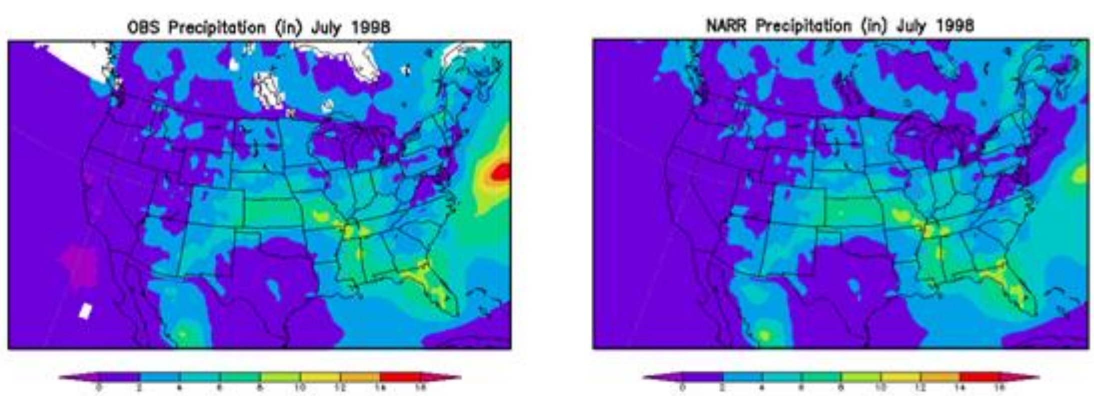

Figure 10: Comparison of NARR Assimilated Observed Data and NARR Precipitation

The left graph above shows the observed station data and this assimilated observed precipitation field was used to correct the initial NARR generated precipitation and the graph on the right hand side is the final precipitation after assimilation correction.

First, it is obvious to see that the final NARR data matched well with the assimilated precipitation field; on the other hand, it also showed that the NARR data was heavily influenced by the assimilated precipitation correction.

Secondly, it is obvious to see that along the Canadian-US border, there is a distinctive border line indicating the discontinuity in the observed precipitation. This finding is significant as it proves that the anomaly discovered in NARR data is originated from the assimilated data. Shafran (Shafran et al, 2005) also mentioned that the assimilation process did not make use of all the Canadian station data due to time concerns. This leads to the poor quality of the assimilated data on the Canadian side.

Since the NARR is heavily influenced by assimilated station data, but only using few Canadian stations for assimilation. It leads to poor quality of the assimilated precipitation over the Canadian area. Therefore by fitting the model generated results to a poor quality assimilated data would only leads to the final precipitation product that has bad quality as well.

Furthermore, using fewer stations would lead to unable to capture storm events and coarser grid resolution leads to smoothened temporal and spatial variance of precipitation. Therefore, Most of the anomalies occurred in final NARR products over border and Canadian area were purely event driven as it failed to capture the magnitude, variations and timing of the events. These anomalies would be hard to correct without introducing extra station information. Considering a dense climate station net work already exists over the Canadian side of the basin, we decided to use the hybrid approach instead of correcting NARR precipitation.

In summary, the sources of the NARR's anomaly is from

1) NARR's assimilated precipitation fields.

2) Different interpolation method and grid size for observed data over Canada and USA NARR did not use all the available station data on the Canadian side that leads to fail of capturing precipitation events in the summer and less spatial and temporal variations. Due to the nature of the error source, it would be hard to correct the DSNAR precipitation field without using more precipitation stations. However, under the situation like Red River Basin where a intense climate station network exists, it would be easiest to just use the DSSTA data on the Canadian side as it is a faster and more effective correction

Chapter 6 Recommendations

Few recommendations were made to Manitoba Hydro based on this study

1. Manitoba Hydro should not consider using NARR data on the Canadian side for hydrological modeling purpose.

NARR is developed for USA, assimilated observe station data quality is very poor over Canada, While NARR is heavily influence by the poor quality assimilated precipitation. Therefore, NARR is correcting its precipitation against errors on the Canadian side.

Moreover, over the northern Manitoba area where station data is very sparse or even not available, the effectiveness of assimilation method using only daily climate station is questionable.

Furthermore, Correction of NARR data would be hard and ineffective over northern Manitoba. As we can see that there are different types of anomalies (the border area's 30% anomaly and Canadian area's 15% anomaly), and through the discussion section, we concluded that the anomalies are event based, but not systematic model errors. If only station data were used to correct event based anomaly, the effectiveness of the correction method would still be questionable at the area where we don't have much stations, like the Churchill and Nelson River.

2. Manitoba Hydro should be looking for a better precipitation data product which fully utilized the available data source (observed hourly and daily station data, satellite, radar, land use, elevation, etc...), these data should have a focus on the northern Manitoba area where there are always lack of stations.

3. Future study needs to look at if this latent heat parameters assimilated from observed precipitation data is affecting other NARR model outputs if we want to use them

4. Considering the flow station net work is more intense than the weather stations, combining the flow station net work with a validated the hydrological model, Manitoba Hydro could achieve a better understanding on the quality of the climate station data. Future study could be looking into developing a quality analysis method based on comparing validated hydrological model results with flow records to assess the quality of the climate station data.

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