Quantifying the Water Footprint: Growing Crops Sustainably in Northwest India

Paper submitted in partial requirements of the Undergraduate Honors Program

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2010

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ABSTRACT

When the Green Revolution was ushered in India in the 1960s, the historically-diverse and rain-fed agricultural practices followed for millennia changed dramatically. The decline in groundwater resources across Northern India, especially from agricultural production, is a well known environmental concern and a critical one to address. There is much less awareness that the temporal and spatial distribution of freshwater across the globe is greatly affected by production chains and global exchange. This study applies the concept of water footprint analysis to compute the water demands of the process of growing two principal crops (wheat and rice) in Punjab, India. As a quantitative indicator of fresh water use, the water footprint illuminates the gap between Punjab's natural resource supply and the state's intense water demands. The dependence on aquifers to irrigate croplands has only replaced the alarming issue of food scarcity, with water scarcity, and thus, renewed concerns of famine. The water footprint of wheat and rice from planting to harvest, only represents one snapshot of the entire picture of consumptive water use. As this is only an application of footprint accounting, additional research that incorporates the production process that includes transportation, processing, and export would create a more complete assessment of water resources allocated for agriculture.

INTRODUCTION

Water and food. Development and sustainability. The duality of these concepts is unmistakable in the contemporary environmental, economic, and social-cultural literature. With the addition of a fifth term –human population, the soup of recurrent environmental topics has nearly all the essential ingredients. While each of these terms embodies a multitude of environmental problems, one resource in particular, common to all and of greatest concern according to global public opinion, is: *water* (CSRwire, 2009). Concerns about the availability, accessibility, and quality of the world's freshwater resources are all well-founded. To realize the indispensability of a resource such as freshwater is simply to recognize its life-sustaining property. Thus, the importance of regulating both the quality and the distribution of freshwater makes quantifying this resource as a paramount task. The implications of exchanging the term 'overuse' with quantified metrics allows local, regional, and national communities to hold each other, and more importantly themselves, accountable.

Men and women of my generation are pursuing the path of higher education in an era of heightened environmental awareness and realization. The limitations of earth's natural resources are being, and in many cases, have already been tested. Our growing ecological awareness has come from the sound scientific knowledge that Nature's many paths and processes have limitations and tipping points. These tipping points are what ecologists call "positive feedbacks". Since the 1980s, human activities have exceeded the biological productivity of the planet (Wackernagel et al., 2002). Referred to as "ecological overshoot" by Meadows et al. (1992), this concept embodies the extent to which humans have exceeded ecosystem services.

A combination of advancing technologies, resource management, and lifestyle changes are necessary to support a growing population on Earth's limited resources. The idea related to matching human consumption with resource supply is termed 'sustainability.' However, the many and widely variant definitions of 'sustainability' make it difficult to address such a broad concept without defining the term in context. To make sure that resources for human welfare are *sustained*, the level of human resource consumption has to be maintained at or below the planet's bio-productive or recharge capacity. Without sufficient mitigation, any extension beyond this hypothetical capacity would be creating a negative balance –an ecological hole– or alternately, a *footprint*.

Overview and Objectives

Arjen Y. Hoekstra first introduced the concept of water footprints in 2002 at the International Expert Meeting on Virtual Water Trade. The initial concept for my Honors thesis was not to pursue water footprint analysis; however, my interests and questions continually mirrored the footprint concept so closely, that my objectives were merged with Hoekstra's methodology. The fundamental question addressed in this thesis asks if the water footprint of growing wheat and rice in Punjab, India exceeds the natural water supply of the region. And if so, by how much? Current literature amply documents water scarce regions and watersheds that are in jeopardy. Most water resource concerns stem from anthropogenic activities such as over-consumption, contamination, or both.

If water troubles are so abundant, why focus on India? Although Ohio's water regime could serve as a suitable and convenient study area, this project chose to concentrate on the assessment of freshwater resources in the State of Punjab, India. The main reason to tackle challenging international research is a sense of urgency amongst the scientific community. India's livelihood may be on the brink of collapse without sustained food production in what has been termed the "bread basket of India." There are tremendous environmental pressures imposed upon a country with a population exceeding one billion (India, 2010).

The estimated water requirements for the growth in urban and rural populations present the possibility that resources are exploited to exhaustion. While water covers approximately 70% of the earth's surface, less than 2.5% is fresh water and less than 1% is available for human use. Of total global water withdrawals, irrigated agricultural accounts for a massive 70%, maintaining lands that supply almost 40% of the world's food production (Lal et al., 2004). Using India as a case study, the overarching ambition of this work is to address how a nation can make strides toward sustainable consumption of freshwater resources.

The objective of this study is to quantify the water footprint of two key crops in the northwest state of Punjab, India. Operating as an agriculturally dominated and heavily irrigated state, the water footprint of Punjab is predicted to be higher than most other Indian states. The Green Revolution brought dramatic changes to what crops were traditionally grown and by what methods they were cultivated. The two staple food grains under consideration are wheat (*Triticum* spp.) and rice (*Oryza sativa)* (Clay, 2004). Following Hoekstra's methodology, a water footprint will be modeled for both wheat and rice fields within the boundaries of Punjab, India averaged over four years. Accounting the water footprint of the entire production process, from planting to harvesting, will quantify the over-consumption of resources by volume. This will provide the contrast between Punjab's supply of natural resources and the demands of current food grain production.

RECENT WORK AND RESEARCH JUSTIFICATION

The looming water crisis in India is a prominent environmental issue in international science and social science. While groundwater overdraft and runoff contamination are common accompaniments in most agricultural regions around the world, India's threatening situation is magnified by one significant factor: *population growth*, both human and livestock. Since Thomas Robert Malthus's *Essay on the Principles of Population* in 1798, the debate about whether food production will keep pace with population growth has persisted. While Malthus did not foresee how technological advances could overcome stressful environmental pressures, one cannot discount that population and consumption growth both possess the ability to overwhelm gains in technology (Postel, 1999). Cornucopian optimism or Malthusian pessimism aside, India's current state of environmental stress is quite clear: India's natural resource issues are intensified by extreme population pressures. The effects, evident in both rural and urban areas, provide the nation-states of the world with a preview of the ramifications of overpopulation. India's Green Revolution of the 1960s unveiled both the successes and dangers of combating population-related agriculture issues with technology. Certain technologies were found to have exacerbated environmental concerns when food security concerns were buried with high crop yields (Clay, 2004). Despite a growing awareness of environmental degradation resulting from the Green Revolution, interconnected economic and social pressures have continued to push crop production to extreme and unsustainable limits.

People, Food, and Water

India works relentlessly to support its current population of 1.15 billion – a number that is expected to increase to 1.66 billion by 2050 (India, 2010). Nourishing over one billion individuals requires massive amounts of food; massive amounts of food require vast quantities of water. India accounts for an astonishing 17.2% of the world's population, yet contains only 3.5% of the world's available freshwater (Hoekstra and Chapagain, 2007). With this staggering disproportionality, international investigations on the water policy, science, and infrastructure of

India can be justified, despite the ubiquitous nature of the issue. The effects of such a large gap in India's available water resources and resource demands are apparent at local, state, and international levels.

Indian farmers are first to face the consequences of over-pumping groundwater for irrigation. Exploiting aquifers “is a way of satisfying food needs that virtually guarantees a future drop in production when aquifers are depleted” (Brown, 2009). The localized consequences of exploitation have been realized sooner than predicted. Punjabi farm families are plagued with unreliable irrigation sources, dry tube-wells, and debilitating debt. Farmers are continually forced to deepen wells, invest in costly farm equipment, and purchase genetically modified seed varieties on an annual basis. Agriculture subsidies have only encouraged the massive drawdown of local water tables. As a result, groundwater harvesting has continued in a state of water free-for-all. The Indian government has perpetuated an 'every farmer for himself' mentality, as neighbors battle to dig deeper, more efficient wells. Threatened by the imposition of feeding more and more Indians, farmers have no choice but to demand more of their lands. As the nation's population soars and food production is maximized, “the tragedy of the commons is playing out full tilt” with groundwater resources (Postel, 1999).

On a state level, the demands of high production in Punjab have taken a heavy toll on the region's freshwater resources. From 1984 to 2004, the groundwater table, which supplies the majority of Punjab's irrigated fields, has dropped between 5 to 20 m – an average drop rate of 54.9 cm per year (Tiwana et al., 2007). Even NASA's Gravity Recovery and Climate Experiment (GRACE), could detect the water exploitation in northwest India from twin satellites orbiting 480 km above the Earth (Cook-Anderson, 2009). Through subtle variations in the pull of Earth's gravitational field, GRACE measured a 2000 km “swath” from eastern Pakistan, across northern

India, and into Bangladesh that measured a loss of over 100 km^3 of groundwater from 2002 to 2008 – a volume three times the size of the United States' largest man-made reservoir (Cook-Anderson, 2009, Figure 1). Despite alarming scientific evidence, detrimental irrigation practices continue in order to protect national food security for over one billion Indians. The agriculturally dominated states are exploiting aquifers to "meet today's needs, leaving less to meet tomorrow's (Postel, 1999).

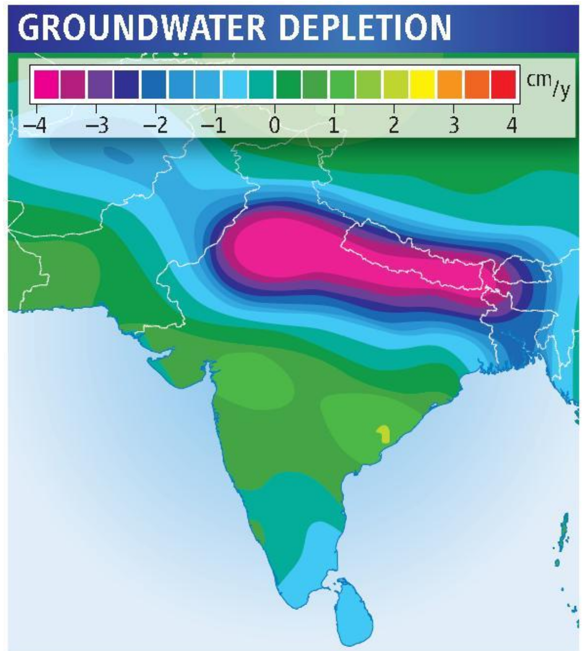

Figure 1. Graphical representation of GRACE findings (Kerr, 2009).

Securing food supplies for the world's second largest populated country does not come without sacrifices. "Any use of natural resources has impacts" (Clay, 2004). Shortsighted innovations replace complex problems with complex answers –answers that contain their own inherent problems. In *The Collapse of Complex Societies*, author Joseph Tainter illustrates a long running pattern where civilizations progress, increasing in complexity, until they can no longer manage their own complexity (Brown, 2009). India's Green Revolution was a giant step forward in Tainter's pattern of civilization.

Punjab Agricultural History

Widespread water scarcity concerns emerged in India's history only recently. "Current day" Punjab lies in the Indus River Basin; the basin is an extremely water rich region and an area considered one of the cradles of civilization (Lal, 1997). The regime's natural abundance of freshwater even lent itself to the name 'Punjab'. The Persian word 'Punjab' translates into the land of “five rivers” (Postel, 1999).

From the ancient Indus Valley people to the current Indian Punjabis, agriculture has held fast as a strong backbone to civilization in the region. Throughout history and prior to the Green Revolution, agriculture relied on seasonal monsoons for rain-fed irrigation (Hira, 2009). It was not until the effects of the Green Revolution became apparent, that the limiting nature of water became a realization in Punjab. Given the added climatic variability, great famines caused by periodic droughts were simply accepted as part of the region's long history. However, after many technological changes implemented by the Green Revolution, India has yet to experience another famine-like situation: an amazing fact considering the region's 5,300 year-old record (Hira, 2009)!

Pre-Independence India

Traditional agriculture in Punjab, India was diverse. More often than not, a variety of crops were intermixed, contributing to ecosystem health and productivity. Crops such as wheat, maize, millets, pulses, and oil seeds were grown amongst each other and rotated regularly (Shiva, 1991). Such diversity contributed to stability and resiliency within the environment. Because rainfed agriculture is highly susceptible to drought and thus crop failures, devastating famines occurred every few years. The first irrigation schemes where constructed when the British conquered Punjab in 1849. The changes in agricultural practices and natural groundwater flow brought about state-wide water logging and increased soil salinity (Hira, 2009). The introduction of irrigation through headworks and canal networks primed the state for the next era of major changes when India gained independence from British rule in 1947. In 1947, 52.3% of Punjab was irrigated, and the state produced 1.99 million metric tonnes of food grains (Randhawa, 1977).

Post-Independence India

During post-independence years in the 1950s, Indian government focused growth efforts on the newly acquired province of Punjab and its sister agricultural state, Haryana. The country's Ministry of Agriculture organized a detailed farming strategy and immediately went to work to increase crop production on these fertile lands (Shiva, 1991). Punjab and Haryana were prepped for the implementation of an extensive canal system and electricity grid, among other infrastructure projects for rural development. In 1960-61, the irrigated land area increased slightly to 54% of net sown area; food grain production improved to 3.16 million tonnes (Punjab Government, 2010). Considerable attention was given to the new agricultural states to alleviate food security concerns of the nation. The government's post-independence push for projects and policies to increase crop production laid the groundwork for the over-consumption and degradation of once abundant water resources.

Green Revolution

Nothing was more fundamental to India's booming growth in the twentieth century than the Green Revolution. The timing was just right for Punjab to lead the revolution because the infrastructure and policies were new, the lands were fertile, and the people were educated and eager. The Green Revolution was fueled through the international influence of Norman Borlaug's work in developing high-yielding seed varieties (HYVs) of wheat and the International Rice Research Institute's later HYVs of rice (Shiva, 1991; Hira, 2009). In addition to HYVs of food grains, other new technologies were introduced to the agricultural sector such as pump and canal irrigation systems, chemical fertilizers and pesticides, heavy machinery, and 'improvements' in cropping patterns and intensities.

By 1970, as a result of these technological breakthroughs, Punjab increased food production to 5.6 million tonnes of food grains (Randhawa, 1977). The traditionally diverse crops and agricultural practices in Punjab were substituted with the stringent management rules of wheat and rice monocultures (Larson, 2004). From 1960-61 to 2000-01 “at the expense of other crops,” the area under wheat production increased from 37% to 78% and rice from 6% to 60% (Hira, 2009). More taxing on the land's natural resources than increased cultivated area was the increased intensity of farm operations. From 1962-65 to 1990-93, the number of tractors rose from 10,646 to 234,006; the number of pump sets for irrigation rose from 45,900 to 721,220; fertilizer consumption increased from 30,060 tonnes to 1,212,570 tonnes; and cropping intensity increased from 126% to 185% (Punjab Government, 2004).

Once farmers began observing the miracle yields of their neighbors, word traveled quickly that these high yielding seed varieties and new agricultural practices were truly successful. ('Successful' here implies the benefits of production outweighed the costs of change). Unfortunately, higher *outputs* only came about after increasing *inputs*, and Punjab's water resource exploitation began.

Post-Green Revolution

Punjab is now widely referred to as the “bread-basket” of India. While Punjab occupies only 1.57% of India's total land area, it produces two-thirds of the country's grains (Tiwana et al., 2007). At the expense of generations to come, Punjab, as of 2007, has reached grain production yields of 25.2 million tons – a number 12.7 times the food grain production yields of 1947 (Tiwana et al., 2007).

Dominated by the nation's two major food grains, Punjab contributes nearly 40% and 60% to the national central pool of wheat and rice respectively. These remarkable production levels are possible because over 94% of the agricultural fields are intensely irrigated (Tiwana et al., 2007). The livelihood of the entire country of India, and other countries that rely on India's food grain exports, are dependent on Punjab's source for irrigation: groundwater. There is agreement among scholars that the state's wheat-rice cropping pattern is responsible for the continuous decline of the groundwater table (Sarkar, 2009). As much as 86% of the state is experiencing groundwater depletion through the overdraft of tube-well irrigation (Sakar, 2009). In addition, the production of water-intensive crops is predicted to grow 80% from 2000 to 2050 (Grail Research, 2009).

Punjab's undeniable dependence on groundwater irrigation has serious ramifications for the regional ecosystem and overall resiliency and stability of the country. The conversion to intensive monocultures of wheat and rice creates a heavy reliance on a very small number of crops. The concentration of the nation's food grains in a small area creates vulnerability to massive famine. These two troubling statements outline the most important factors in focusing this study of water footprint analysis on Punjab, India.

India has essentially displaced its pre-Green Revolution concerns of food scarcity with post-revolution concerns of water scarcity. Inherent to the nature of problem solving, switching one issue for another creates a cyclical process and encourages temporary fixes. The dynamics of food and water are so fundamentally interconnected that it is imperative we find a balance between the two scarcity extremes. To begin establishing that balance, water must be viewed and managed as an equal to food; water must be treated as an economic commodity (Patel, 2009). The use of water in agriculture and industry is difficult to manage because water is still priced far below its real costs (Chapagain and Hoekstra, 2008). Most products in the global market do not reflect the costs associated with water throughout their production process. Consumers are “generally not aware of and do not pay for the water problems in the overseas countries where their goods are being produced" (Chapagain and Hoekstra, 2008). These challenges have remained water policy roadblocks until recently.

Water Footprint as an Instrument for Change

The conceptual tools necessary to compare, quantify, and price water consumption and trade have emerged within the last 15 years. These tools, namely virtual water theory and water footprint theory, have opened windows of public awareness and water policy action. Virtual water is the water embodied or "embedded" in commodities such as grain (Allan, 1998). If a nation exports or imports a product, it also exports or imports the water consumed or polluted over its full production chain in "virtual form" (Hoekstra and Chapagain, 2007). The water footprint concept takes the appropriation of water use a few steps further than virtual water. It is a comprehensive and multidimensional indicator of water consumption (Hoekstra et al., 2009).

The water footprint is similar to its parent concepts of ecological footprints and carbon footprints. A "footprint" has been generally defined as a "quantitative measure showing the appropriation of natural resources by human beings" (Hoekstra, 2008). The footprint aims to make the public and policymakers aware that water management is *not* a local issue. It is rooted in the search to reveal hidden links between human consumption and use of water resources, and between global trade and resource management.

Water footprint analysis is a "geographically and temporally explicit" indicator of different water sources (Hoekstra et al., 2009). These 'sources' can break down into direct and indirect water use, or into a specific type of water (i.e. blue, green, and grey water). Blue water refers to the volume of fresh ground and surface water consumed along the supply chain of a product; green water quantifies the volume of precipitation stored in the soil as soil moisture; and grey water measures the volume of water required to dilute pollutants associated with a product's production chain to meet ambient water quality standards (Hoekstra et al., 2009).

METHODS

A water footprint can be modeled for a wide variety of applications. “Any well-defined group of consumers, including a family, business, village, city, province, state, or nation” has a unique footprint (Hoekstra, 2009). A water footprint can also be defined for any process, activity, good, or service. This study examines the production process of a product: specifically, the cultivation and harvest of wheat and rice crops in Punjab. The wide range of possible footprint 'subjects' makes it crucial to clearly define a study's goals, system boundaries, and scope of analysis. Hoekstra's (2009) *Water Footprint Manual* provides several checklists, tables, and examples to help delineate these goals. The projects design is addressed according to Hoekstra's manual in the sub-section immediately following; the mathematical models used to calculate a footprint are then reviewed; and finally, a brief discussion on data collection identifies the sources utilized to satisfy the footprint models.

Design

A water footprint presents a wide perspective on how a consumer, producer, or product relates to the consumption and pollution of freshwater systems (Hoekstra et al., 2009). A footprint does *not* measure the extent of environmental impact due to consumption and pollution. Several possibilities exist in defining the purpose of a water footprint, so narrowing a study's approach is one of the most important steps in Hoekstra's methodology. In reference to Hoekstra's “Goals of water footprint assessment – a checklist,” the goal of this study is two-fold (Table 1). The broad, but underlying goal is to raise awareness of the connection between development and water resource consumption. On a more applied level, the goal of this research project is to implement and execute the step-by-step procedure of conducting water footprint assessment.

Table 1. Defining the goals of footprint assessment through a checklist illustrated by Hoekstra (2009).

General

- What is the ultimate target? Awareness raising, hotspot identification, policy formulation or quantitative target setting?
- Is there a focus on one particular phase? (On accounting, sustainability assessment or response formulation?)
- What is the scope of interest? Direct and/or indirect water footprint? Green, blue and/or grey water footprint?
- How to deal with time? Aiming at assessment for one particular year or at the average over a few years, or trend analysis?

Product water footprint assessment

- What product to consider? One stock-keeping unit of a particular brand, one particular product, or a whole product category?
- What scale? Include product(s) from one field or factory, one or more companies, or one or more production regions?

Consumer or community water footprint assessment

- Which community? One individual consumer or the consumers within a municipality, province or state?

Assessment of the water footprint within a geographically delineated area

- What are the area boundaries? A catchment, river basin, municipality, province, state or nation?
- What is the field of interest? Assess the virtual-water balance of the area (to examine how the water footprint within the area is reduced by importing virtual water and how the water footprint within the area is increased by making products for export), analyse how the area's water resources are allocated over various purposes, and/or examine where the water footprint within the area violates local environmental flow requirements and ambient water quality standards.

National water footprint assessment (water footprint within a nation and of national consumption)

- What is the scope of interest? Assess the water footprint within a nation and/or the water footprint of national consumption? Analyse the internal and/or the external water footprint of national consumption?
- What is the field of interest? Assess national water scarcity, sustainability of national production, export of scarce water resources in virtual form, national water saving by import of water in virtual form, sustainability of national consumption, impacts of the water footprint of national consumption in other countries and/or dependency on foreign water resources?

There are four distinct phases of water footprint assessment: setting goals and scope, accounting, sustainability assessment, and response formulation. This case study focuses exclusively on the accounting phase (Figure 2). Due to the nature and time frame in undergraduate research, a more in-depth assessment of possible social, economic, and environmental policy responses must be left to further research. While a water footprint can continue to incorporate water resources used for transportation and trade, this study does not extend into the distribution of agricultural products to their respective local and international destinations.

Phase 1		**Phase 2*		*Phase 3*		*Phase 4*
Setting goals and scope	→	Water footprint accounting	→	Water footprint sustainability assessment	→	Water footprint response formulation

Figure 2. The four phases of water footprint assessment (Hoekstra et al., 2009).

The study area, of 50,362 square kilometers, is the state of Punjab located in the northwest region of India (29.30 N to 32.32 N and 73.55 E to 76.50 E). The climate is characterized by extreme hot and cold temperatures, heavy rainfall around the foothills of the Himalayas, and variable rainfall in the southeast (Punjab Government, 2010). The state's water regime is largely determined by the Beas, Ravi, Sutlej, Chenab and Jhelum rivers, which are tributaries of the larger, cross-boundary Indus River. Considering the abundance of major water networks within the small area of Punjab (slightly half the land area of Ohio), the state's boundaries will serve as the system boundaries for this study. The footprint accounts for Punjab's net sown agricultural field area of rice and wheat combined. On a three tier spatiotemporal scale, the water footprint of the agricultural production processes is classified as Level B analysis: this is a state specific, annual assessment (Table 2). Since water availability fluctuates from year to year over any given season, the data were collected for an "average year given the existing climate"; this can be done by combining the average production yields over five years and the average climate (mainly precipitation) over the past thirty years (Hoekstra et al., 2009).

Table 2. Three spatiotemporal levels of footprint accounting (Hoekstra et al., 2009).

	Spatial explication	Temporal explication	Source of required data on water use	Typical use of the accounts
Level A	Global average	Annual	Available literature and databases on typical water consumption and pollution by product or process	Awareness raising; rough identification of components contributing most to the overall water footprint; development of global projections of water consumption
Level B	National, regional or catchment	Annual or monthly	As above, but use of nationally, regionally or catchment specific data	Rough identification of spatial spreading and variability; knowledge base for hotspot identification and water allocation decisions
Level C	Local, site and field specific	Monthly or daily	Empirical data or (if not measurable) best estimates on water consumption and pollution, specified by location and over the year	Knowledge base for carrying out a water footprint sustainability assessment; formulation of a strategy to reduce water footprints and associated local impacts

Note: Three levels can be distinguished for all forms of water footprint accounting (e.g. product, national, corporate accounts).

Components of Water Footprint

Water footprint analysis is a relatively new area of research that is continually improving its methodology. Several methods of modeling a water footprint exist, and there are multiple ways to calculate the variables for each model. Hoekstra's *Water Footprint Manual* is the most comprehensive literature to guide the natural resource accounting process; the manual provides a solid framework for footprint analysis to interested consumers, businesses, or nations. Consequently, all procedural methods and the majority of modeling resources and databases used in this study originated from the unprecedented 2009[1] manual.

The total water footprint of an agricultural production process (WF_{proc}) is the sum of the blue (WF_{blue}), green (WF_{grn}), and grey (WF_{grey}) water footprints (Hoekstra et al., 2009). Expressed in water volume per mass of product, the total water footprint is segmented in order to distinguish water consumption volumes by source. Each blue, green, and grey water source represents different availabilities, different steps in the process, and different economic values. The categorization of sources is unique to water footprint analysis and helps scientists and policy-makers alike to formulate more informed conclusions and decisions.

The blue and green water footprints are modeled using similar methodology, whereas grey water requires a separate approach. The blue water footprint is a measure of consumptive use of fresh surface or ground water by humans. WF_{blue} is the sum of blue water evaporation, incorporation, and lost return flow. Blue water is mainly used in the process steps of withdrawal and irrigation. WF_{grn} is the sum of green water evaporation and incorporation. The green water footprint combines the 'permanent' water embodied in the crop, with the rainwater consumed during plant growth (here 'rainwater consumption refers to evapotranspiration from plants and

1 Since the proposal of this project, an updated version of the manual has been announced; *The Water Footprint Assessment Manual: Setting the Global Standard* is not scheduled for publishing until February 2011.

soils). Green water is the “precipitation on land that does not run off or recharge the groundwater” (Hoekstra et al., 2009). The separate summations of blue and green water by volume are calculated from day one of planting up until the day of harvest: a time span referred to as the total length of growing period (*lgp*). The different *lgps* and other crop parameters of wheat rice are taken into account when modeling crop water usage in steps prior to the final footprint calculation. The actual equation to determine the WF_{blue} and WF_{grn} is rather simplistic; the crop water use (in cubic meters per hectare) is divided by product yield (expressed in tons per hectare).

$$WF_{proc,\ blue} = \frac{CWU_{blue}}{Y} \qquad WF_{proc,\ green} = \frac{CWU_{green}}{Y}$$

'Crop water use' requires estimations of evapotranspiration rates for a specific crop, in the specific climate of the agricultural region of study. Such site specific information was obtained using the Food and Agriculture Organization of the United Nation's (FAO) CROPWAT 8.0 and CLIMWAT 2.0 modeling programs. CROPWAT uses CLIMWAT precipitation data, crop growth inputs, and general soil data to calculate crop water requirements under ideal conditions over a crop's entire *lgp.* After all yields and variables in the CROPWAT program are accounted for, the blue and green water footprints can be determined. The last step in blue and green water accounting is summing the blue and green water embodied in the physical harvested crop. While the 'actual crop water' is typically a negligible fraction of the total water footprint, it helps add to the overall picture of footprint analysis.

The grey water footprint is a different segment of quantifying available water resources; calculations require much different data inputs than the blue and green counterparts. Grey water takes into consideration the degree to which water consumed throughout the process is polluted. When applied to growing an agricultural crop such as wheat or rice, the grey component of the total footprint is calculated as follows: the chemical application rate (mass per hectare) is multiplied by the leaching fraction, and then divided by the difference in maximum pollutant concentration and natural pollutant concentration. Lastly, the volume per hectare is divided by the crop yield (ton per hectare) (Hoekstra et al., 2009).

$$WF_{proc,grey} = \frac{(\alpha \times AR)/(c_{\max} - c_{nat})}{Y}$$

In an agricultural study such as this, it is important to include the grey water in the total water footprint because pollutants such as fertilizers, pesticides, and insecticides have a significant impact on the water demands of a farm. Often times, enforced water quality standards require pollutants to be diluted by freshwater to attain certain ambient legal levels.

Data Collection

Modeling water resources used in rice and wheat production in Punjab, India requires an examination of large international databases for small bits of information. The calculations depend on credible and consistent secondary data, rather than primary- hands-on data collection. Hoekstra's *Manual* is comprehensive enough to provide international database links and resource recommendations, as well as possible data alternatives. With these resources as a base, and with supplemental country-, state-, university-, and non-governmental organization sources, the data collection process becomes feasible.

A significant portion of CROPWAT data inputs for wheat were derived from the FAO's crop water information resource available on the web (FAO Water, 2010). The FAO's link for rice crop water information was under construction, so various sources were used to collect rice crop parameters. India's Ministry of Agriculture's statistical report (Section six) provided the documentation of production areas and yields of principal crops by state (Director of Land Records, 2009). The data collected from the Punjab statistical report are recorded in 'agricultural years' which start on July 1st and end on June 30th.

RESULTS

In Punjab, as in many other parts of India, agriculture is life. Punjab lies in the agroecological zone number six, characterized by warm sub-humid subtropics with summer rainfall (Maclean et al., 2002). The two main cropping seasons are known as kharif and rabi. Rice, *Oryza sativa*, is a kharif crop grown in the summer months (mid-June to October). Spring wheat, *Triticum spp.*, is a rabi cereal crop grown in the winter months (November to mid-April) (Khurana et al., 2008). In the 2008-2009 cropping season, 2.735 million hectares of rice and 3.526 million hectares of wheat were under production. Of those two staple crops, 100% were high-yielding varieties. In that same year, 99.5% of the area under rice cultivation was irrigated as was 98.5% of wheat fields (Director of Land Records, 2009). To compare Punjab's extensive use of groundwater for irrigation to national figures, only 39.5% of India's total agriculture area operates under irrigation; when analyzed by state, Punjab leads with 97%, followed by Haryana (83%) and Uttar Pradesh (68%) (Hira, 2009). The water-intensive inputs allow Punjab lands to support India's demand for rice and wheat.

Crop Yields

To calculate the water footprint of an agricultural product under an "average year given the existing climate," Hoekstra suggests averaging yield data over a recent period of 5 years and climate data averages over the past 30 years (Hoekstra et al., 2009). Unfortunately, the most recent statistics are only available for the past four years. As a result, the crop area, production, and averaged yields of rice and wheat are taken between agriculture years 2005-2006 and 2008-2009 (Table 3). As production in Punjab has begun to plateau, it is not expected that adding in a previous 5^{th} year would alter the calculation considerably.

Table 3. Area, Production, and Yield of Rice and Wheat in Punjab						
Year	Area (10^3 ha)*		Production (10^3 ton)*		Yield (ton/ha)	
	Rice	Wheat	Rice	Wheat	Rice	Wheat
2005-2006	2647	3464	10207	14476	3.856	4.179
2006-2007	2621	3467	10138	14596	3.868	4.210
2007-2008	2609	3487	10486	15716	4.019	4.507
2008-2009	2735	3526	11000	15733	4.022	4.462
Average					**3.941**	**4.340**

*Source: Director of Land Records (2009)

CLIMWAT 2.0 Meteorological Data

The FAO's CLIMWAT 2.0 is a database comprised of over 5,000 stations worldwide. The program, designed to supplement CROPWAT 8.0, organizes agroclimatic data of any selected station into files which are then opened through CROPWAT. Three meteorological stations are located within Punjab: Ludhiana, Ambala, and Amritsar. The Ludhiana station was most centrally located in the state, and was thus chosen for the crop water requirement modeling. The CROPWAT program uses CLIMWAT files for the 'climate and reference evapotranspiration rate' module and for the 'rain/effective precipitation' module. Using these imported files, evapotranspiration (ET_o) was calculated following the Penman-Monteith formula (Table 4). Rainfall data were used to calculate effective rainfall (Eff rain) by applying the USDA Soil Conservation Service formula (Table 5).

Table 4. Climate/ET_0 Penman-Monteith module screen shot. Data imported from CLIMWAT 2.0 (Grieser, 2006).

Country: Location 6 Station: LUDHIANA

Altitude: 255 m. Latitude: 30.86 °N Longitude: 75.93 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	6.7	18.9	66	69	6.5	11.8	1.58
February	8.5	21.0	63	95	7.1	14.6	2.24
March	12.8	26.0	51	95	7.9	18.2	3.33
April	18.8	34.6	42	95	9.1	22.3	4.94
May	23.3	38.8	31	121	10.0	24.8	6.51
June	26.2	39.6	40	121	10.1	25.1	6.85
July	26.1	34.9	69	95	7.1	20.6	5.09
August	24.8	32.9	76	69	6.6	18.9	4.29
September	23.4	33.4	68	69	8.2	19.4	4.28
October	17.7	32.0	56	52	9.0	17.6	3.41
November	11.6	26.4	62	52	8.3	14.1	2.27
December	7.4	20.7	72	52	7.1	11.6	1.52
Average	**17.3**	**29.9**	**58**	**82**	**8.1**	**18.2**	**3.86**

Table 5. Rain module screen shot. Data imported from CLIMWAT 2.0 (Grieser, 2006).

Station: LUDHIANA Eff. rain method: USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	21.0	20.3
February	39.0	36.6
March	31.0	29.5
April	20.0	19.4
May	20.0	19.4
June	60.0	54.2
July	229.0	145.1
August	189.0	131.8
September	85.0	73.4
October	5.0	5.0
November	13.0	12.7
December	21.0	20.3
Total	**733.0**	**567.6**

CROPWAT 8.0 Variables

CROPWAT for Windows is a program created to aid in the calculation of crop water requirements (CWR) and irrigation requirements; the program can also develop irrigation schedules for different management conditions and create water supply schemes for different crop patterns (Swennenhuis, 2009). For the purposes of this study, only the CWR component was utilized.

Compared to the ET_o and rainfall modules, the crop module requires the most data collection by far. The two setting options for crop data input are 'dry crop' or 'rice'. Rice also requires extra inputs of soil data because the CWR for rice includes water requirements for land preparation. The required crop data and sources of the collected data are listed below (Table 6).

Table 6. Sources referenced to satisfy crop data inputs.

Data	Wheat	Rice
Planting date	(Allen et al., 1998)	(Hira, 2009)
Harvest date	Automatically calculated	Automatically calculated
Stage (days)	(Allen et al., 1998)	(Swennenhuis, 2009)
Crop coefficient (K_c)	(Allen et al., 1998)	(Swennenhuis, 2009)
Rooting depth (m)	(FAO Water, 2010)	(Mishra, 1997)
Puddling depth (m)	n/a	(Swennenhuis, 2009)
Nursery area (%)	n/a	(Swennenhuis, 2009)
Critical depletion fraction (p)	(FAO Water, 2010)	(Swennenhuis, 2009)
Yield response factor (K_y)	(FAO Water, 2010)	(Swennenhuis, 2009)
Max crop height (m)	(Allen et al., 1998)	(Swennenhuis, 2009)

The soil data necessary for rice programming was the most difficult to find relying only on secondary sources. Data collected first-hand would undoubtedly make the rice-CWR computation more applicable to Punjab specifically. The soil properties were instead derived from Singh’s (2009) assessment of the effect of continuous rice-wheat rotations on Punjab soils. The study divided Punjab soils into four zones, of which zones 2 and 3 comprised the majority of land area. The percent sand, silt, and clay of these two zones were entered into an online “Soil Hydraulic Property” calculator (Table 7) (Global Soil Science Educators and Knowledge

Managers, 2009). The hydraulic properties were then averaged and data units were algebraically manipulated[2] for use in the CROPWAT soil module.

Table 7. Soil hydraulic properties based on soil texture inputs from Singh et al., 2009. (Global Soil Science Educators and Knowledge Managers, 2009).

Percent Sand	51	52
Percent Clay	28	29
	Calculate	Calculate
Percent Silt	21	19
Texture (Canadian System)	Sandy Clay Loam	Sandy Clay Loam
Bulk density *(g/cm^3)*	1.38	1.38
Saturated hydraulic conductivity *(cm/hr)*	0.35	0.31
Saturation *(cm^3 water/cm^3 soil)*	0.48	0.48
Field capacity *(cm^3 water/cm^3 soil)*	0.27	0.27
Wilting point *(cm^3 water/cm^3 soil)*	0.16	0.17
Plant Available water *(cm^3 water/cm^3 soil)*	0.11	0.11
(inches water/foot soil)	1.3	1.27

Once all CROPWAT's required data[3] for wheat and rice were collected and entered into their own sessions[4], the 'crop water requirement' module was run. The measures of green water evapotranspiration (ET) are derived from the minimum values between total crop ET and effective precipitation (P_{eff}). Blue water ET is estimated as the difference between total ET and P_{eff}. If the P_{eff} is greater than total ET, ET_{blue} is equal to zero (Hoekstra, 2009). The CROPWAT outputs and ET of wheat and rice are presented in Tables 8 and 9. The total ET_{green} and ET_{blue} in mm are converted to crop water use (CWU) in m^3/ha by a factor of ten (Hoekstra, 2009). CWU

2 See Appendix A for complete calculations.

3 See Appendix C. All data entered for wheat and rice are displayed in the corresponding CROPWAT screen shots.

4 The CROPWAT program only runs one crop at a time. Wheat and rice CWR are modeled in separate "sessions," but use the same Ludhiana, Punjab climate station files from CLIMWAT.

divided by average yield results in the water footprints related to evaporated water from the field.

Table 8. Total green-blue water evapotranspiration of wheat based on the CWR output table of CROPWAT 8.0. Table set up adapted from Hoekstra et al. (2009).

Month	Decade	Stage	K_c -	ET_c mm/day	ET_c mm/dec	P_{eff} mm/dec	Irr. Req. mm/dec	ET_{green} mm/dec	ET_{blue} mm/dec
Nov.	2	Initial	0.30	0.68	1.4	0.8	1.4	0.8	0.6
Nov.	3	Initial	0.30	0.61	6.1	5.1	1.0	5.1	1.0
Dec.	1	Initial	0.39	0.69	6.9	6.1	0.8	6.1	0.8
Dec.	2	Develop	0.71	1.08	10.8	7.1	3.7	7.1	3.7
Dec.	3	Develop	1.04	1.60	17.6	7.0	10.6	7.0	10.6
Jan.	1	Mid	1.12	1.75	17.5	6.3	11.2	6.3	11.2
Jan.	2	Mid	1.12	1.77	17.7	6.0	11.7	6.0	11.7
Jan.	3	Mid	1.12	2.02	22.2	8.1	14.1	8.1	14.1
Feb.	1	Mid	1.12	2.26	22.6	11.1	11.6	11.1	11.5
Feb.	2	Late	1.09	2.45	24.5	13.2	11.2	13.2	11.3
Feb.	3	Late	0.87	2.27	18.2	12.1	6.1	12.1	6.1
March	1	Late	0.61	1.82	18.8	10.7	7.5	10.7	8.1
March	2	Late	0.35	1.17	9.4	7.9	0.0	7.9	1.5
Total over entire growing period					**193.7**	**101.5**	**90.9**	**101.5**	**92.2**

Table 9. Total green-blue water evapotranspiration of rice based on the CWR output table of CROPWAT 8.0. Table set up adapted from Hoekstra et al. (2009).

Month	Decade	Stage	K_c -	ET_c mm/day	ET_c mm/dec	P_{eff} mm/dec	Irr. Req. mm/dec	ET_{green} mm/dec	ET_{blue} mm/dec
May	3	Nursery	1.20	0.80	0.8	0.8	0.8	0.8	0
June	1	Nurs/LPr	1.19	1.47	14.7	12.4	59.1	12.4	2.3
June	2	Nurs/LPr	1.06	7.51	75.1	15.4	59.6	15.4	59.7
June	3	Initial	1.07	6.84	68.4	26.4	255.4	26.4	42.0
July	1	Initial	1.10	6.17	61.7	41.5	20.2	20.2	20.2
July	2	Develop	1.10	5.49	54.9	53.3	1.7	1.7	1.6
July	3	Develop	1.11	5.26	57.9	50.2	7.8	7.8	7.7
Aug	1	Develop	1.12	5.08	50.8	46.8	4.0	4.0	4.0
Aug	2	Mid	1.13	4.82	48.2	46.0	2.2	2.2	2.2

Aug	3	Mid	1.13	4.83	53.1	38.9	14.3	14.3	14.2
Sep	1	Mid	1.13	4.83	48.3	31.3	17.0	17.0	17.0
Sep	2	Mid	1.13	4.82	48.2	24.9	23.3	23.3	23.6
Sep	3	Late	1.13	4.49	44.9	17.2	27.7	17.2	27.7
Oct	1	Late	1.10	4.05	40.5	4.3	36.2	4.3	36.2
Oct	2	Late	1.06	3.61	36.1	0.0	36.1	0.0	36.1
Oct	3	Late	1.02	3.11	21.7	0.5	21.0	0.5	21.2
Total over entire growing period					**725.5**	**410.0**	**586.4**	**167.5**	**315.7**

Green and Blue Water Footprint Components

Table 10. Overview of all major 'green' and 'blue' components of the WF

	ET_{green}	ET_{blue} (mm/dec)	ET_{total}	CWU_{green}	CWU_{blue} (m3/ha)	CWU_{total}	Y (ton/ha)	WF_{green}	WF_{blue} (m3/ton)
wheat	101.5	92.2	193.7	1015	922	1937	4.340	*233.9	212.4
rice	167.5	315.7	483.2	1675	3157	4832	3.941	*425.1	801.1

*WF of the *process* of growing crops. This WF does not yet include the water incorporated into the harvested crop (Hoekstra et al., 2009)

Grey Water Component

The grey water component was calculated based on the application of nitrogen (N) fertilizer to Punjab crop fields. The average N fertilizer applied to wheat and rice crops in Punjab is 143 and 148 kg/ha respectively (Khurana, 2008). Lacking Punjab-specific data, several assumptions regarding fertilizer use and transport had to be made based on Hoekstra’s Manual, Appendix I: Example for sugar beet in Valladolid, Spain (2009). The leaching fraction (quantity of N that reaches water bodies) was assumed to be 10% of the applied fertilizer rate. Due to unavailable local ambient N water quality standards, the US EPA recommendation (maximum of 10mg of nitrate per L of water) was used (Hoekstra, 2009). The natural concentration of N in the receiving water body was assumed to be zero. Only the nitrogen fertilizer use was incorporated into the grey water footprint[5], because the grey component is expressed as a dilution water requirement. This means only the most critical pollutant with the greatest application rate need be considered (Hoekstra, 2009).

Table 11. Data and calculation of the grey water component for wheat and rice in Punjab, India.

	Average fertilizer application rate* (kg/ha)	N leaching fraction	US EPA N ambient water quality standard (mg/L)	Y (ton/ha)	Total WF_{grey} (m3/ton)
wheat	143	.10	10	4.340	330
rice	148	.10	10	3.941	380

*Source: Khurana et al., 2008

Total Water Footprint

The estimated total water footprint of an agricultural production process (WF_{proc}) is the sum of the green (WF_{grn}), blue (WF_{blue}), and grey (WF_{grey}) water footprints. Averaged over four agricultural years (from 2005-2009) and based on meteorological data from the Ludihana, Punjab (India) climate station, the water footprint of growing wheat and rice are as follows:

Wheat: 234 + 212 + 330 = **776** m^3/ton

Rice: 425 + 801 + 380 = **1606** m^3/ton

In the crop year 2008-2009 alone, Punjab produced 15,733,000 tons of wheat and 11,000,000 tons of rice. According to the water footprints, these two staple crops required a combined total of 2.9 $x10^{10}$ m^3 of water to be planted, grown, and fertilized (1.2 $x10^{10}$ m^3 for wheat and 1.7 $x10^{10}$ m^3 for rice).

DISCUSSION

The lands below the foothills of the Himalayas have supported agriculture long before India's independence and the state of Punjab existed. The fertile flood plains, rivers, and high

5 See Appendix B for complete calculations and unit conversions.

annual rainfall, created fresh groundwater reserves that ranged from a depth of 30m along the foothill zone to 52m toward the southwestern end of Punjab (Hira, 2009). The aquifer was left virtually undisturbed until 1849 when the British introduced irrigation schemes and was left largely untapped until the Green Revolution introduced irrigation by tubewells. Considering the inception of tubewell irrigation and the ever-increasing demands for high crop yields, “a falling water table across the northern Indian subcontinent comes as no great surprise” (Kerr, 2009).

The wheat and rice water footprints support previous observations that intensive agriculture practices in Punjab are the primary cause of the falling groundwater table. In India, the yields of rainfed rice range between 0.5-1.6 ton/ha, whereas irrigated rice yields 2.3-3.5 ton/ha (Chapagain and Hoekstra, 2010). Irrigation is the clear connection between high agricultural production and diminishing water resources.

The aquifers across northern India cannot be reported in exact water volumes, but *changes* can be observed. These can be quantified either on a local scale by measuring the water table, or on a much larger scale by experiments such as NASA’s GRACE project. While the water footprints of wheat and rice cannot be directly compared to the volume of groundwater reserves, the water footprint can serves as a tool to help in minimizing groundwater use. Water footprints can be calculated and compared in order to select the most efficient irrigation schedules with the smallest water footprint. When footprints quantify even larger processes (such as adding in the water requirements of transporting crops) even more significant observations and changes can be made. Assigning a concrete number to put resource consumption into perspective can help local consumers, even entire nations, support agriculture that makes an effort to avoid excessive water use.

Agricultural water footprints are likely most effective in bringing about awareness of the significant changes that resource management needs to make. After NASA adjusted for natural variations in precipitation and evaporation, the gravity decline determined by GRACE translated into a net loss of 54±9 km^3 of groundwater per year in northern India's aquifers. A water deficit this large is not likely to balance itself out with only small, temporary, or localized changes in management and consumption. A call-to-action by Lal (2004) reveals the scale at which changes must be made:

> *"Humanity will need to bring about a 'Blue Revolution' in the 21st century to complement the so-called Green Revolution of the 20th century in order to feed a growing world population within the parameters of likely water availability. The Blue Revolution will require that water-use productivity be wedded to land-use productivity."*

The scarcity problem of water, and of sinking water tables in particular relation to crop production, is not confined to India alone but to the world at-large. In his forthcoming book (2011), Lester Brown provides an excellent globe-wide assessment of the "falling water tables and shrinking harvests." Brown notes that "half of the world's people live in countries where water tables are falling as aquifers are being depleted." This decline in resources has begun to reduce crop harvests in the African countries, China, India, the Middle East and other regions. Water problems have begun to show their severity as well in the southwestern United States.

With wheat and rice as two of the world's largest staple crops, it seems daunting to think the production and irrigation of these crops can be changed to conserve water without largely disrupting crop yields. Plants require water to grow. So it is logical that massive agriculture productions require massive amounts of water. However, steps are being taken to begin treating water as a limited resource, and more specifically in regions such as northern India where precipitation and freshwater reserves have been historically regarded as abundant. If the Green Revolution introduced and implemented brand new agriculture techniques over a single decade, the onset of a successful “Blue Revolution” in the coming years is not only a necessary milestone, but a realistic one. Continuing water conservation research and the small scale testing of options such as rainwater harvesting and grey water re-use have and will continue to push this global issue to the front of both government and independent research agendas. The key in aiding any global problem in finding possible solutions is, put simply: increase awareness.

Please visit www.waterfootprint.org for updated research and publications on this issue.

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APPENDIX A. Soil Hydraulic Property Calculations

Total available moisture (TAC) in mm/m = Field Capacity (FC) – Wilting Point (WC)

FC = $0.27\ cm^3$ water/cm^3 soil

(Cube root (.27))*10^3 = 646.33 mm/m

WP = $0.16\ cm^3$ water/cm^3 soil

(Cube root (.16))*10^3 = 542.88 mm/m

TAC= 646.33 mm/m – 542.88 mm/m = 103.45 ≈ 100mm/m

Maximum rain infiltration rate (mm/day) = soil hydraulic conductivity at saturation

Average soil hyd. cond. at saturation of zones 2 and 3 = (.35 + .31) / 2 = .31 cm/hr

(.31cm/hr)*(24hr/day)*(10mm/cm) = 74.4mm/day ≈ 74mm/day

Max rooting depth (cm) = 60cm (Mishra, 1997)

Initial soil moisture depletion (%TAM): Default at 0% which represents fully wetted soil @ FC

Initial available soil moisture: automatically calculated by CROPWAT

Drainable porosity (DP) = Saturation (SAT) – Field Capacity (FC)

SAT = $0.48\ cm^3$ water/cm^3 soil

(Cube root (.48))*10^3 = 782.97 mm/m

DP= 782.97 mm/m – 646.33 mm/m = 136.64 mm/m

(136.64)*(10^3)*100 = 13.6% ≈ 14%

Critical depletion for puddle cracking: estimated from CROPWAT 'medium' soils data file
Max percolation rate after puddling (mm/day): automatically calculated by CROPWAT
Water availability at planting: "Not limiting factor." Estimated at 300cm (Mishra, 1997)
Max water depth (mm): Estimated at 600cm

APPENDIX B. Grey Water Footprint Calculations and Unit Conversions

$$WF_{proc,grey} = \frac{(\alpha \times AR)/(c_{\max} - c_{nat})}{Y}$$

Wheat:

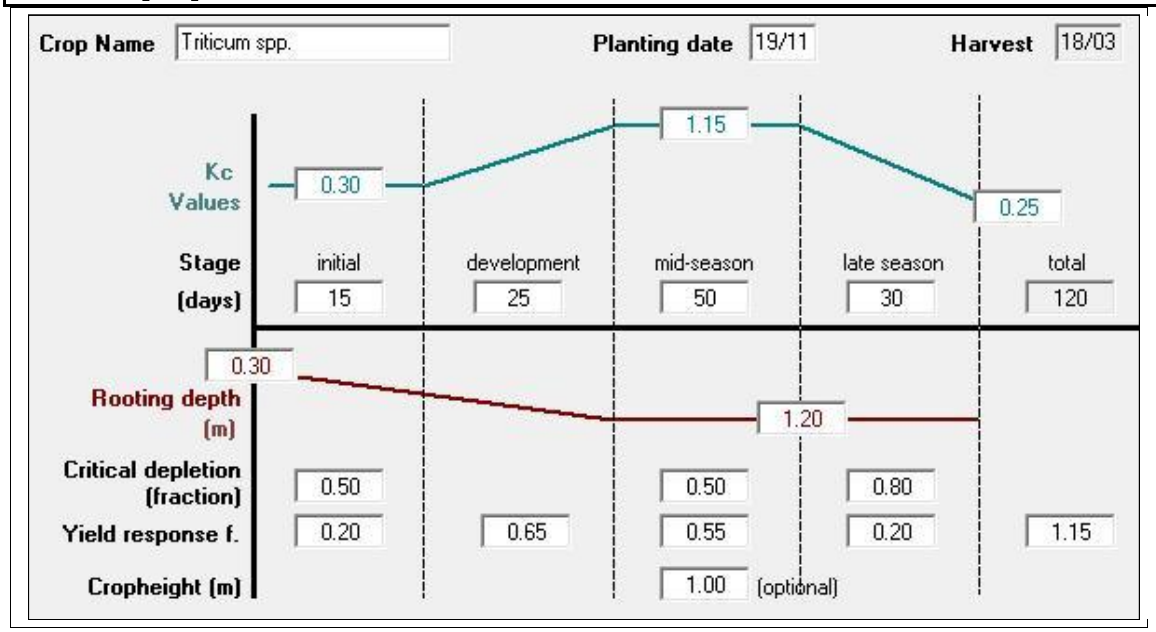
$WF_{proc,grey}$ = [(.10)*(143kg/ha) / (10mg/L – 0mg/L)] / 4.340ton/ha
= 0.32949 kg-L-ha/ha-mg-ton * ($1m^3/10^3L$)*(10^6mg/1kg) = 0.32949*10^3 m^3/ton
= 329.49 m^3/ton ≈ 330 m^3/ton

Rice:

$WF_{proc,grey}$ = [(.10)*(148kg/ha) / (10mg/L – 0mg/L)] / 3.941ton/ha
= 0.37545 kg-L-ha/ha-mg-ton * ($1m^3/10^3L$)*(10^6mg/1kg) = 0.37545*10^3 m^3/ton
= 375.45m^3/ton ≈ 380 m^3/ton

APPENDIX C. CROPWAT screen shots of wheat and rice showing acquired crop data.

Wheat crop input values



Rice crop input values