ESTIMATION OF SNOWMELT CONTRIBUTION TO DISCHARGE IN UPPER INDUS BASIN IN PAKISTAN USING DEGREE DAY METHOD

Muhammad Afzal* **Supervisor: Ai SUGIURA****
MEE13629 **Advisers: Takahiro SAYAMA*****
Akira HASEGAWA**

ABSTRACT

Pakistan is an agricultural country and needs much water for irrigation. Indus river system provides the water supply by receiving its inflow from steady snowmelt runoff from the highlands in the upper Indus basin (UIB). Snowmelt modeling is an important part of hydrological analyses where significant proportion of precipitation falls in snow form. Integrated Flood Analysis System Upper Indus Model (IFAS-UIM) is used in this study by considering snowmelt based on Degree day model (DDM) as input to simulate discharges at Skardu, Partab Bridge and Tarbela dam. The DDM has three main parameters including degree day factor (DDF), temperature lapse rate (TLR) and critical temperature (Tc). This study analyses the sensitivity of DDM and calibrate the parameters to estimate the snowmelt contribution in discharges. MODIS eight-day snow cover and PMD precipitation and temperature data were used to model snowmelt contribution up to Tarbela dam. According to simulations without snowmelt consideration, the simulated discharges mostly were less than the observed discharges, which indicates the importance of snowmelt in upper Indus basin. DDF 2.5mm/°C/day along with TLR 6.5°C/km and Tc 0°C was found adequate to give the discharges comparable to the observed values from mid-June to mid-August, whereas DDF 1.5mm/°C/d was more appropriate factor for snowmelt phenomenon from mid-August to the end of September. Snowmelt contribution at Skardu was estimated to be 12 to 18% of total discharge from June 15th to September 30th during 2010-2012. Snowmelt contribution from sub-catchments between Skardu and P. Bridge was estimated to be 28 to 32% of total discharge at P. Bridge. Similarly at Tarbela the snowmelt contribution from sub-catchments between P. Bridge and Tarbela was calculated as 5 to 6% of total discharge at Tarbela. Overall this study obtained the appropriate parameters and estimated snowmelt contribution in UIB. Moreover the use of DDM has improved the IFAS-UIM prediction of discharges for snow covered area.

1. INTRODUCTION

1.1. Background

The Indus basin water contributes to agriculture, industry and sustaining daily life over a large area (65%) of Pakistan, so it is imperative to calculate the water regime in the basin. Most of precipitation in Upper Indus Basin (UIB) is received as snowfall resulting from the westerly weather systems and orographic effects of HKH ranges. Sometimes easterly and westerly systems overlap causing severe rainfall, accelerating snowmelt in monsoon, resulting torrential flow in the channels which leads to flooding and inundation along the river course. Reservoirs are not enough to hold water, so every year

*Meteorologist, Pakistan Meteorological Department, Pakistan.
** Research Specialist, ICHARM, Public Works Research Institute, Japan.
*** Senior Researcher, ICHARM, Public Works Research Institute, Japan.

70% of water has to be released before the monsoon season (Rasheed, 2013). For management purpose and accurate flood forecasting, the flow caused by melting in Upper Indus basin (altitudes 90-8000 m above sea level) is necessary to be estimated. Different efforts have been made to calculate melting share in runoff of different sub catchments of UIB by ICIMOD, Ev-K2-CNR (Hoermann, 2011; Orsatti, 2010). With limited resources, PMD and WAPDA have established gauging stations and conducted some field surveys at some approachable places but it is very difficult to establish dense network of observing stations or long term expeditions to estimate the runoff due to financial and severe weather complications in high altitude areas of Karakoram and Himalaya's ranges. All the attempts made were related to runoff in valleys, mostly related to glacial melt influence. Seasonal snow-cover relates to areal extent over the whole area including physically unapproachable heights. Then snowmelt runoff modeling is an important option for sustainable development and disaster prevention in the study area. Recently Indus IFAS is being used to predict the discharges for improvement of flood forecast. Snowmelt is not considered as input to simulate the discharges in UIB, which may reduce the accuracy of the predictions. Snow cover satellite data (with 500m resolution) is available; the same data has been successfully applied in different basins over the globe. Due to limited data and resources this study covers the snowmelt over the surface while the impact of glacial melt is not evaluated.

1.2. Objective of the Study

IFAS Upper Indus Model (IFAS-UIM), developed by ICHARM is being used in this study to predict the discharges in UIB. It is an effort to analyze the discharges at different locations of Indus river using IFAS-UIM. The main task is to improve the IFAS-UIM prediction by adding snowmelt contribution. This study also tests the applicability of Degree Day Model (DDM) and calibrates DDM parameters for UIB. Quantification of melting contribution in the discharges at different locations of Indus river course is also one of the objectives of this study.

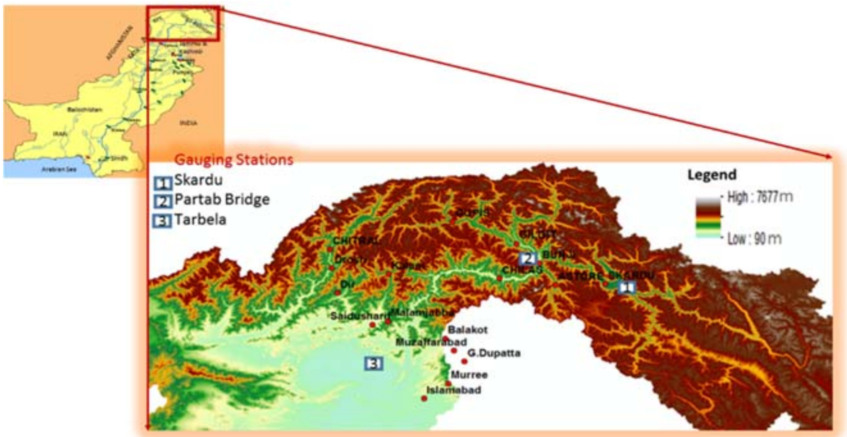

Figure 1: Study area showing 17 meteorological and three discharge gauging stations

2. DATA AND METHODOLOGY

2.1. Data

Satellite and reanalysis rainfall and temperature data sets have coarse resolution. In the last decade several studies (Mayer, 2010; Archer, 2003 & 2006; Tahir, 2011 Furrukh, 2008) have been conducted successfully on snow and glacial melt runoff in sub catchments of UIB by using observed data. Hence this study is being conducted by using PMD daily observed temperatures and precipitation. By using 17 PMD stations temperature data and corresponding elevations, Temperature Lapse Rate (TLR) for the study area has been calculated as 6.5°C/km. Summer (Jun-Sep) temperature analysis shows that July to August is the warmest period and September is relatively cooler. Partab Bridge (near Bunji) is the warmest location among all the observing stations. Yearly data analysis (2011-2012) revealed that 2011 remained the normal year with respect to temperature and precipitation. Whereas 2010 was the severe rainfall year of the regional history.

UIB is monsoon shadow area and most of precipitation received as snowfall in winter, while rainfall is received in summer (Immerzeel *et al.*, 2009). Snow cover satellite data (with 500m resolution) is; downloaded from http://modis.gsfc.nasa.gov/, the same data has been successfully applied in different basins over the globe. Snow covers maximum area of UIB in February and March and minimum snow cover is left in August, as shown in Figure 2. It means snowfall starts in September every year. Figure 3 shows that the observed discharges depends on the temperature variations, it is also obvious Bunji (near P. Bridge) shows large discharges because of higher temperatures than Skardu.

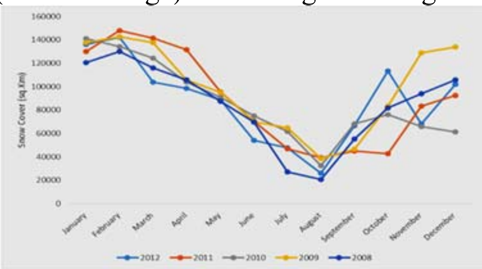

Figure 2: Monthly snow cover in upper Indus basin

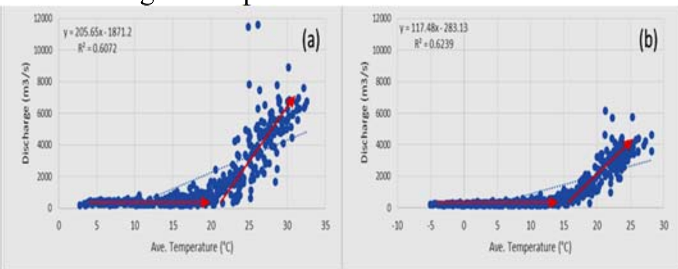

Figure 3: Discharge vs Average Temperature for the period 2001-2012 at (a) Bunji and (b) Skardu

2.2 Methodology

In UIB researchers widely applied Snowmelt Runoff Model (Martinec, 1994) to calculate river discharge at different sub-catchments. It has been observed that Snowmelt Runoff Model (SRM) works well in snow cover region but it is not much sensitive to precipitation data input. In general, during the summer season (JJAS) precipitation in the study area below 5000m occurs in liquid form (Young et al, 1990). Thus it was decided to use IFAS-UIM for this study in combination with DDM. Calculation of runoff has been summarized in two steps, shown in Figure 4.

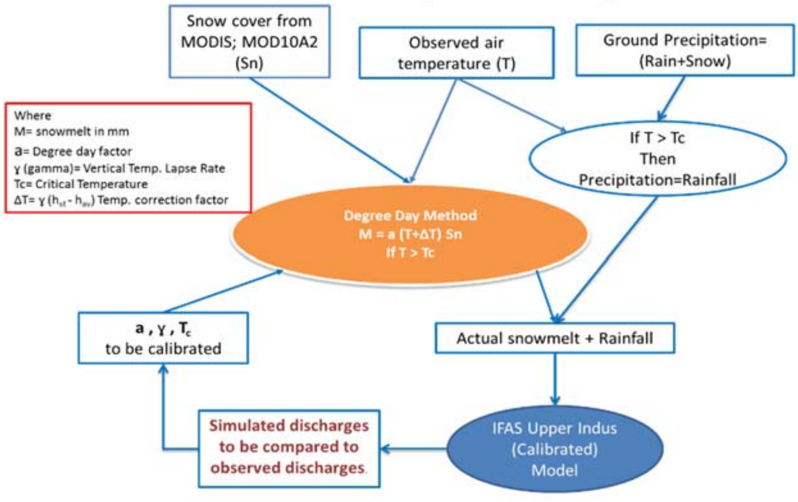

Figure 4: Methodology for the study

In the first step, Degree Day Model (DDM) was used to calculate the snowmelt. Formula for calculation of snowmelt (mm/day) is given as Eq.1.

$$\mathrm{M} = \mathrm{a}(\mathrm{T} + \Delta\mathrm{T})\mathrm{S_n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (1)$$

Where M is the total snowmelt (mm/day) and a is the DDF (mm/°C /day). T denotes the mean air temperature in °C, while ΔT is the change in temperature with elevation by considering vertical temperature lapse rate (TLR) denoted by ɣ. $\mathrm{S_n}$ is 1 or 0 if IFAS pixel is covered or not covered by snow. MODIS snow cover product (MOD10A2) is used to evaluate the Sn value. If MOD10A2 suggests the existence of snow in each IFAS pixel within the eight-composite days, the Sn value becomes 1.

$$\Delta T = \text{ɣ}(h_{st} - h_{av}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

where ‘h_{st} ‘is the altitude of each 5km cell and ‘h_{av}‘ is average hypsometric elevation of the basin. TLR is represented by ɣ having unit °C/m.

Snow cover and air temperature were used as input along with DDF. Air temperature was corrected by using DEM and TLR for the study area. When air temperature reached a threshold called critical temperature (Tc), snow was considered to melt according to the rate defined by DDF. Observed precipitation was considered as rainfall for the air temperature, greater than Tc.

In the second step, the snowmelt and rainfall were provided as distributed input to the IFAS-UIM. By taking these inputs and evapotranspiration estimates, discharges were simulated at three locations and compared with gauging station observed discharges in UIB. The MODIS/Terra snow cover 8-Day (MOD10A2) data set contains data fields for maximum snow cover extent over an eight-day compositing period. The data has 500m resolution, it was upscaled to 5km (IFAS-UIM mesh) resolution. By using appropriate DDF, TLR and Tc this snow cover is used in DDM (Eq.1) to estimate the snowmelt.

3. RESULTS AND DISCUSSION

Figure 5 shows the importance of snowmelt contribution to estimate accurate discharges. It can be observed the observed discharges remained larger than the simulated values, considering no snow melt.

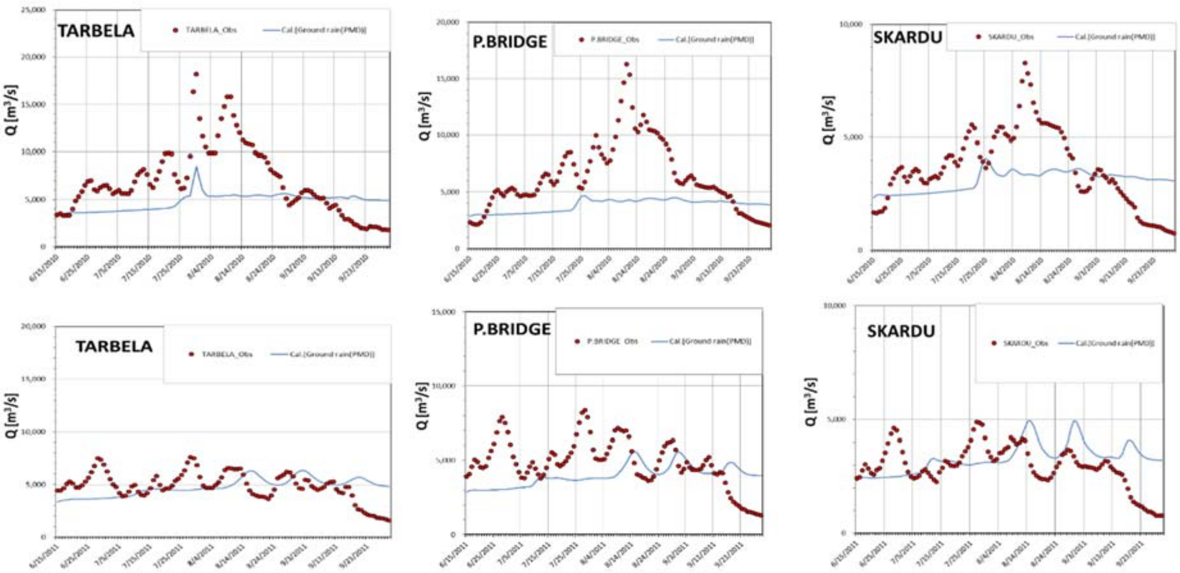

Figure 5: Simulated discharges without snowmelt and observed discharges for 2010 and 2011

Degree day model (DDM) needs calibration of parameters to estimate the actual snow melt contribution. Year 2011 has been selected for the calibration as it was the normal year with respect to precipitation and temperature in the study area, 2012 has been selected for validation as it was also the normal year with respect to precipitation and with relatively cooler temperatures. To look in to the severe weather behavior for melting process, 2010 has been also selected for the validation. Nash-Sutcliffe coefficient was calculated to find efficiency of hydrological model (Nash and Sutcliffe, 1970). By applying the three sets of DDM parameters (a2ɣ6.5Tc0, a2.5ɣ6.5Tc0, a3ɣ6.5Tc0), no value of Nash-Sutcliffe coefficient was satisfactory. After taking into account difference of temperatures between August and September and solar radiation decrease in September (due to position of sun) it was decided to use parameter set a2.5ɣ6.5Tc0 from 15th June to 15th August and for the rest of the period (16th Aug-30th Sep.) a1.5ɣ6.5Tc0 was calibrated for all three stations. The observed discharge from one upstream gauge was incorporated as boundary conditions for the downstream.

Table 1: Nash-Sutcliffe coefficients using DDM parameters a2.5ɣ6.5Tc0 and a1.5ɣ6.5Tc0

Year \ Station	TARBELA	P.BRIDGE	SKARDU
2011	0.34	0.78	-0.97
2012	0.5	0.6	-0.1
2010	0.8	0.5	0.3

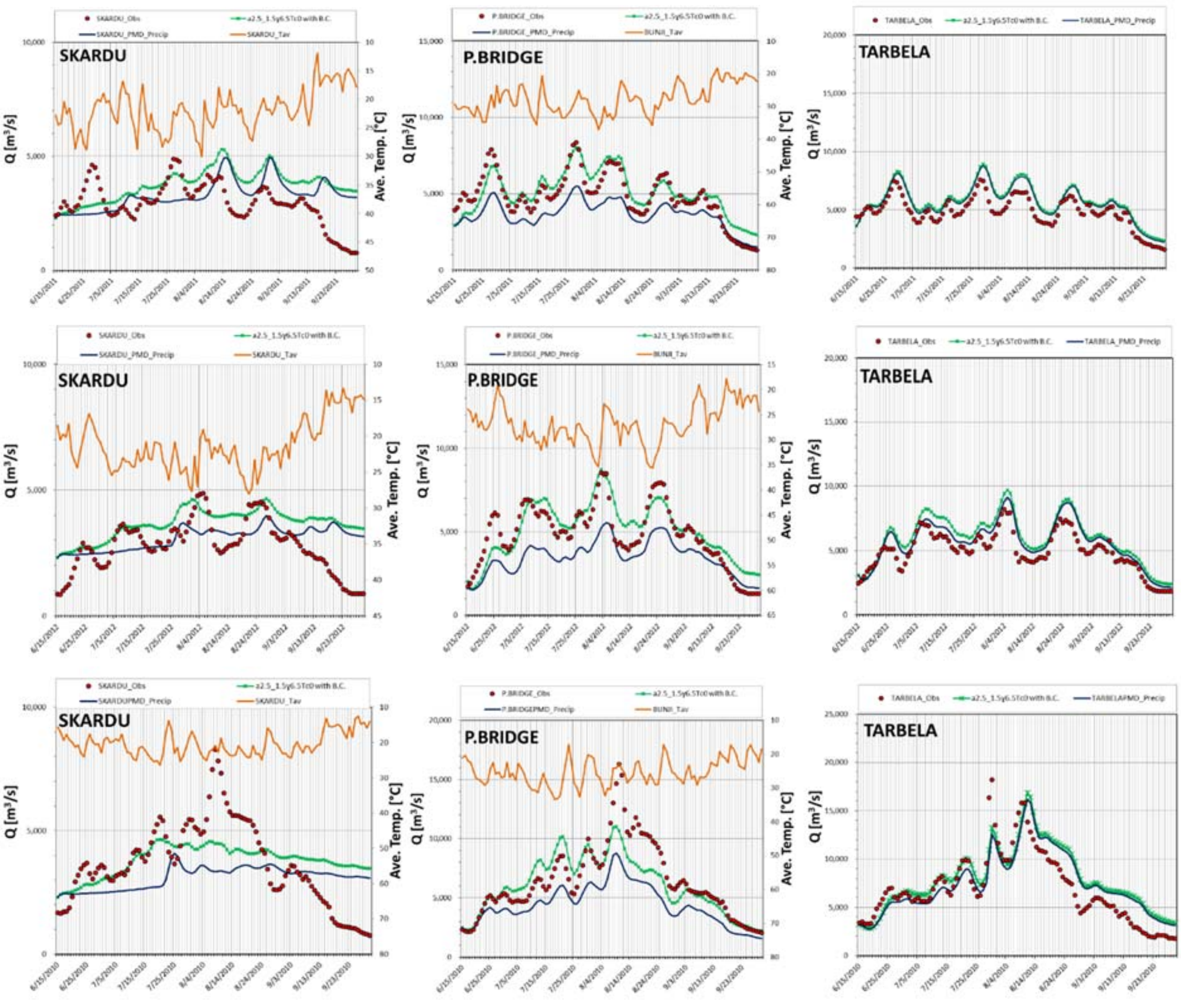

Figure 6: Observed vs simulated discharges with and without snowmelt consideration for (Calibration) 2011, (validation) 2012 and 2010

For snowmelt calculations for Tarbela, simulations were made at Tarbela by using P. Bridge observed discharge as input along with snow cover with snowmelt conditions (calibrated parameters). In the second simulation no snowmelt was considered and discharge was simulated for Tarbela importing ground precipitation and observed discharge from upstream station (P. Bridge) as input. The difference of simulated discharges gave the estimated snowmelt contribution between P. Bridge and Tarbela. In case of Skardu, no boundary conditions can be applied as it has no upstream gauge, that's why the results showed some discrepancies. Table 2 shows the snowmelt contribution in the individual sub catchments.

Table 2: Snow melt contribution at different locations of UIB

Year \ Station	Tarbela	P. Bridge	Skardu)
2011	3%	29%	12%
2012	6%	32%	16%
2010	7%	28%	18%

4. CONCLUSIONS

Agriculture plains of Pakistan are irrigated by Indus river steady flow resulted by snowmelt runoff from the Himalayas and Karakorum ranges. Snowmelt contribute to base flow of Indus and forms reservoir volume of multipurpose Tarbela dam. Even for flood season the snowmelt actually contributes the flow in the monsoon. Current Indus-IFAS forecasting system does not consider snowmelt which may cause wrong flood prediction. Hence snowmelt modelling is useful to predict accurate discharges which may help the authorities in water management and improvement of flood prediction capacity.

Snowmelt from degree day model (DDM) was incorporated to IFAS upper Indus model (IFAS-UIM) to simulate discharges at Skardu, Partab Bridge and Tarbela dam. MODIS eight-day snow cover and PMD precipitation and temperature data were used to model snowmelt contribution up to Tarbela dam. The results without snowmelt consideration showed that the discharges were less than the observed values at the three locations of the river course. Different sets of parameters in DDM were tested to find their impact on snowmelt used as input for discharge simulations. Out of the several attempts to simulate the discharges, DDF 2.5mm/°C/day along with TLR 6.5°C/km and Tc 0°C was found satisfactory to give the discharges comparable to the observed values in UIB from 15th June to 15th August. For the second half (16th Aug-30th Sep), DDF 1.5mm/°C/day gave the appropriate inflows at all gauging stations.

With above calibrated sets of parameters, at corresponding stations, the simulations were made by taking into account snowmelt and without snowmelt. It was concluded that snowmelt contribution at Skardu was estimated to be 12 to 18% of total discharge from June 15 to September 30, during 2010-2012. Snowmelt contribution from sub-catchments between Skardu and P. Bridge was estimated to be 28 to 32% of total discharge at P. Bridge. Similarly at Tarbela the snowmelt contribution from sub-catchments between P. Bridge and Tarbela was calculated as 5 to 6% of total discharge at Tarbela.

Different sets of parameters are needed to estimate the snowmelt in UIB because of start of transition of the season after mid of August with less radiation effect on the snow cover area. It is also found that Partab Bridge receives more melting as compared to the upstream and downstream. The main reason is very large extent of the basin comprises of very hot region in the center of two relatively colder regions (Hunza and Astore).

Finally although the incorporation of the snowmelt modeling into IFAS-UIM improved the predictability of hodographs at the three locations. There are still discrepancies in simulated discharges as compared to the observed, especially at the end of melting season. These may be associated with the parameters of the tanks in IFAS-UIM itself.

ACKNOWLEDGEMENTS

I would like to express my heartiest gratitude to Dr. Ai Sugiura for supervising me and giving me very sincere guidance and valuable advice and suggestions during my individual study. Thanks to Prof. K. Takeuchi, Director, ICHARM, Public Works Research Institute for is immense support and continuous encouragement throughout the Master degree session. I am glad to thank Dr. Takahiro Sayama and Dr. Akira Hasegawa whose kind guidance paved my way to conduct this research. I want to express my thankfulness to JICA for philanthropic support and facilitation without which this training would only be a notion.

REFERENCES

Archer, D. (2003). Contrasting hydrological regimes in the upper Indus Basin.Journal of Hydrology, 274(1), 198-210.

Arslan, M., M Tauseef, M. Gull1, M. Baqir, I. Ahmad, U. Ashraf and B.S. Al-Tawabini. (2013). Unusual rainfall shift during monsoon period of 2010 in Pakistan: Flash flooding in Northern Pakistan and riverine flooding in Southern Pakistan. Afri. Jr of Env. Sc. and Tech. DOI: 10.5897/AJEST12.164

Rasheed, B. (2013). Impact assessment of hydro-climatic change on water stress in the Indus Basin (Doctoral dissertation, Massachusetts Institute of Technology).

Siddique, M and D. Hashmi (2013). Recent trends in high altitude temperatures and river flows in upper Indus basin. Centenary Celebration (1912 – 2012), WAPDA, Page 151-165