Water Footprint of Major Cereals and Some Selected Minor Crops of Pakistan

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Abstract- **This study deals with the consumptive water use of some selected crops of Pakistan, including major crops, such as cereals and oil seeds and minor crops including vegetables, fruit, tobacco, tea etc. Water footprints have been calculated using CROPWAT 8.0 (developed by Land and Water Division of FAO). The software bases its calculations on Penman Monteith equation. The study enables us to assess the use of water not in a conventional way of water withdrawal but in terms of water footprint (WF) which characterizes the use of water that does not return to its source or origin in a small time scale. The study compares the water footprint values obtained in current research, with the WF averages globally for the same crops. It has been observed that sorghum, barley, millet and oil crops such as ground nut, soybean and sunflower notably use high quantities of water in the local conditions as compared to the global averages of the same. Most of these are estimated at a higher side of WF, as high as double of the global averages. Most of the crops in Pakistan indicate water footprint either equal to or greater than the global averages which can be attributed to various factors, most important is principally arid conditions, dry subtropical climate, poor irrigation techniques and water management systems and also low yields lead to higher WF calculation. There have been observed only three crops, viz. wheat, potato and tobacco whose water footprint is lower than the global averages. Tobacco has a water footprint smaller than global average based on the fact that in Pakistan tobacco is the crop whose yield exceeds the global average yields, so its high per unit area production translates into low water footprint. A reduced water footprint is a recommended condition wherein the entity under question uses the least possible amount of water thus demonstrating sustainable use of water.**

Keywords- Water Footprint (WF); Cereals; Oil Crop; Minor Crops; CROPWAT 8.0; Penman Monteith Equation; Tobacco; Wheat

I. INTRODUCTION

The concept of water footprint was first developed by Hoekstra & Hung, 2002 and latterly elaborated by Chapagain and Hoekstra (2003 – 2010, published several research articles on WF), are among the authorities of this field of study. The recent concept of water footprint essentially emerges from the concept of ecological footprint developed by William Rees in 1992, which is useful for the measurement of the sustainable level of social and economic development (Wang & Wang, 2009). Water footprint is the amount of water used directly or indirectly by a consumer or producer during a specified time period. Water footprint could be calculated for nations, areas, products, services, etc. (Hoekstra, *et. al.*, 2011).

Water footprint distributes the consumptive use of water into 3 major and distinctive parts *viz* green water, blue water and grey water. By definition, rain water consumed is known as Green water; blue water is the freshwater from surface and ground water resources and grey water is the part of freshwater used to dilute pollutants produced to such limits as are prescribed in domestic or international laws. Grey water as a separate part was not included in Chapagian & Hoekstra (2004), but later it was included in Chapagain and Hoekstra (2007). Green and blue uses of water actually represent the consumptive uses while grey water is non-consumptive use of water. Grey water use is not the measure of use of water but it deals with its quality. The use of dividing the total water footprint into its green, blue and grey constituents is relevant because the environmental and economic costs of using the three types of waters is different from one another. For example opportunity cost of blue water use is higher, as the infrastructure like tube wells, pipelines, canals and aqueducts are needs to be established but that of the green water it is very low because relatively small infrastructure or almost no infrastructure is required to use green water. This study does not divide the water footprint into its constituent types instead total water footprint of the crops is calculated by using CROPWAT 8.0 software which is developed by FAO and bases its calculations of reference evapotranspiration (ET_o) on Penman Monteith method (Al-Najar, 2011; Falkenmark, 2003, Morrison et al., 2009). Water use may take two forms: *water withdrawal* and *water consumption*. Water withdrawal is the removal of water from a source of water some part of which returns back to the source unused as opposed to water consumption which accounts for the use of water which does not return back to the source because it trapped in the products, plants transpired it or people used it disallowing it to return to the source in a time period of interest.

WF is consumptive use of water that differs from conventional measure of water use in 3 ways:

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(i) WF is consumptive use of water while water withdrawal includes non-consumptive uses of water as well.

(ii) WF also accounts for green (rain water) and grey (use of freshwater to dilute pollutants to or above agreed limits) use of water as opposed to its counterpart which looks at only blue (surface and ground water sources) part of used water.

(iii) It considers the total appropriation of fresh water, both consumptive and non-consumptive, over the complete production and supply chain.

1.1 Internal and external water footprints

Consumption of water at national scale identifies the need to divide the water footprint into two categories: internal and external WF. Internal WF is the volume of water used in a country over a specified time period to five services and produce goods by the inhabitants of the country. Normally there are three principle sectors where water consumption takes place: agricultural, industrial and domestic. The water used to produce or contained in the products that are exported from a country is excluded from the total water footprint to calculate the water footprint of a country.

$TWF = AWU + IWW + DWW - VWE_{domestic}$

TWF = Total Water Footprint

AWU = Agricultural Water Use

IWW = Industrial Water Withdrawal

DWW = Domestic Water Withdrawal

VWE_{dom} = Virtual Water Export $_{domestic}$ (Hoekstra *et al.,* 2011)

External water footprint is the water used to produce goods and services for inhabitants of a country outside that country of use i.e. water used to produce imports. The water used to produce imports for a country has been termed 'virtual water', *i.e.* the water that is not real and is used to produce the product or service imported. The idea of virtual water was introduced by Allen et al., (1998) when he was studying virtual water imports to Middle East as partial solution to water scarcity there.

$EWF = VWI – VWE_{re\text{-}exp}$

EWF = External Water Footprint

VWI = Virtual Water Import

$VWE_{re\text{-}exp}$ = Virtual Water $_{re\text{-}export}$ (re-export of imported water) (Hoekstra *et al.,* 2011)

1.2 Specific Examples of water footprints

Water footprint can be calculated for almost anything. Hereunder are a few examples:

A. Crop water footprint

Water footprint of a crop is the amount of fresh water evaporated or transpired from a crop divided by its yield. It is actually the sum of the green, blue and grey water uses during the process of growing crop which can be broken down as under (Hoekstra et al., 2011):

$WF_{proc} = WF_{proc,\ green} + WF_{proc,\ blue} + WF_{proc,\ grey}$

$WF_{proc,\ green} = CWU_{green} /\ Yield$

It doesn't take into account the water incorporated into a crop. Calculation of crop water footprint is critical to evaluate various irrigation management practices.

B. Product water footprint

Product water footprint is the sum of water footprints during each step in the production process of the product. It is sometimes also known as 'virtual water content' but this term has a narrower meaning.

$$WF_{product} = \sum_{N}^{i=1} WF_{process,\ i} / p\ [quantity]$$

1.2.1 Water footprint of a geographically delineated area

It can be calculated by summing up all the water consuming and polluting processes over a specified period of time in the area under question.

$$WF_{area} = \sum WF_{proc}\ q$$

Where q is the water footprint of a process.

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1.2.2 Water footprint of a business

Water footprint of a business can subdivided into two parts/types:

1.2.2.1 Operational water footprint

It is the direct use of water by a producer to produce, manufacture or use water for supporting activities.

1.2.2.2 Supply-chain water footprint

It is the indirect use of water during the supply-chain operations to convey the product to the end consumer.

1.3 Virtual water chain

Business water footprint can be understood by virtual water chain which places farmer at one end and end consumer at the other and the intermediate steps cover various chain members to convey the product to the consumer which vary depending on the product. Each step of the virtual water chain involves the use of one, two or all of the three types of waters in various amounts. **Farmer →Food processor →Retailer →Consumer**

1.4 Virtual water flows

Virtual water is the amount of water used to produce a commodity or service. It is closely linked to water footprint but has a rather narrower meaning. The term was coined by Allen in the early 1990s when he was studying virtual water flows as partial solution to the problem of water scarcity in Middle East.

While calculating the water footprints of the nation's virtual water flows are accounted for by subtracting the virtual water imported and adding the virtual water trapped in the products exported. It is important to account for virtual water flows among countries because they are not negligible rather substantial (Hoekstra & Chapagain, 2004; Ge et al., 2011).

A number of studies have revealed that global virtual water flows exceed 1000 billion cubic meters of water. (Hoekstra & Hung, 2002; Chapagain & Hoekstra, 2003a; FAO 2003a and 2003b; Ma et al., 2006). Virtual water flow into Pakistan in a study conducted by Hoekstra and Chapagain in 2004 was 0.67 Gm^3/yr.

1.5 Why to calculate water footprint

Water is an important resource. It is to a great extent synonymous with life. Barren lands and deserts are not inhabited by humans because of the very fact that these land features lack the most important pre-requisite of life - water. Humans use water in three of their principle sectors: (1) Agriculture (70%), (2) Industry (20%) and (3) Domestic (10%), while agriculture sector accounts for about 85% of global blue water consumption (Shiklomanov, 2000). Global freshwater withdrawal has increased nearly sevenfold in the past century (Gleick, 2010; Morrison et al., 2010).

In view of such startling statistics quantifying the stress on this important resource by humanity is imperative to ensure its sustainable use. Water footprint in this regard provides us with a numerical value that reflects our water management practices and allows us to compare it with that of other parts of the world. WF intensity refers to the ratio of per capita water footprint to per capita GDP of the country. Hence, low water footprint intensity of a nation means better management practices and vice versa. Water footprint allows us to have a detailed breakup of the use of water in any sector up to the end product used by the end user. Specially the incorporation of grey water addresses the issue of water pollution comprehensively by quantifying the freshwater appropriation against each unit of product of interest. As stressed in UNDP's Human Development Report 2006, which was devoted to water, water consumption is not the only factor causing water scarcity; pollution plays an important role as well (UNDP, 2006; WAAP, 2009)). Many studies have been conducted on international levels to calculate water footprints of various nations including Pakistan notably Hoekstra and Hung (2002) were the first to make a global estimate of consumptive water use for a number of crops per country, but they did not explicitly distinguish consumptive water use into green and blue component. Hoekstra and Chapagain (2004) and Hoekstra and Chapagain (2007a) gave a figure of 8.55 Gm^3/yr for Pakistan's agricultural water footprint during 1997 to 2001. The present study focuses on calculating water footprint of 20 crops *viz* wheat, maize, barley, sorghum, millet, potato, sunflower, sugar beet, cabbage, tomato, sugarcane, citrus, banana, grapes, soybean, groundnut, rapeseed , cotton, tea and tobacco, belonging to eight crop categories that have major share in the use of water in Pakistan, with updated data on various parameters specially yield Chapagain and Hoekstra (2008).

C. Objectives of the study

The evaluation of the water footprint of some selected crops of Pakistan belonging to eight different crop categories for the year 2012. Reasons of deviation of water footprint values in Pakistan from global average counterparts will also be analyzed.

II. METHODOLOGY

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One of the main focus points of this research is to calculate the water footprint of the selected crops in Pakistan and compare respective footprints with the global averages. Calculating evapotranspiration (ET_c) is essential to calculate the water footprints of crops. ET_c of crops has been calculated using CROPWAT 8.0 software which is developed by FAO, UNO. CROPWAT 8.0 software bases its calculations of ET_c on Penmann Monteith equation as described (Allen *et al.*, 1998; Al-Najar, 2011).

2.1 The Penman-Monteith Equation

The Penman–Monteith (PM) evapotranspiration (ET) equation predicts the rate of total evaporation and transpiration from the earth's surface using commonly measured weather data (solar radiation, air temperature, vapor content, and wind speed).

$$ET_o = \left[\frac{0.408\,\Delta\,(R_n - G) + \gamma \left(\frac{900}{T+273} \right) u_2\,(VPD)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \right] \quad \text{...... (Eq. 1)}$$

Where:

ET_o = daily reference ET [mm/d], for longer periods 900 becomes 37

T = air temperature at 2 m high [°C]

VPD = vapor pressure deficit [kPa]

u_2 = wind speed at 2 m height [m/s] = 2 m/s

R_n = net radiation at the crop surface [MJ m^{-2} d^{-1}]

Δ = slope vapour pressure curve [kPa $°C^{-1}$]

γ = psychometric constant [kPa $°C^{-1}$]

G = soil heat flux density [MJ m^{-2} d^{-1}]

1 ET_o is reference crop evapotranspiration which is a hypothetical grass crop adequately watered with minimal or no stress. Evapotranspiration of a particular crop (ET_c) is determined by the crop coefficient approach whereby the effect of the various weather conditions are incorporated into ET_o and the crop characteristics into the K_c coefficient:

2 $ET_c = K_c \times ET_o$ ...... (Eq. 2)

Differences in evaporation and transpiration between field crops and the reference grass surface can be integrated in a single crop coefficient (K_c) or separated into two coefficients: a basal crop (K_{cb}) and a soil evaporation coefficient (K_e), i.e., $K_c = K_{cb} + K_e$. In our study we employed the values of K_c to reach ET_c.

The crop coefficient varies in time, as a function of the plant growth stage. During the initial and mid-season stages, K_c is a constant and equals $K_{c,ini}$ and $K_{c,mid}$ respectively.

Figure 1: Map of Pakistan

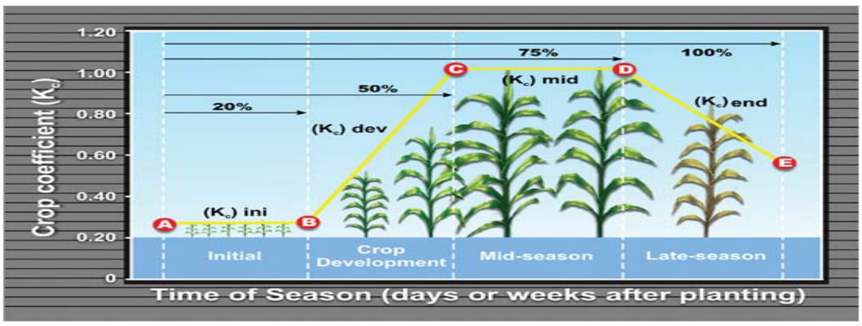

Figure 2. Crop coefficients (K_c) vary according to plant growth stage [$(K_c)_{ini}$: crop coefficient for initial growth stage; $(K_c)_{dev}$: coefficient for plant development stage; $(K_c)_{mid}$: coefficient for mid season; and $(K_c)_{end}$: coefficient toward the end of the season].

During the crop development stage, K_c is assumed to linearly increase from $K_{c,ini}$ to $K_{c,mid}$. In the late season stage, K_c is assumed to decrease linearly from $K_{c,mid}$ to $K_{c,end}$.

2.2 CLIMWAT 2.0 for CROPWAT

The CLIMWAT is a climatic database to be used in combination with CROPWAT. It allows the calculation of crop water

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requirements, irrigation supply and irrigation scheduling for various crops for a range of climatological stations worldwide. CLIMWAT 2.0 for CROPWAT is a joint publication of the Water Development and Management Unit and the Climate Change and Bioenergy Unit of FAO.

The climatic data for 22 climatological stations (CLIMWAT 2.0 provides data on 22 stations out of 25 available on its list due to unavailability of data on 3 stations) in Pakistan was taken and used in CROPWAT to calculate the values of ETc staions whose data is taken from CLIMWAT 2.0 are: Astore, Skardu, Chilas, Gilgit, Gupis, Dal-Bandin, Hyderabad, Peshawar, Jacobabad, Karachi Airport, Karachi Manora, Sargodha, Multan, Nawabshah, Nokkundi, Parachinar, Quetta (S Manda), Zhob, Chaman, Lyllpur-Risalawal, Islamabad Airport and Kalat.

2.3 Seven Climatic Parameters Provided by CLIMWAT 2.0

CLIMWAT 2.0 provides long-term monthly mean values of seven climatic parameters, namely:

1. Mean daily maximum temperature in °C & Mean daily minimum temperature in °C
2. Mean relative humidity in %
3. Mean wind speed in km/day
4. Mean sunshine hours per day
5. Mean solar radiation in MJ/m^2/day
6. Monthly rainfall in mm/month & Monthly effective rainfall in mm/month
7. Reference evapotranspiration calculated with the Penman-Monteith method in mm/day.

The data can be extracted for a single or multiple stations in the format suitable for their use in CROPWAT. Two files are created for each selected station. The first file contains long-term monthly rainfall data [mm/month]. Additionally, effective rainfall is also included calculated and included in the same file. The second file consists of long-term monthly averages for the seven climatic parameters, mentioned above. This file also contains the coordinates and altitude of the location.

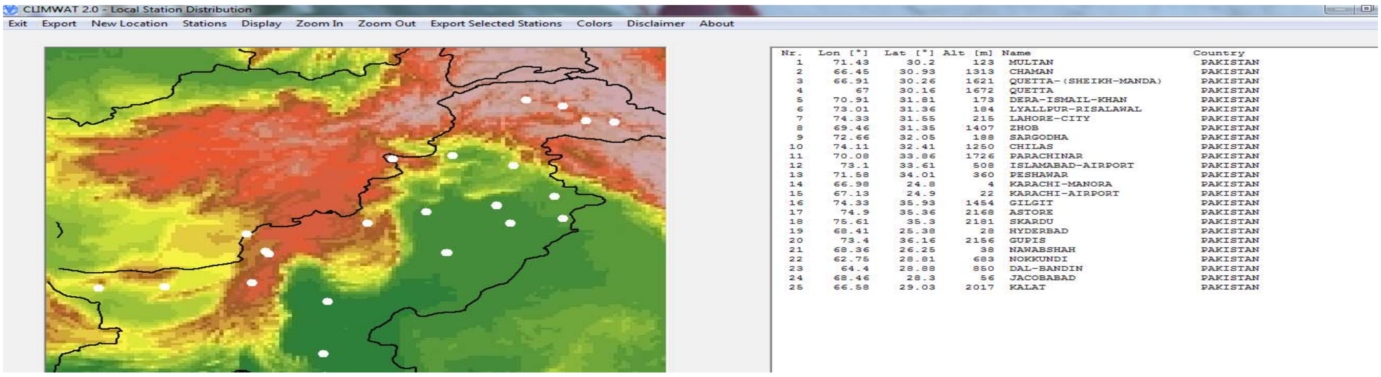

Fig. 3 The GUI of CLIMWAT 2.0 showing the loaded stations for which data is extracted for the use in CROPWAT 8.0

CROPWAT 8.0 was entered with the data from files extracted from CLIMWAT 2.0 against the stations mentioned above for all crops. Data for some crops was also taken from Water Footprint of Nations, Volume 2: Appendix for K_c and length of development stages of crops.

2.4 Pictoral description of CROPWAT 8.0

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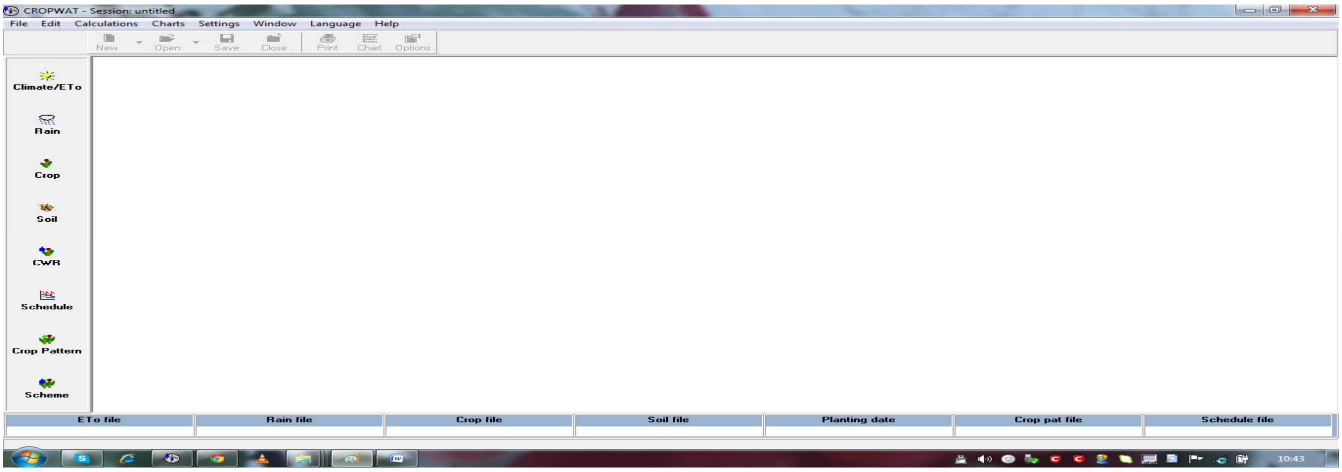

Fig. 4 The GUI window of CROPWAT 8.0

Tabs such as Climate/ET_o, Rain, Soil, etc can be seen on the left margin of the above picture. In our study we used only Climate/ET_o, Rain, Crop and CWR tabs because they were sufficient to calculate the required ET_c for all crops.

Below is the figure showing the final output of wheat crop for the sake of an example showing ET_c value of the wheat crop.

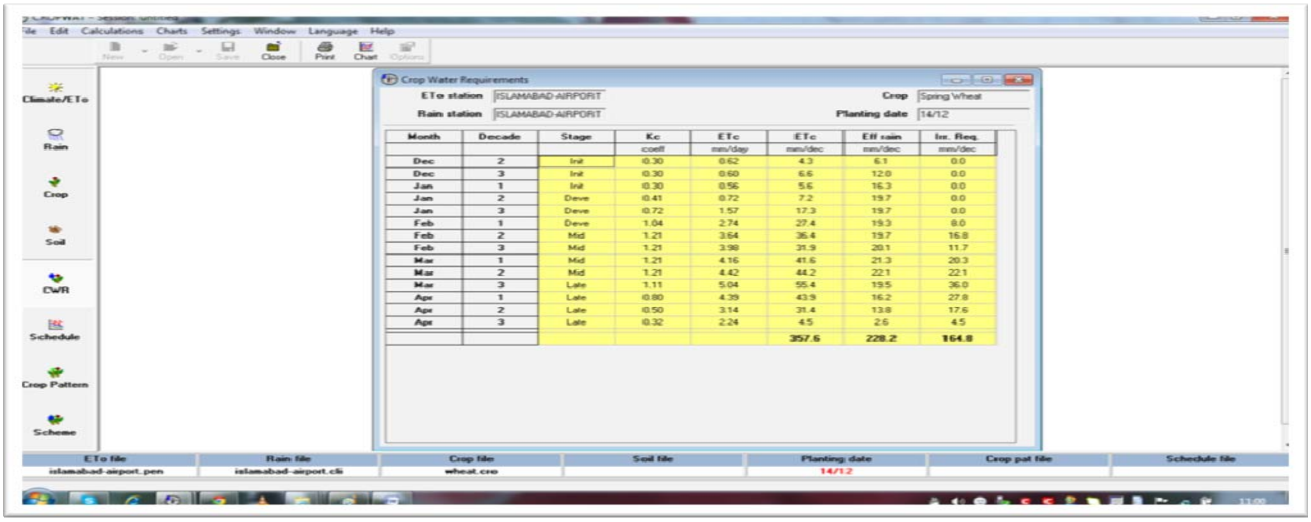

Fig. 5: Output window of CROPWAT 8.0 for wheat showing ETc value for wheat near Islamabad Airport Metrology Station

The CROPWAT 8.0 window for ET_c of wheat with customized options of Islamabad Airport (ET_o station and Rain Station), Spring Wheat (Crop) and 14/12 (Planting Date).

There are also windows/options such as rain showing effective rainfall and crop where data are entered in fields such as rain and effective rain, K_c values, length of stages of crop growth, yield response factor, critical depletion fraction, crop height and rooting depth, etc before reaching the final window. Data for such field is obtained mostly from CLIMWAT, while some other websites (e.g. www.pakkisan.com, www.gardeningpakisan.com and www.fatima-group.com) also proved helpful.

ET_c values of all crops were obtained against all stations. Average values of ET_cs were obtained by calculating the arithmetic mean and subsequently dividing the value by the average yield of the specific crops in Pakistan. Most of the data on yields were obtained from official website of Pakistan Agricultural Research Council (PARC).

$$WF_{crop} = \frac{\text{ET in cubic meters per hectare}}{\text{Yield in kg per hectare}}$$

III. RESULTS & DISCUSSION

A total of 20 crops were considered for the calculation of water footprint. Selected crops in Pakistan showed the values either comparable to the global average values of the crop or slightly exceeding in some cases and substantially in others. While most of the numbers exceed the global averages with only three crops showing results below the global average of their counterparts. The following table shows global values and values observed in Pakistan for some selected crops:

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TABLE 2: COMPARISON OF GLOBAL WATER FOOTPRINT AND WATER FOOTPRINT OF PAKISTAN

CROP CATEGORY	FAOSTAT CROP CODE	CROP	GLOBAL AVERAGE WATER FOOTPRINT (M3KG-1)	WATER FOOTPRINT OF PAKISTAN (M3KG-1)
CEREALS	15	WHEAT	1.79	0.95
	56	MAIZE	1.20	1.23
	44	BARLEY	1.40	2.45
	83	SORGHUM	2.98	4.80
	79	MILLET	4.40	4.70
OIL CROPS	236	SOYBEAN	2.11	5.96
	242	GROUNDNUT	2.73	8.30
	270	RAPESEED	2.56	3.31
	267	SUNFLOWER	3.31	4.30
SUGAR CROPS	157	SUGAR BEAT	0.12	0.50
	156	SUGARCANE	0.20	0.38
FRUIT CROPS	495	CITRUS	0.60	0.90
	486	BANANA	0.78	3.48
	560	GRAPES	0.59	2.59
COTTON	328	COTTON	9.31	16.08
VEGETABLES	116	POTATO	0.27	0.23
	388	TOMATO	0.21	0.86
	358	CABBAGE	0.27	0.30
TEA	674	TEA	8.71	16.35
TOBACCO	826	TOBACCO	3.84	1.14

Pakistan's water footprint for almost all categories of crops differs from global, average water footprint of the same crops (Table 2).This is mainly due to the yield produced which shows water productivity of the agriculture management practices where Pakistan lags substantially and its water productivity is measured at as low as 422. Second reason attributed to the issue of enhanced WF can be that Pakistan approximately lies between 23˚ and 38˚ north latitude in the sub-tropical region outside the Tropic of Cancer. The typical feature of this region is drift of the moisture during day with winds carrying it towards the equator. So the area is left with very little moisture (Liu and Savenije, 2008; Kumar and Jain, 2007) to support crop cultivation except those falling along the Himalayan region most part of the crop cultivation is highly dependent on the irrigation.

The results indicate that in Pakistan irrigated lands bears more pressure of water footprint in terms of crops as compared to their rain-fed counterpart, although this is not a common phenomenon in many parts of the world e.g. United States of America (Gleik, 2010). As far as the major agricultural product is concerned, Pakistan's agriculture is dominated by cereals. Among cereal crops wheat is the dominating one for Pakistan approximately making 65.3-72.1% of the total crop production round the year. It is interesting to note for wheat crop in Pakistan that the WF value is approximately half of the global average. It supports the overall scenario of the water footprint of Pakistan's crops, as if the key crop is low in WF value the other crops with the elevated WF can be neglected being minor in nature (Hubacek et al., 2009). Maze has almost the equal WF value as world's average while barley and sorghum have quite raised WF values mainly based on its small yields, whereas millet follows the trend shown by maize. Pakistan has large water footprints in the category of oil crops mainly due to the reason that its domestic yields are small and almost 70% of edible oil is imported (Ridoutt et al., 2012). Domestic production of edible oil

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during 2000-2001 was 642 thousand tons which substantially decreased to 475 thousand tons during 2002-2003. Reduced yield decreases the denominator of the water footprint formula in turn increasing water footprint.

Sugar beet and sugarcane are cultivated on a small area as compared to cereal crops. The cultivated area under the two crops has increased in the recent years but even then water footprint has not reduced substantially.

Pakistan contributes 3.5 % of the total area in the world to the production of orange (FAO, 2003). Hence small contribution in yield worldwide translates into higher water footprints of citrus in Pakistan but even then water footprint of citrus is comparable to global averages.

With more than 349,000 hectares, Pakistan is a key player in the banana industry. 90% of this land lies in the Sindh province in the south-east of the country. The majority of banana farmers in this area are small farmers with land less than 20 hectares (Morrison et al., 2009). However, due to lack of knowledge, outdated techniques and the use of planting materials carrying pests and diseases, yields have been disappointing – only a quarter of those obtained by farmers use modern techniques (Rockstorm, 2001). Poor farming practices result in loss of water during irrigation from water bodies and ground water thus increasing water footprints.

The reduced production of tomato from 2004 on (ASP, MINFAL, 2005-06) has resulted in high water footprints of tomato in Pakistan. While cabbage and potato indicate quite comparable results.

Pakistan does not grow tea herself rather imports most of it from Kenya. Because it requires almost 50 inch of rain per year to grow and Pakistan has just 7.9 inches so if cultivated if requires a lot of water from irrigation making footprint quite high.

In Pakistan the yield of tobacco is quite high as compared to global average (1900 $kgha^{-1}$) reducing its water footprint substantially. It is the only crop in Pakistan whose yield is more than the global average yield. Poor management practices in case of cotton result in high water footprints of cotton. Better management practices (BMPs) can ensure a reduced water footprint of cotton in Pakistan (Mekonnen et al., 2012; Mekonnen, & Hoekstra, 2001).

IV. CONCLUSIONS

Consumptive water use is different from conventional measures of water withdrawal because in the former we discuss the use of water that doesn't return to the source within our time frame of interest hence it is said to be removed permanently.

Calculation of water footprint requires calculation of evapotranspiration (ET) of the area under question. CROPWAT 8.0 in conjunction with CLIMWAT 2.0 enable us to reach the numeric values evapotranspiration of crops. The findings reveal that in Pakistan, which is an agrarian economy, relies heavily on agriculture for its GDP which in turn depends on water resources of Pakistan. The Indus River is the ultimate source of water that flows across Pakistan feeding agricultural fields. Mainly Punjab and an appreciable portion of Khyber Pakhtunkhwa are the main producers of Pakistan. Sindh is notable in case of some fruits' production. The soft wares involved are bound to have inaccuracies and inconsistencies because natural phenomena like climate can't exactly be simulated by soft wares. The work contained herein and on water footprint in general are novice; they have surely shortcomings that are hoped to be overcome in future by more extensive research with better calculation procedures and more reliable and up-to-date sources of data.

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