Assessing Energy and Water Footprints for Increasing Water Productivity in Rice Based Systems

R Tripathi, M Debnath, S Chatterjee, D Chatterjee, A Kumar, D Bhaduri, A Poonam, PK Nayak, M Shahid, BS Satpathy, BB Panda and AK Nayak

SUMMARY

Water is one of the important elements responsible for life on earth. Globally, three major sectors i.e. agriculture, domestic consumption and industry compete for water. India presently has the world's second largest population and there is a net export of agricultural products from India, which is likely to continue. These developments will lead to a larger water demand for the agricultural sector in near future. Water management is becoming a key issue affecting the availability and distribution of already scarce fresh water to growing population. The data regarding water usage and availability of water is not available which poses a challenge for sustainable management and development of water resources. Hence, measurement and quantification of the energy footprints, water footprints and water balance components are fundamental for understanding the hydrological behaviour of a system for effective water management. The objective of this chapter is to discuss the water footprints of rice in different cultivation practices in comparison to other crops and discussing the key challenges and issues related to the water management and water balance studies particularly in river basins of India and need for advance methodologies for studying water footprint, and energy balance components. Globally, water footprint of rice paddy production is 784 $km^3 yr^{-1}$ with an average of 1325 $m^3 t^{-1}$. The mean water footprint of cereals is about 1644 $m^3 t^{-1}$. Among them, the water footprint for millet is comparatively large (4478 $m^3 t^{-1}$), while for maize it is comparatively small (1222 $m^3 t^{-1}$). Water productivity differs with different cultivation systems and irrigation techniques, which is discussed. The mean water footprint of rice (1673 $m^3 t^{-1}$) is close to the average for all cereals together. In India there are about 20 river basins which are presently the source of surface and ground water for many sectors including the irrigation sector. There is a need to work out on the estimation of the water budget [illegible]er resources and Indian riverine system may face water scarcity situation in near future to come. In this chapter we have discussed the modern tools, techniques and models such as remote sensing, GIS and hydrological models (such as METRIC and SEBAL) which can be used for precise estimation of water budget components in these major river basins.

1. INTRODUCTION

Water is going to be one of the important issues concerning humanity in this century and coming years. The world is already facing a crisis of water supply in terms of both quantity and quality. Water is the most critical requirement of living organisms, and it affects human behaviour in a very significant way. Water is regarded as a gift of nature when available in plenty but becomes precious when its scarcity occurs. Water is also a source of dispute and even conflict between its different stakeholders and users. For 21st century, water management is becoming a key issue since growing pressures are negatively affecting the availability and distribution of already scarce fresh water to growing population. There are so many factors behind diminishing water resources such as expanding populations, economic growth, pollution and seasonal climatic conditions. Regular monitoring and forecasting the global water cycle using modern techniques is becoming increasingly important for efficient water management (Ray 2008).

Three major sectors i.e. agriculture, domestic consumption and industry are competiting for water. Globally and in most major river basins, the biggest volumes are withdrawn for irrigation purposes. Water use in agriculture is approximately 70% worldwide. While populations are increasing at a faster rate, the available fresh water resources are diminishing leading to greater scarcity. Precipitation is the major source of fresh water, which is stored temporarily in natural areas or in man-made reservoirs. Around 8% of the annual fresh water renewable resource is used, with 26% of evapotranspiration of water and 54% of runoff (Ray 2008).

1.1. Global fresh water availability and growing pressure

Even though two-thirds of the global surface is covered by water, only 2.5% is fresh water. This fresh water is not evenly distributed across the globe. Freshwater resources are shrinking more rapidly now compared to previous decades due to population explosion. Since 1970, world population has increased by 1.8 billion whereas per capita water availability worldwide is a one third now. From 1970 to 2000, freshwater usage by the agriculture increased by 175% which is consuming 70% of global fresh water. Only an extremely small portion of the 1.36 billion m^3 of global freshwater is available for use. Various complex processes like evaporation and rainfall between the sea and the land surface contribute very small quantities of freshwater, to the tune of 40,000 km^3 annually. Globally, in last 25 years, there is a decrease of 27 percent in per capita water availability; in 1970 it was 10,000 m^3 which declined to 7,300 m^3 in 1995. Countries are regarded as water-stressed when the per capita annual freshwater supply remains between 1,000 and 2,000 m^3 and water scarce when the supply falls below 1,000 m^3. In India, over the past 50 years, per capita availability of fresh water has declined from 3,000 m^3 to 1,123 m^3.

Loss of fresh-water due to high evaporation rates is critical in tropical and arid regions. In India, agriculture is mainly dominated by cereal crops such as rice and wheat, and yield of cereals is sensitive to changes in temperature. The projected temperature rise in the twenty-first century, therefore, will have serious implications for India where high evapotranspiration rate and rising temperature, have profound implications for freshwater management policies.

1.2. Fresh water withdrawal in India

Rainfall in India and sub-continental countries (Bhutan, Nepal, Bangladesh, and Pakistan), is limited to three or four months of the year. This monsoon rain also depends on the same riverine systems for freshwater. India currently withdraws a little more than 26% of the available freshwater which is far less than Pakistan, with its rate of 70%, is considered a high water stressed country. Whereas other South Asian countries are using more than 40% of their available water resources. The annual Indian evapotranspiration (ET) rate varies between 1,400 and 1,800 mm. It is highest in west Rajasthan, some parts of Karnataka, Andhra Pradesh, and Tamil Nadu. In some part of country, evaporation some time exceeds 1,800 mm.

With over a billion people, India presently has the world's second largest population and estimate of the population in the year 2050 is 1.7 billion. This is an increase of approximately 50% in population in the coming 50 years. There is a net export of agricultural produces from India, which has shown an increase in the past decade and this trend is likely to continue. These developments will lead to a larger demand in the total food grains production and ultimately more water for the agricultural sector in near future.

1.3. Knowledge gap

In most cases data regarding water usage and availability of water is not available which poses a challenge for sustainable management and development of water resources. Hence, measurement and quantification of the energy footprints, water footprints and water balance components is fundamental to understanding the hydrological behaviour of a system for effective water management. In the assessment of water resources and derivation of the water balance, it is important to understand the spatial and temporal dynamics of water footprints, the different components governing the surface energy balance such as evapotranspiration. This information is crucial for planning and development of water resources infrastructure and also agricultural planning. There is a strong need for studying the water and energy balance for integrated water management at river basin scale along with the water footprint of crops. Quantitative evaluation of water resources and their change on the basis of the water balance approach under the influence of human activities are possible if various components of hydrological cycle are studied. Additionally, decision making on water management issues are strengthened by water balance estimates.

Although small scale measurements of components of energy balance and Evapotranspiration (ET) measurements over a crop canopy are done usually by Lysimeters and Eddy Covariance approaches, large spatial scale measurements are still not available. However, estimations of actual ET on large spatial scales would be useful for many water resource applications including estimating agricultural water use and monitoring water rights compliance.

The objective of this chapter is to discuss the water footprints of rice in different cultivation practices in comparison to other crops and discussing the key challenges and issues related to the water management and water balance studies particularly in river basins of India and need for advance methodologies for studying water footprint, and energy balance components.

2. WATER FOOTPRINT CONCEPT AND CURRENT SCENARIO

Currently, the ratio of volume of consumptive water use to the quantity of produce of interest which is termed as water footprints may be used to indicate direct and indirect utilization/appropriation of fresh water resources. Both consumptive water uses i.e. the green and blue water footprints and the grey water footprint which is required to assimilate pollution may be used for fresh water appropriations. Lower water footprints from a management system indicate its efficiency to produce more biological yield or product with less amount of water. The water footprint of a product can be used to provide information to consumers about the water-related impacts of products they use or to give policy makers an idea of how much water is being "traded" through imports and exports of the product.

Some major determinants of the magnitude of the water footprint from any area are (Chapagain and Hoekstra 2004):

- the average consumption volume per capita, generally related to gross income
- the consumption pattern of the inhabitants
- climate, in particular evaporative demand
- agricultural practices

2.1. Water footprints in rice production system

There are two major systems of rice cultivation: low wetland and upland cultivation systems. Around 85% of the global rice harvest area is resulting from wetland systems and around 75% of rice production is obtained from irrigated wetland rice (Bouman et al., 2007). In Asia, paddy fields are generally prepared by tillage followed by puddling where the top soil is saturated and water remain stagnated during most of the crop growth period. Whereas, in the USA, Australia and Europe rice fields are dry and flooding is done later.

Chapagain and Hoekstra (2011) made a global assessment of the green, blue and grey water footprint of paddy, using a higher spatial resolution and local data on actual irrigation. They reported that water footprint of rice paddy production globally is 784 $km^3 yr^{-1}$ with an average of 1325 $m^3 t^{-1}$ (48% green, 44% blue, and 8% grey). They also observed that the ratio of green to blue water varies significantly over time and space. They estimated 1025 $m^3 t^{-1}$ of percolation in rice production. They reported that the green water fraction is significantly larger than the blue one in India, Vietnam, Indonesia, Thailand, Myanmar and the Philippines, whereas, in Pakistan and the USA the blue water footprint is four times higher than the green constituent and the virtual water flows which is related to rice trade internationally was 31 $km^3 yr^{-1}$. They also reported that rice products consumption in the European nations was accountable for evaporation of 2279 Mm^3 of water and polluted return flows of 178 Mm^3 across the globe, annually mainly in Thailand, India, Pakistan and the USA and the water footprint due to consumption of rice created moderately low stress on the water resources in India as compared to that in Pakistan and the USA.

The calculated mean water depth used in cultivation of rice in each of the 13 major rice-producing countries is presented in Table 1(Chapagain and Hoekstra 2011).

They calculated the total water use ($m^3 yr^{-1}$) for rice cultivation in each country by multiplying the national harvested area of crop ($ha\,yr^{-1}$) with the corresponding depth of water ($mm\,yr^{-1}$) used in rice fields. The water footprint of rice cultivation is thus calculated as the sum of water evaporated from the crop fields and the volume of water polluted in the process (Table 2)

2.2. Different Irrigation and tillage methods for reducing the water footprints of rice

Water plays a major role in global agriculture. Due to rising demand of water among various sectors, it is going to be a scarce commodity worldwide. Reduction of crop water footprint is therefore very much essential which can be achieved by lowering the crop water use from the crop fields. Work on improving the water productivity of crop by reducing amount of applied irrigation water, which in turn reduces the crop water footprint through adoption of various irrigation methodologies like alternate wetting and drying, mulching, micro irrigation, namely, drip, sub surface drip and sprinkler irrigation, are going on globally.

Table 1. Depth of water used in rice production ($mm\ yr^{-1}$) for the 13 major rice-producing countries for the period 2000–2004.

S.No.	Countries	Evaporation (green)	Evaporation(blue)	Pollution (grey)
1.	China	228	302	73
2.	India	314	241	34
3.	Indonesia	260	217	53
4.	Bangladesh	192	202	36
5.	Vietnam	139	92	58
6.	Thailand	252	149	31
7.	Myanmar	297	133	18
8.	Japan	219	258	39
9.	Philippines	277	139	26
10.	Brazil	260	220	20
11.	USA	168	618	75
12.	Korea, Rep.	232	253	55
13.	Pakistan	124	699	26

Table 2. Total national water footprint of rice production and percolation of water in the 13major rice-producing countries (billion m^3 yr^{-1}) for the period 2000–2004.

	National water footprint of rice production (evaporation + pollution)			
	Green	Blue	Grey	Total
China	65.2	86.5	20.8	172.5
India	136.3	104.5	14.7	255.5
Indonesia	30.3	25.3	6.1	61.7
Bangladesh	20.4	21.5	3.8	45.7
Vietnam	10.5	6.9	4.3	21.7
Thailand	25.2	15.0	3.1	43.3
Myanmar	19.1	8.5	1.1	28..8
Japan	3.7	4.4	0.7	8.8
Philippines	11.2	5.6	1.0	17.9
Brazil	8.8	7.4	0.7	16.8
USA	2.2	8.0	1.0	11.1
Korea, Rep.	2.4	2.6	0.6	5.6
Pakistan	2.9	16.3	0.6	19.9

It was found that the moderate alternate wetting and drying technique was able to increase grain yield by 6.1% to 15.2% and water productivity by 27% to 51% at the same time reducing the amount of irrigation water applied by 23.4% to 42.6% when it was compared with conventional irrigation practices (Yang et al. 2017). Alternate wetting and drying of paddy fields under the System of Rice Intensification (SRI) was found to be effective in increasing paddy yield by 78% with about 40% reduction in total amount of applied water for irrigation, which also reduced the costs of production compared to conventional continuous flooding (Sato and Uphoff 2007). Drip irrigation method was found more effective with SRI to minimize water losses and also to increase the rice yield based on field evaluation in India. It has been found that adoption of SRI along with drip irrigation with a dripper spacing of 20 cm with plant to plant spacing of 30 x 30 cm was able to give the highest net return (B:C ratio 3.23) with highest water productivity of 0.90 kg m^{-3} and highest water-energy productivity of 7.85 kg kW h^{-1} as compared to conventional paddy cultivation (0.16 kg m^{-3} and 1.02 kg kW h^{-1}, respectively) under continuous flooding (Rao et al. 2017).

A study conducted on winter wheat in Northern China showed that deficit irrigation reduced blue WF (by 38%) with an average yield reduction by 9% and increased irrigation efficiency by 5%. It was also reported that the organic or synthetic mulching practices reduced blue WF by 8% and 17%, respectively with the same yield level with an improvement in water use efficiency by 4% and 10%, respectively. It was also found that under the deficit subsurface drip irrigation (SDI) with organic mulching, irrigation efficiency decreased blue WF by 44% and increased it up to 45% from 36% as was found in case of sprinkler irrigation without mulching.

In a study, consumptive WF of different crops such as potato, maize, and tomato were studied. Data on four irrigation techniques viz. furrow, drip, sprinkler, and subsurface drip (SSD) with four irrigation strategies like full (FI), deficit (DI), supplementary (SI) and no irrigation were analyzed under different mulching treatments. Data from different countries were analyzed. Analysis revealed that water footprint (WF) was found to be reduced to 8–10%, 13%, 17–18%, and 28%, respectively under drip or subsurface drip irrigation, surface drip or subsurface drip with organic mulching, and surface drip or subsurface drip in combination with synthetic mulching, respectively as compared to the control (furrow irrigation, full irrigation, no mulching). They reported that the water footprint of growing a crop was the lowest under drip irrigation, followed by furrow irrigation, sprinkler irrigation and rain-fed condition. It was also observed that growing crops with sprinkler irrigation system gave the largest consumptive water footprints, followed by furrow irrigation, surface drip irrigation and subsurface drip irrigation. This study interestingly gave the finding that furrow irrigation was able to give less consumptive water footprint of crop as compared to the sprinkler irrigation system, though irrigation efficiency of sprinkler irrigation is higher than that of furrow irrigation.

2.3. Water footprint in different crops

In the past century the drawing of fresh water has been increased by 7 times due to increase in population pressure and industrialization. At present, the agriculture alone consumes around 85% of global blue water and 99% of global green plus blue water (Hoekstra and Mekonnen 2012). The variation of water footprint was found significant among crops and production regions. Crops having higher yield or biomass generally have a less water footprint as compared to the crops having lower yield and biomass. The mean global water footprint varied largely from sugar crops (197 $m^3 t^{-1}$), vegetables (322 $m^3 t^{-1}$), fodders (253 $m^3 t^{-1}$), roots and tubers (387 $m^3 t^{-1}$), fruits (967 $m^3 t^{-1}$), cereals (1644 $m^3 t^{-1}$), oil seed crops (2364 $m^3 t^{-1}$) and pulses (4055 $m^3 t^{-1}$). The mean water footprint of cereals is about 1644 $m^3 t^{-1}$. Among them, the water footprint for millet is comparatively large (4478 $m^3 t^{-1}$), while for maize it is comparatively small (1222 $m^3 t^{-1}$). The mean water footprint of rice (1673 $m^3 t^{-1}$) is close to the average for all cereals together (Fig.1). Crops like soybean, sorghum and cotton has larger water footprint than rice (Mekonnen and Hoekstra 2013).

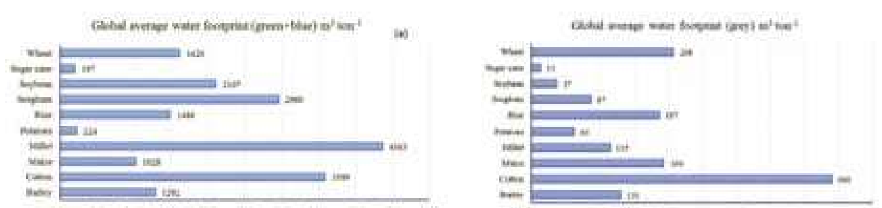

Fig. 1. Global average water footprint ($m^3 ton^{-1}$) (a) green+blue (b) grey (modified after Mekonnen and Hoekstra 2014).

Kar et al. (2014) has analyzed the water foot prints for maize crops, irrigated rice, rainfed rice and water footprints of some winter crops (maize, groundnut, sunflower, wheat, potato) grown in rice fallow in Odisha. They reported a higher yield by 59%, 29 %, 33-%, 58-%, and 19% in respective crops when three irrigations was applied and with four supplemental irrigation there was an increase of yield by 214%, 89%, 78%, 81% and 54%, respectively, for maize, groundnut, sunflower, wheat and potato over two irrigation. They also reported that water footprints of the crops were less when there was an increase in the crop yield at higher irrigation levels. They also estimated the water footprints of crops like lathyrus, black gram, pea and chickpea under various seeding or tillage methods in rainfed lowland rice fallow like relay (farmers' practice), one ploughing and sowing on same day, two ploughing in different days and sowing after second ploughing, zero tillage and conventional tillage. They reported a less blue water footprint under the tillage treatment, two ploughing in different days and sowing after second ploughing (5941, 6754, 6678, 8500 m^3ton^{-1} for lathyrus, black gram, pea and chick pea, respectively), whereas the water footprint was maximum under farmers' practice (298, 8657, 12833, 9850 and 15455 m^3ton^{-1} for lathyrus, black gram, pea and chick pea, respectively).

3. WAYS TO MINIMIZE THE WATER FOOTPRINTS UNDER DIFFERENT CROPPING SYSTEM

The crop evapotranspiration and thereby water foot prints in various crop production system can be minimized by minimizing irrigation water losses through adoption of modern scientific irrigation approaches like adoption of micro-irrigation technology, adoption of conservation agriculture like SRI technique of rice cultivation and mulching, precision land leveling techniques for uniform water application in field, and optimal use of fertilizer in fields in order to reduce the grey water foot print.

4. THE PROJECTED FUTURE WATER DEMAND FOR MAJOR RIVER BASINS OF INDIA

Different river basins have their reach in different states of India. Water demand in industrial and domestic sectors besides the irrigation sector is on a rising trend day by day. River basins are mainly the sources of water for all those sectors. Due to rising water demands from various sectors many river basins are going to be water scarce by 2050. It has been projected that several basins in India would deplete more than 60% of potentially utilizable water resources that will be available in 2050, and face acute water scarcities. Some of the major river basins like Indus and Ganga, will have as high as 0.07181 billion m^3 and 0.02425 billion m^3 deficit water supply for industrial and other sectors by 2050, whereas river basin like Mahanadi will be able to supply 20% and 33% less water as compared to water available in 2010 for industrial and other sectors due to a rising demand of water amongst various sectors (Gaur et al. 2011). This serious threat of water scarcity from various Indian river basins must be dealt with priority.

In India there are about 20 river basins which are presently the source of surface and ground water for many sectors including the irrigation sector. Among surface and ground water, the availability of surface water is highly seasonal, whereas the groundwater is a steady source of water throughout the year. In terms of water availability from the river basins which comprises both the surface water and the groundwater, groundwater constitutes on an average 50%, though inequalities exists across river basins. As per estimation from the Ganga river basin, the share of groundwater in the total water storage is about 64%, whereas, from basins like Krishna, Mahanadi, Subernarekha, and Narmada it is about 35% or less. At present irrigation sector in India is the most consumer of water from most of the river basins from India. Due to rise in population the water demands in industrial and domestic sectors besides the irrigation sector is increasing rapidly due to which many of the Indian river basins are becoming water scarce. It is going to be more serious in 2050 when Ganga and other river basins like Mahanadi and Pennar will also face severe water availability problems (Gaur et al. 2011). Estimating the water balance components on river basin scale will help in taking best water management measures especially in irrigation sector to combat the water scarcity situation at basin level.

5. EVAPOTRANSPIRATION IN DIFFERENT RIVER BASINS

Evapotranspiration (ET) percentage for Narmada, Godavari, Cauvery and Krishna basins, varies between 48.5 and 59.8% of precipitation. For these basins, overall ET value is 58.3%. For the trans-boundary basins, such as Indus, Ganga and Brahmaputra, ET is 23.1% of precipitation for Ganga and 71.7% for Indus basins. For these basins, overall ET is 17.6%.

5.1. Water balance studies: Current status and future scenario

Based on hydrological simulation of Mahanadi River Basin and impact assessment of Land Use and Land Cover (LULC) change on surface runoff generation through use of hydrological model, an increased pattern in the annual flow of stream by 4.53% was found in the Mahanadi river basin which was contributed to the reduction in forest cover by 5.71% (Dadhwal et al. 2010). Water budget components estimation on a point scale using basic water budgeting equation with the help of GIS was done in the Lower Yamuna Basin, Delhi. Based on water balance estimation, it was found in the study that all stations in the region are dry as the annual rainfall in the region remains short of annual potential evapotranspirative demands (Ahlawat 2014).

Water resource assessment of Narmada Basin, India was done by using the Variable Infiltration Capacity (VIC) hydrological model. It was observed that there was a substantial increase in evaporation component by 0.56% whereas with a decrease in runoff, base flow and stream discharge by 42.42%, 34.18% and 34%, respectively in year 2005 in comparison with year 1975 due to change in LULC because of construction of Indira Sagar Dam during the analysis period (Shiradhonkar 2015).

The water balance components of Chambal river basin using VIC model was estimated. It was observed that the land use and land cover, soil and slope characteristics were the main parameters influencing the hydrological processes in considerable manner. The annual runoff over the basin was 50% with a higher runoff from areas having less vegetation, higher slopes. The runoff was also found to be affected in considerable manner with respect to soil type and soil characteristics over the area.

Impact study of Climate Change on the Hydrology of Mahanadi river basin was done using Statistical Downscaling Model (SDSM). A decrease in precipitation pattern for the time period 2020s and 2080s annually and seasonally was found from downscaling of the precipitation in future scenarios through use of SDSM (Pandey 2015).

Impact of climate change on water balance in Krishna river basin was under taken where the water balance components were estimated using semi-distributed hydrological model namely Soil and Water Assessment Tool (SWAT). Based on climate projections estimated that in the period 2041-70 (2050s) there will be increase in the annual precipitation, surface runoff, water yield and actual evapotranspiration as compared to the baseline simulation period (1961-1990) whereas no substantial change for these parameters were observed by the model runs in 2020s (2011-2040).

The runoff, sediment and water balance components of Ken basin, India, were estimated using remote sensing derived products (SRTM DEM), gridded precipitation and temperature data (LANDSAT TM data), and using Soil and Water Assessment Tool (SWAT) within a geographic information system (GIS) modeling environment. It was found that evapotranspiration was more predominant which was around 44.6% of the average annual rainfall falling over the area whereas the stream runoff was 34.7% and deep aquifer recharge is 19.5% for the river basin (Himanshu et al. 2017).

5.2. Estimating the evapotranspiration

For studying the water balance over a river basin, the most important, challenging and variable component is the Evapotranspiration (ET) over the river basin.

Quite a few methods are used to measure or estimate ET, including hydrological approach, micrometeorological method and plant physiological approaches. Eddy covariance (EC) is the only direct and accurate measurement method which provides latent heat flux (LE) and sensible heat flux (H) as independent variables. Globally though works in this field has been done by researchers but literature availability on works related to eddy covariance method from India are rare. Eddy covariance method was used in Philippines for estimating the actual ET in direct-seeded rice field and it was observed that the average growing season ET rate varied from 4.13 to 4.36 mm d^{-1} in 2011 and 2012, respectively. They observed ET of growing rice in the range of 400–556 mm in Philippines. Timm et al. (2014) in Brazil reported that ET reached almost 7 mm d^{-1} at the end of the reproductive phase (flowering) of rice crop when leaf area index was at its peak (4.57 $m^2 m^{-2}$). Hatala et al. (2012), using the eddy covariance method, estimated daily evaporation up to 10 mm d^{-1} in a rice paddy field. In India, Tyagi et al. (2000) reported an ET of 587mm in rice through eddy covariance method, and the same was found to be 701mmthrough water balance approach.

5.3. ET measurements over spatial scales

Because it involves the transfer of large quantities of water away from earth's surface, the combined effects of evaporation from soil and leaves and transpiration from plants can have important implications for water resources. Small scale measurements of evapotranspiration (ET) are already prevalent and well-established. Eddy-covariance stations, for example, are frequently used to determine turbulent fluxes, representative of a relatively small surface area, up to hundreds of meters. Unfortunately, these measurements cannot be easily extrapolated over larger landscapes due to heterogeneities in land characteristics such as elevation, vegetation, and soil types (Choi et al. 2009).

A number of algorithms utilizing remote sensing to retrieve ET on a large scale have been developed. In addition to providing estimates for larger scales than in situ measurements, remote sensing is often inexpensive for the user to implement as many of the satellite platforms are developed by the government and data are freely available to the public. Two such operational ET modeling schemes include METRIC (Mapping Evapo Transpiration at high Resolution with Internalized Calibration) and the Fusion scheme made up of ALEXI (Atmosphere-Land EXchange Inverse model), DisALEXI (Disaggregated ALEXI) and STARFM (Spatial and Temporal Adaptive Reflectance Fusion Model).The basis for both the METRIC and Fusion modeling schemes is the surface energy balance.

6. ENERGY BALANCE OVER RIVER BASINS COVERING RICE CULTIVATION AREAS

Agro-ecosystem productivity rapidly responds to all the climatic variables like atmospheric temperature, precipitation, humidity, solar radiation, and photosynthetically active radiation (PAR). The formation of clouds and succeeding precipitation is dependent on the heat fluxes which are governed by incoming and outgoing radiations. The dynamics of heat fluxes are determined by the nature and type of vegetation covering the soil. Therefore, the determination of a correct energy balance (EB) mechanism is a crucial prerequisite to understand and model an agroecosystem and its interaction with the climatic variables, which is associated with the yield of the crop. Energy and mass transfer are two most important biophysical processes that influence the EB in an agroecosystem. The lowland river basins are mainly favoured for lowland rice and rice based cropping in eastern India. The lowland rice has a unique characteristic, since it grows under semi-aquatic environment or flooded environment. Such environment differs greatly from other upland based crop ecosystem since a continuous water layer is maintained above the soil surface which strongly influenced the surface EB components. Therefore, the exchange of carbon dioxide, methane, water vapour and energy in flooded rice ecology varies to a great extent and shows a close interrelationship between carbon cycle, hydrological cycle and energy balance. Such differential nature of rice cultivation may modify the surface runoff, groundwater storage, water cycle, surface energy budget and possibly the microclimate of the region.

Surface EB is mainly described by four types of energy fluxes, i.e. net radiation flux (Rn), sensible heat flux (H), latent heat flux (LE), and soil heat flux (G) approaching into or going out of the soil or water medium. The H is directed away from the surface throughout the daytime, while it is in opposite direction during the evening and nighttime. The LE is the result of evaporation and evapotranspiration at the surface. The Rn is a consequence of radiation balance at the surface, a resultant effect of upwell and downwell radiations. During the daytime, solar radiation is usually dominated and Rn is directed towards the surface of the soil, while vice-versa at nighttime. The G at the surface of soil was dissimilar with the soil beneath after certain depth, and the G at the surface achieved better closure.

6.1. Land characteristics influencing energy balance

The nature of soil and land plays an important role in the EB by influencing energy flux in the soil profile. These influences determine the change in soil temperature in the soil profile, which ultimately control microclimate of the crop-soil-water continuum. The thermal characteristic of soil varies with soil water content, maximum and minimum air temperature, porosity, vapour pressure, saturated vapour pressure and water vapour content. The ground surface gets heated more during the day by insolation than layers underneath, resulting in temperature gradient between the surface and subsoil on the one hand and surface and air layers near the ground on the other. Within the soil this causes heat flow downward as a thermal wave, the amplitude of which changes with depth. Estimation of soil heat flux (G) from the soil temperature data can provide an understanding of the gain or loss of heat by the soil from the atmosphere. The Bowen ratio method is an indirect method that has been widely applied and tested in various environments to characterize the land. This ratio describes the relationship between sensible (H) and latent heat (LE) fluxes and can be used as a measure of evapotranspiration including tall vegetation. Surface albedo is another important land characteristic which determines the surface energy budget and inuences the distribution of radiation energy in earth–atmosphere system and further regulates the atmospheric circulation patterns and hydrologic processes. It strongly depends on soil moisture and temperature (Zheng et al. 2014). Surface emissivity is a measure of the efficiency with which surfaces convert kinetic into radiant energy.

6.2. Estimating energy balance using a single eddy covariance system

A field experiment was conducted using a single eddy covariance (EC) system to study the surface energy budget and energy balance closure (EBC) in rice-rice ecology at ICAR-National Rice Research Institute, Cuttack (Unpublished). Due to the presence of standing water in the rice field, the average latent heat flux at surface and canopy height was higher than sensible heat flux at surface and canopy height, respectively. The average value of residual heat flux (R) was 10.3-12.0% higher in wet season compared to dry season. Soil temperature (Tg) was highest in dry fallow, while the skin temperature (Ts) was highest in dry season. Average Bowen ratio (B) ranged from 0.21-0.60 and large variation in B was observed during the fallow periods as compared to the cropping seasons. The magnitude of aerodynamic, canopy and climatological resistances increased with progress of cropping season was found smallest during the fallow period. The actual evapotranspiration (ET_a) measured during both the cropping seasons was higher than the fallow period.

6.3. Remote sensing for energy balance studies

Satellite technologies are now helpful in quantifying the radiation and energy exchanges between sun, earth, and space. Nevertheless, satellites cannot directly measure the magnitude of the energy flows within the atmosphere and at the Earth's surface. Evapotranspiration is the most difficult hydrological flux to estimate or model especially at regional or global scales for assessing the water resource base. Evapotranspiration estimation based on weighing lysimeter, Energy Balance Bowen Ratio (EBBR), eddy covariance techniques, pan-measurement, sap flow, scintillometer, etc. are mainly based on complex models and equations. Moreover, these methods are variable for local, field, and regional scales. These conventional methods can provide the accurate estimates of ET over a homogeneous area. But natural heterogeneity of the land surface and complexity of hydrologic processes do_not favor upscaling of such measurements. Remotely sensed images are a promising source of data for mapping regional- and meso-scale patterns of ET on the Earth's surface. Remote sensing images with visible, nearinfrared, and thermal infrared bands are used to retrieve the land surface temperature. These surface parameters estimated from satellite data are used for simulating surface fluxes and ET.

6.4. Advantages of space technologies for energy and water balance studies

Remote sensing data presents an interesting opportunity as it allows for the quantification of key water balance components such as evapotranspiration. Space technology applications have begun to permeate many aspects of life in our modern societies. A growing number of activities–weather forecasting, global communications and broadcasting, disaster prevention and relief–increasingly depend on the unobtrusive utilisation of these technologies. The main advantages of using satellites are summarised by Payne et al. (2006). Satellite data may be collected year-round and can provide information when field data collection is not possible, due to remote locations or bad weather conditions. This method also reduces cost when compared to traditional field data collection methods in remote environments (landcover classification for example). Remote sensing may be an option for supplementing more intensive sampling efforts and help extrapolate findings. It is also possible to measure elements of the global water cycle using diverse space-based systems. The estimated residence time for water range from one week (*e.g.* biospheric water) to 10,000 years (e.g. ground water) – hence the need for reactive, timely and long-term observations.

6.5. Limitations of remote sensing for energy balance studies

Uncertainties in the radiance measurement caused by atmosphere require the corrections for the atmospheric effects. There is requirement of increasing accuracy of some land surface variables derived from remote sensing images for increasing the accuracy of ET estimation. It's very difficult to estimate the surface parameters such as surface temperature from heterogeneous surfaces compared to homogeneous well-watered vegetative surfaces. Differences in received radiances will occur due to the differing amounts of soil and vegetation in the field of view when sensor viewing changes from one angle to another.

Different models are used for different land surface characteristics. However, till date, there is no universal model, which could be used throughout the world irrespective of the changes in land surface characteristics, in the climate and terrain without any modification or improvement to estimate the ET from satellite data. Meteorological data which are collected at near-surface height required in most of the ET models. These meteorological parameters are estimated at a satellite pixel interpolation. Accuracy of the interpolation methods are required to be improved while using the data for different climate and terrain conditions.

Nocturnal transpiration and dew may also affect significantly the ET estimation. Nocturnal transpiration has been widely observed using sap-flow and gas exchange measurements with ratios of night-time to day-time transpiration as large as 25% being reported (Dawson et al. 2007). If nocturnal transpiration occurs at sites with high LAI, this process could be an important source of error in remote sensing based ET estimation because of its association with nocturnal vapor pressure difference and wind speed. Adversely, at sites with low LAI, this process will tend to reduce this source of error so that it may be ignored when considering daily TIR-based estimates of ET.

7. WAY AHEAD AND FUTURE WORK SCOPE

To check the decline of surface and ground water resources in India it is highly essential to adopt suitable agricultural techniques and agricultural management practices for yield maximisation with less consumption of water. At present there is a need for prioritising the appropriation of fresh water resources to different components or crop production system, domestic and industrial sector to produce a particular product or to complete one process requiring water from a particular management system. The appropriation of water among different sectors or different crop production systems is very difficult unless there are some sound methods or indices for quantifying the water requirement from this production system.

There is a need to work out on the estimation of the water budget components of the basin to go for proper utilization of water resources as water resources and Indian riverine system may face water scarcity situation in near future to come. Remote sensing, GIS and hydrological models are the modern tools that can be used for precise estimation of water budget components in these river basins. As part of the National Communication (NATCOM) project by the Ministry of Environment and Forests, impact of the climate change on the water resources of Indian river systems was quantified and the initial analysis revealed severity of droughts and intensity of floods in various parts of the country may get deteriorated. Governments must increasingly ensure that farmers use water resources efficiently, and that they are allocated among competing demands in a way that enables farmers to produce food and fibre, minimise pollution and support ecosystems, while meeting social aspirations. Also, the government should ensure the internal water-sharing issues based on sound, internationally accepted principles. A failure to do so would create internal water-related conflicts.

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