# Water Resources Analysis of the Hai Basin in 2003 and Implications for Water Management

# DRAFT FINAL REPORT

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## Table of Contents

## Executive Summary

The Hai Basin, in P.R. China, is experiencing groundwater overdraft, resulting in dropping groundwater levels and water shortage. The water balance shows a non-sustainable situation, with more water leaving the area than water coming into the area. Rivers in the Hai Basin barely have outflow to the Bohai sea, and most of the water leafs the area through evapotranspiration.

Although much information is available on agricultural water consumption of individual fields, the water consumption on basin level is often difficult to estimate. In the current study, the evapotranspiration for the Hai Basin in 2003 is calculated using remote sensing measurements (SEBAL). The water balance for 2003 is then evaluated, and a water savings scenario is calculated through a water balance model (SWAT).

After the basin evapotranspiration was calculated, a subsequent analysis is applied to find solutions to change the non-sustainable situation of groundwater overdraft into a sustainable situation. There are only two options, namely to increase the water resources (e.g. a South to North water transfer across water basins), or to reduce water consumption. This study focuses on the potential of water savings.

The agricultural year is divided into two separate parts, based on the two major crops grown in the area. A winter crop, wheat, growing from October 1 to June 15, and a summer crop, maize, growing from June 16 to September 30. Most of the rainfall occurs during the summer crop. Irrigation is mainly applied to the winter crop during the months March, April, May and June.

In this study, 27 MODIS daily images were used to calculate the evapotranspiration and biomass production on a per-pixel basis. This shows the spatial distribution over the Hai Basin. Most of the evapotranspiration occurs in the lower plane covering about half of the Hai Basin area, where the focus of agriculture lays. Another area of high water consumption is found in the mountains surrounding the lower plane, in the forests covering these mountains.

To facilitate water management implementation, results are presented on a per-county basis. A comparison between available rainfall and actual evapotranspiration in 2003 shows that the northern part of the Hai basin has a structural water shortage during the whole year, while there is at least a temporal water shortage during the irrigation season in a V-shaped area in the low plain. One arm of the V shape follows the foot of the mountains surrounding the plain, while the other arm of the V follows the southern border of the Hai Basin boundary. This V-shape also describes the area where an intensive wheat crop is found during the winter.

The analysis of the water balance shows that in 2003, a total rainfall of 603 mm (192 km$^3$) was measured over the Hai Basin using radar and satellites (TRMM; Tropical Rainfall Measurement Mission), while a total evapotranspiration (ET) of 589 mm (188 km$^3$) was calculated using SEBAL. This results in an excess of water of 14 mm (4 km$^3$) in 2003. However, spatial and temporal water shortages still existed within the basin in 2003. The long term average rainfall for the area is usually assumed to be 550 mm (175 km$^3$). This year with average rainfall would result in a structural deficit of at least 40 mm, or 13 km$^3$.

To reduce 13 km$^3$ of ET, the potential of improving crop management, as well as improving agricultural (manageable) fields without intensive agriculture are evaluated. It is not possible to save this total volume of water through a better management of the wheat crop. The wheat crop consumes 25 $km^3$ and should be completely eliminated to reach this goal. Not growing wheat will result in a potential saving of approximately 50-60 % of the consumed water, since fallow fields will also have evaporative losses (200 mm based on the 2003 analysis). A total elimination of the wheat crop would socio-economical be likely unacceptable. A better management of the non-intensive agricultural fields during the winter period, which currently contribute to a evaporative loss of 21 $km^3$, would be more beneficial and result in less crop yield loss than the elimination of a wheat crop. Better management of fallow fields would include mulching, zero-tillage and low-cost greenhouses.

The maize crop uses 38 $km^3$ of water (consumptive use). Improved crop management (achieving higher crop water productivity) would contribute to the water savings, but would mainly result in larger recharges to the groundwater than to less extraction of groundwater, since rainfall during most of the maize season is sufficient to fulfill the evaporative demand for the summer crop. The fallow land and non-intensive agriculture during the summer currently uses only 8 $km^3$ and it is estimated that not much water can be saved from improved management during the rainy season on these fields.

Improving crop management for wheat and maize is evaluated using the crop water productivity index (cwp). This index represents the amount of biomass produced per unit volume water. This index can be compared within the basin, but also with other similar areas in the world. Improving the cwp of wheat and maize in the Hai Basin to the current average value would result in water savings of 3 $km^3$ annually, while improving the regional cwp to the currently maximum cwp in the Hai Basin for wheat and maize would result in water savings of 8 $km^3$.

The recommendations of this study are to reduce evaporative losses from fallow fields and low intensity agriculture fields during the winter wheat season in the areas indicated in figure 27 in red. It is also recommended to improve the crop water productivity of maize in the areas indicated in Figure 26 in red. These improvements will achieve a reduction of the water shortage, but will likely not be enough to reach a sustainable and ecological healthy situation. An additional influx of water through a South-North transfer could supply additional water resources. Reduction or elimination of intensive agriculture (wheat or maize) would be sufficient to reduce the water balance to a sustainable level, but would results in a decrease of crop yield and subsequently a reduction in farm income.

# 1. Introduction

## 1.1 Background

The Global Environment Fund (GEF) project on Integrated Water and Environment Planning and Management in China is a World Bank initiative that integrates the knowledge on hydrology present at the Ministry of Water Resources with the environmental data of the State Environmental Protection Agency (SEPA). The major aims are the introduction of water conservation techniques, temper groundwater over-exploitation and decrease environmental degradation in the North China Plain.

The Hai River Basin is one of the seven river basins that flow into the Bohai Sea, and is one of Asia's major problem areas; it has physical water shortages and serious pollution problems. The root cause of ecological decline in the shallow semi-enclosed Bohai Sea is the uncontrolled pollutant discharges from the main tributaries to the Bohai Sea and the reduction in total volume of freshwater reaching the Sea. Most surface water resources are utilized and the basin is virtually closed for a large part of the year. The South-to-North Water Diversion Project is now under construction, and this inter basin transfer project is expected to reduce water shortages in the Hai Basin and diminish flood risks in the lower end of the Yellow river.

Untreated sewage water flows currently in large quantities into the Bo Hai Sea, and this has detrimental effects on the water quality in the coastal belt. The low stream flow causes water quality deterioration throughout most natural streams. Besides the enormous South-to-North water transfers, a short term solution to the scarcity of surface water resources is the acceptance of groundwater exploitation. As a result, fast declinations of the groundwater table occur and aquifers are over-drafted already. Urgent actions are required to change the hydrological situation in the basin, otherwise a living place of some 120 million people can not be longer ensured. A well conceived longer-term water resources management strategy needs to be implemented as soon as possible.

The technical staff of the Project Management Office (PMO), containing representatives of the Ministry of Water Resources and State Environmental Protection Agency (which is a truly collaborative effort to bring water and environmental issues under one umbrella), has to prepare a *desirable* water balance that meet the environmental requirements (maintain streamflow, sufficient outflow to Bohai sea, sustainable groundwater extractions etc.). Such *desirable* water balance can deviate substantially from the *actual* water balance. One of the big uncertainties in any regional scale water balance is the discrete spatial data on evapotranspiration (ET). Despite that many water policy makers recognize the need to understand the hydrological cycle, prior to decision making and water allocation, the same policy makers hardly invest scientifically and economically in techniques to obtain the spatially distributed water balance with sufficient confidence. As a consequence, the water flows, even under water scarce conditions, are not properly understood.

This study quantifies the water balance of the Hai Basin and lower reaches of the Yellow River by making use of advanced remote sensing and GIS technologies. With a better understanding of the *actual* conditions, the *desirable* hydrological conditions can be planned better.

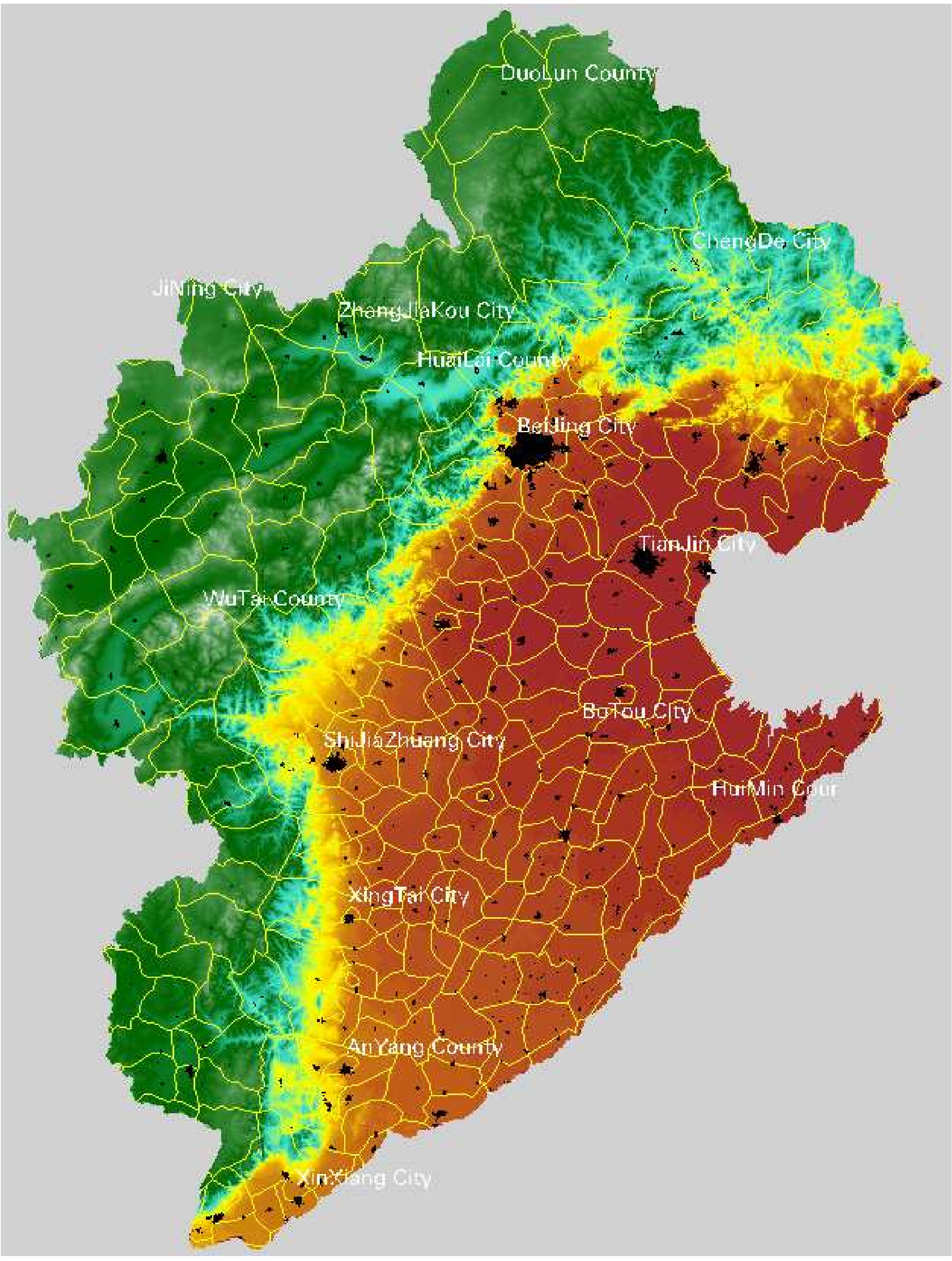

**Figure 1: Topographic map of the Hai Basin with the shapes of the administrative counties superimposed**

In an earlier study in conjunction with the GEF project, WaterWatch has used remote sensing data to obtain the actual evapotranspiration for 2002. This data has been transferred to PMO. PMO has requested WaterWatch to aid with the interpretation of the data, and to get also the data of a second year, because hydrological planning cannot be done on a single year. The current study has therefore the following aims:

1. Provide the PMO with the hydrological data of 2003 as a complement to the 2002 data series
2. Support the PMO with the interpretation of the actual water balance data and comparison with conventional hydrological reports

By execution of the current 'interim-study', the planning for the future water resources can be sped up, and earlier action plans to reduce the water use can be devised. The action plan to save water is no part of this interim project. This project focuses on remote sensing and GIS techniques to identify how the current water resources are depleted and to identify and quantify the various water balance terms.

## 1.2 Problem Description

Under semi-arid and arid conditions ($P/ET_{ref} < 1$), land use development is constraint by sufficient amount of fresh water resources. Fig. 2 depicts the climatological wetness for a part of East Asia. Fig. 2 shows that $P/ET_{ref} \sim 0.4$ in the Hai Basin, hence there is per definition not enough water supply to meet the ET demands on an annual time scale. This implies that not all land can be cultivated and cropped, or that additional water resources should be developed, e.g. groundwater exploitation, inter-basin water transfer or desalinisation of sea water. In the Hai Basin, groundwater over-exploitation is the current solution to meet the high ET demands of irrigated crops.

Under actual hydrological conditions, and especially when rainfall is a limiting factor, actual evapotranspiration ($ET_{act}$) must be lower than $ET_{ref}$. $ET_{act}$ not only should be lower than $ET_{ref}$, it should as an average value for the basin also fulfill the condition that $ET_{act} < P$. If more water is consumed than being supplemented by rainfall ($ET_{act} > P$), sustainability is at threat. This is a highly undesirable situation, because groundwater resources should be tapped only during dry years to compensate for the shortage of surface water resources. Groundwater should not be pumped under ordinary weather conditions. In wet years, rainfall surplus should (artificially) recharge the groundwater system and in dry years, this groundwater should be recovered through pumping. Some rainfall should be allocated to refill aquifers, if so required (see Fig. 3).

The Hai and Yellow River Basins requires an environmental water demand for generating sufficient runoff and outflow from the basin with acceptable concentrations of solutes, suspending matter, heavy metals etc. The subtraction between $P_{net}$ and environmental demand can be used for comprehensive ET. Comprehensive ET comprises all different sources that contribute to ET, such as from crops, forests, bushland, open water bodies, fallow land, desert, build up areas etc. Not all these ET processes can be managed, so it makes sense to discern manageable from non-manageable ET. The part that is non-manageable is the ET from forests, wetlands and other land uses that are committed for environmental conservation. Apart from deforestation, ET from forested catchments in the upper end of river basins can hardly be managed by mankind. The remaining utilizable water resources are after urban and industrial water usage, mainly allocated for manageable ET in cropped and other rural areas. This exemplifies the need to shift from *water supply based* water management, to *water use based* management practices.

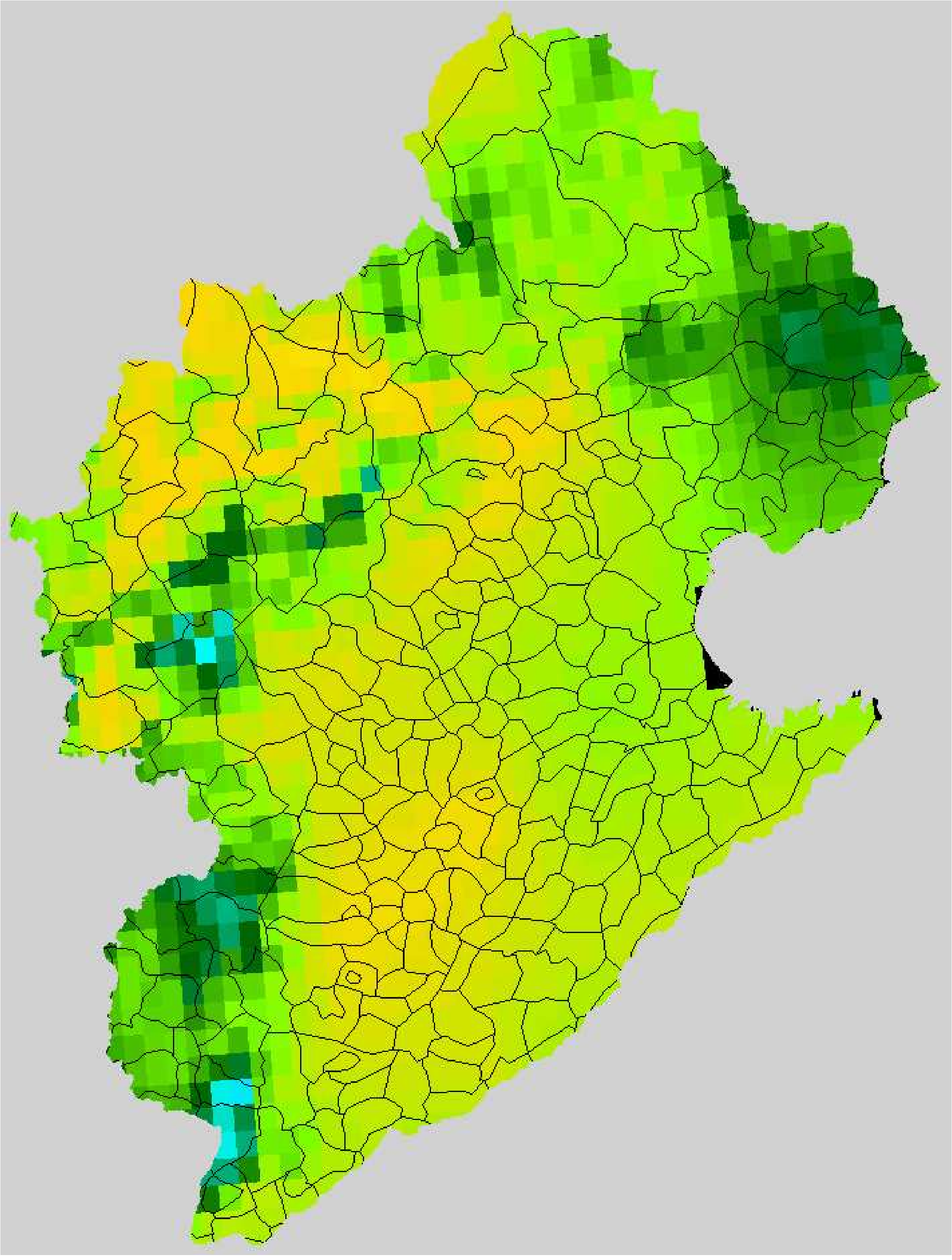

**Figure 2: Climatological wetness over the Hai Basin and lower reaches of the Yellow River expressed as the ratio of average rainfall (P50) and average reference ET according to Penman-Monteith (FAO Irrigation and Drainage Paper no. 56)**

The innovative aspect of real water savings is that the comprehensive ET diminishes and more water remains in the basin for bringing it to intended processes. Improving irrigation system efficiencies and reductions in irrigation water application, does not necessarily help (as often thought). Reducing irrigation water supply will cut off the field scale percolation rates, but the impact

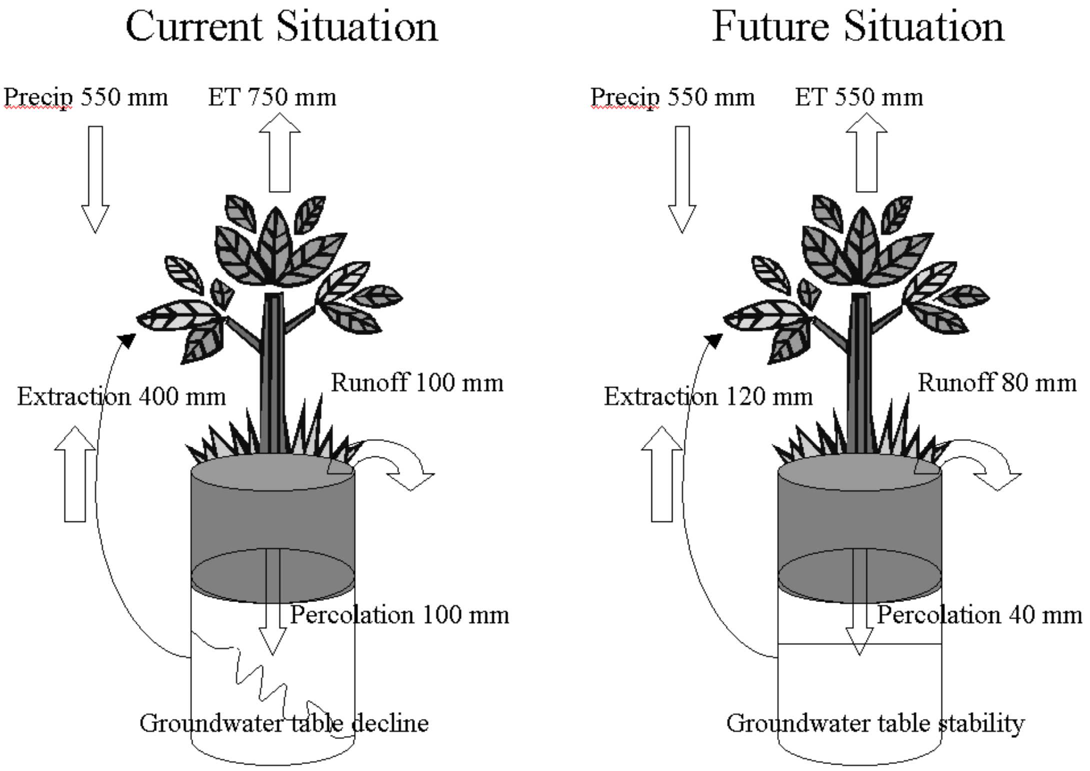

**Figure 3: Good water management practices (right) allocate rainfall to a ceiling of manageable ET and sustains the hydrological systems at basin scale.**

on ET is often minimal. Reduced groundwater extractions for irrigation supply and lower recharge – as a result - compensate each other and it is very well possible that reduction in ET is not achieved at all (this holds true especially in cases were over-irrigation takes place) if less water is irrigated. Reducing irrigation water is sometimes referred to as 'dry savings'[1] . On the contrary 'wet savings' are obtained if ET is reduced. There are two major obstacles for achieving real water savings:

1. The water flows (including all return flows) in a basin are poorly understood, and it is uncertain whether a given water conservation program is a 'dry' or a 'wet' saving
2. There is a need to quantify and monitor the spatial distribution of $ET_{act}$ for heterogeneous landscapes to understand (a) real water savings and (b) assess over-exploitation of groundwater systems

Water rights describe traditionally a certain volume of water that can be diverted from a river of extracted from a groundwater system. This is a typically supply based philosophy. The revolution under the GEF project is to shift from an approach based on limiting *supply* to limiting *consumption*. Less ET will leave more surface water resources in the streams. Less ET will also reduce the reliance on valuable groundwater resources.

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[1] This terminology has been introduced by David Seckler in his address 'The new era of water resources management; from "dry" to "wet" water savings' to the Consultative Group on International Agricultural Research (CGIAR), 1996

## 2. SEBAL Approach and Methodology

### 2.1 Methodology

Satellites measure spectral radiance that is reflected and emitted from the earth surface. Complex physical models have been developed in the last decade that convert these radiances into turbulent heat fluxes. Most of these remote sensing flux algorithms are based on measuring the radiation temperature of the evaporating land surface. Because of evaporative cooling, moist surfaces are colder and the surface temperature therefore is an indirect expression of ET.

One of the heat fluxes is the energy consumed by $ET_{act}$, i.e. the real ET originating from vegetation, soil, water, build-up areas etc. The advantage of using satellite-based information is that ET as one of the most complex hydrological process is directly obtained from satellite measurements. The Surface Energy Balance for Land (SEBAL) developed and intellectually owned by WaterWatch is the world leading model to compute ET for every thinkable agro-ecosystem. SEBAL has been tried and applied in 32 countries worldwide.

Consumptive use of agricultural land will result into agricultural production, food for the own villages and farmer income. Over against that, Non-Beneficial evaporation from fallow land, cities, weeds and waste land with shallow water table is a real loss of water resources that does not yield to any product or value. Evaporation from forests, woodlands and homesteads are associated to be beneficial for keeping environments preserved. It is therefore crucial to distinguish and quantify the ET into Consumptive Use, Beneficial ET and Non-Beneficial ET.

For achievement ET reductions, it is from a productivity point of view most valuable to focus on reducing the Non-Beneficial ET. Since Beneficial ET is directly related to environmental protection (mitigation of soil erosion, carbon sequestration, providing shadow in rural living communities) and this group of ET users are found often in mountainous areas, ET reduction in this group is complex to realize (hills are green because there are windward rains). However, there are several technical opportunities to reduce the Consumptive Use in irrigated agriculture. Real water savings in irrigated agriculture can be achieved by:

i. Reducing the ET for a given land use and crop type class by inducing crop water stress
ii. Land use/cropping pattern adjustments

The scope of item (i) can be studied by monitoring the ET depletion by various land use classes.

### 2.2 Water balance

Rainfall (P) has been collected from satellites (TRMM) and the ET data came from satellites using the SEBAL technology. It should be noted that part of the rainfall is intercepted by wet leaves, and that these droplets evaporate directly into the atmosphere. This implies that the gross rainfall need to be corrected for an interception term. If in a given period the rainfall surplus ($P-ET_{act}$) is positive, excess water will either runoff or percolate to the deeper underground. The runoff is featured into a fast component (i.e. when the infiltration capacity of the soil limits the water to enter the soil matrix or when the terrain is sloping) and a slow component (i.e. drainage of groundwater into a surface water network).

When in a certain decade the rainfall surplus (P-$ET_{act}$) is negative, water for evaporation is withdrawn from either irrigation canals or from groundwater resources. It should be noted, that most of the irrigation activities in the North China Plain are based on groundwater resources, so the magnitude of surface water resources is expected to be less than 30%.

## 2.3 Deliverables

- Monthly values of the comprehensive ET and biomass production for the year 2003 on the basis of MODIS satellite data and the SEBAL model
- ET for all land use classes, including various agricultural, forest, ecological and urban system to support integrated land en water use planning
- Categorized Consumptive Use, Beneficial ET and Non-Beneficial ET to support the framework of water productivity analysis
- Distributed water balance, including rainfall, ET, irrigation, runoff, recharge and groundwater extraction. This balance will be the prime basis for identification of the areas with aquifer overexploitation
- Transfer, explanation and interpretation of results to the Ministry of Water Resources and the Hai Basin Commission in Tianjin during a two-week period in Fall 2005
- Identify gaps in the field and hydrological knowledge and data collection and initiate a research program with Ministries and Universities that deepens the missing knowledge

## 3. SEBAL Results

Figure 4 shows the monthly totals for the evapotranspiration (SEBAL), compared with the monthly rainfall (TRMM) as an average for the Hai Basin in 2003. It can be seen from this figure that there is more ET than precipitation in the period from December to June, and September. The period from December to June is a period that much groundwater extraction takes place for supplemental irrigation of the wheat crop. The precipitation in October 2003 is higher than average, possibly the reason that the annual total rainfall is approximately 50 mm higher than an average year.

The maize crop is planted around the 15th of June, which is followed by a period of higher rainfall than evapotranspiration. During this period, there is an opportunity for groundwater recharge. It should be noted, however, that spatial differences within the Hai Basin still exist.

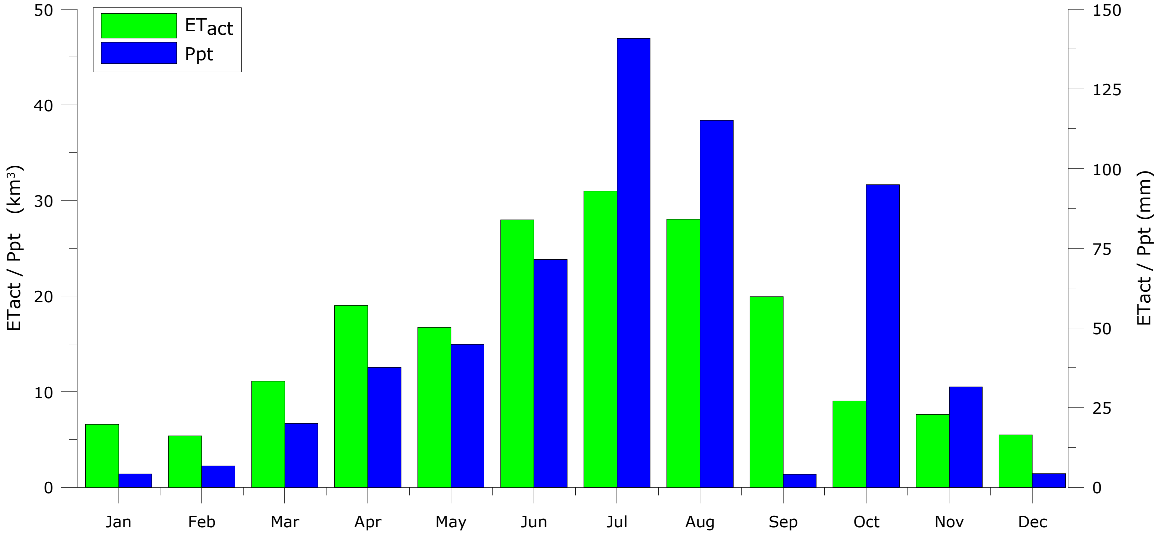

**Figure 4: Actual evapotranspiration (SEBAL calculated) and rainfall measurements (TRMM Measured) for the Hai Basin in 2003.**

The energy balance is the driving force behind the SEBAL calculations. Figure 5 shows the monthly net radiation in the Hai Basin. The months of January and December show a negative net radiation, caused by a high reflectance due to snow cover, as well as a loss of long-wave radiation during this period. In the energy balance, the net radiation is the available energy for sensible heat flux, soil heat flux and latent energy flux (Figure 6). The latent energy flux is the part of the energy balance that SEBAL obtains. It is interesting to see that the sensible heat flux in May is higher than during other months. This is likely the result of a high net radiation, and the end of the wheat season, when the crop is maturing and irrigation is not applied any more. This results in a decrease of latent energy, and an increase in sensible heat.

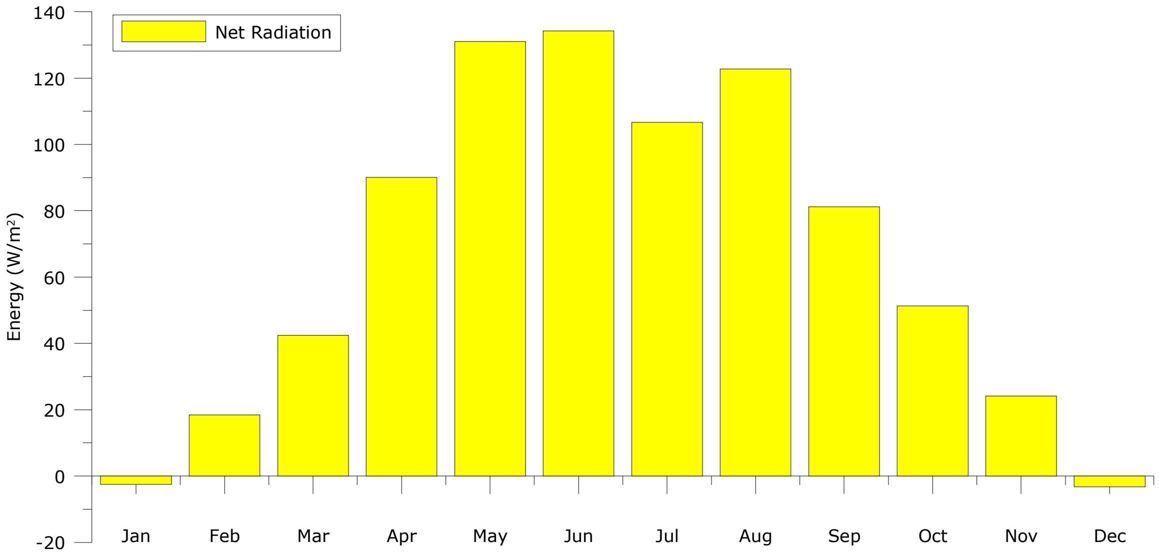

**Figure 5: Spatial average (318,600 km$^3$) net radiation per month for Hai Basin on the basis of actual cloud cover conditions in 2003.**

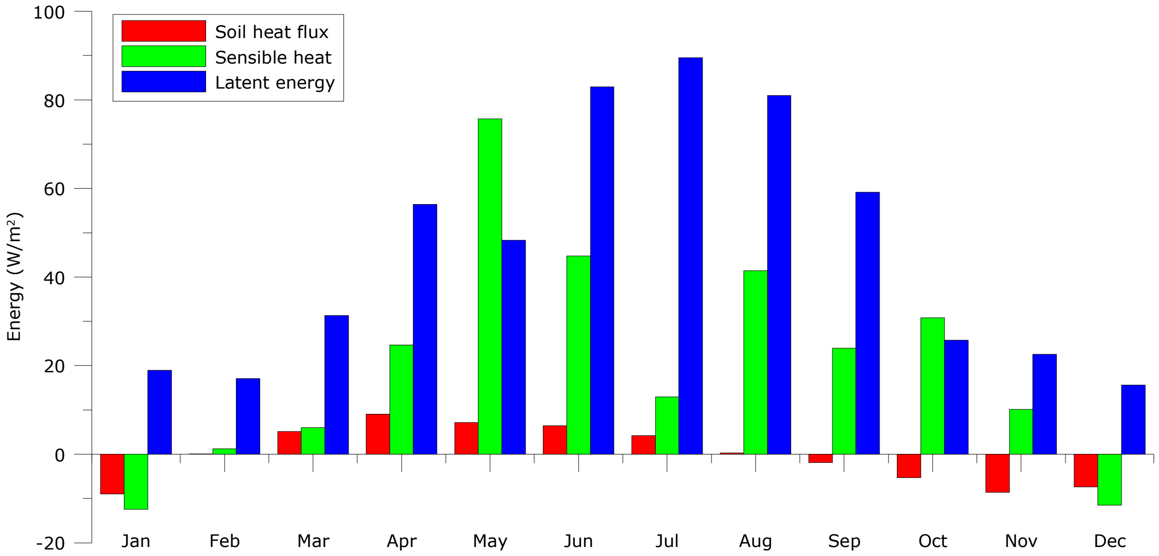

**Figure 6: Spatial average (318,600 km$^3$) Energy Balance components per month for Hai Basin in 2003.**

The monthly average values for the Hai Basin do not give any information on the spatial distribution of evapotranspiration, rainfall and other energy balance components. However, the SEBAL model calculates the energy balance for each pixel of the satellite images (250 x 250 m). Figure 7 shows the results for the annual Etact for the Hai Basin. The low plain, shown with brown colors in Figure 1, clearly shows as a water consumer, indicating a high density of agriculture. The higher plains and valleys show annual ET values below 500 mm, while some of the forests on the southern slopes show some spots of high evapotranspiration. An increase of evapotranspiration can be noticed towards the south border of the Hai basin. Near the southern border of the basin is the Yellow River, possibly providing an area with more water supply than in the northern part of the lower Hai plane. The V-shape showing in the southern part of the Hai plane can also be observed in Figure 8. In this figure, the biomass production from October 1 to

June 15 is shown. This is the period where the main crop cultivated is winter wheat. The V-shape showing in the biomass production indicates where the highest density of winter wheat is grown.

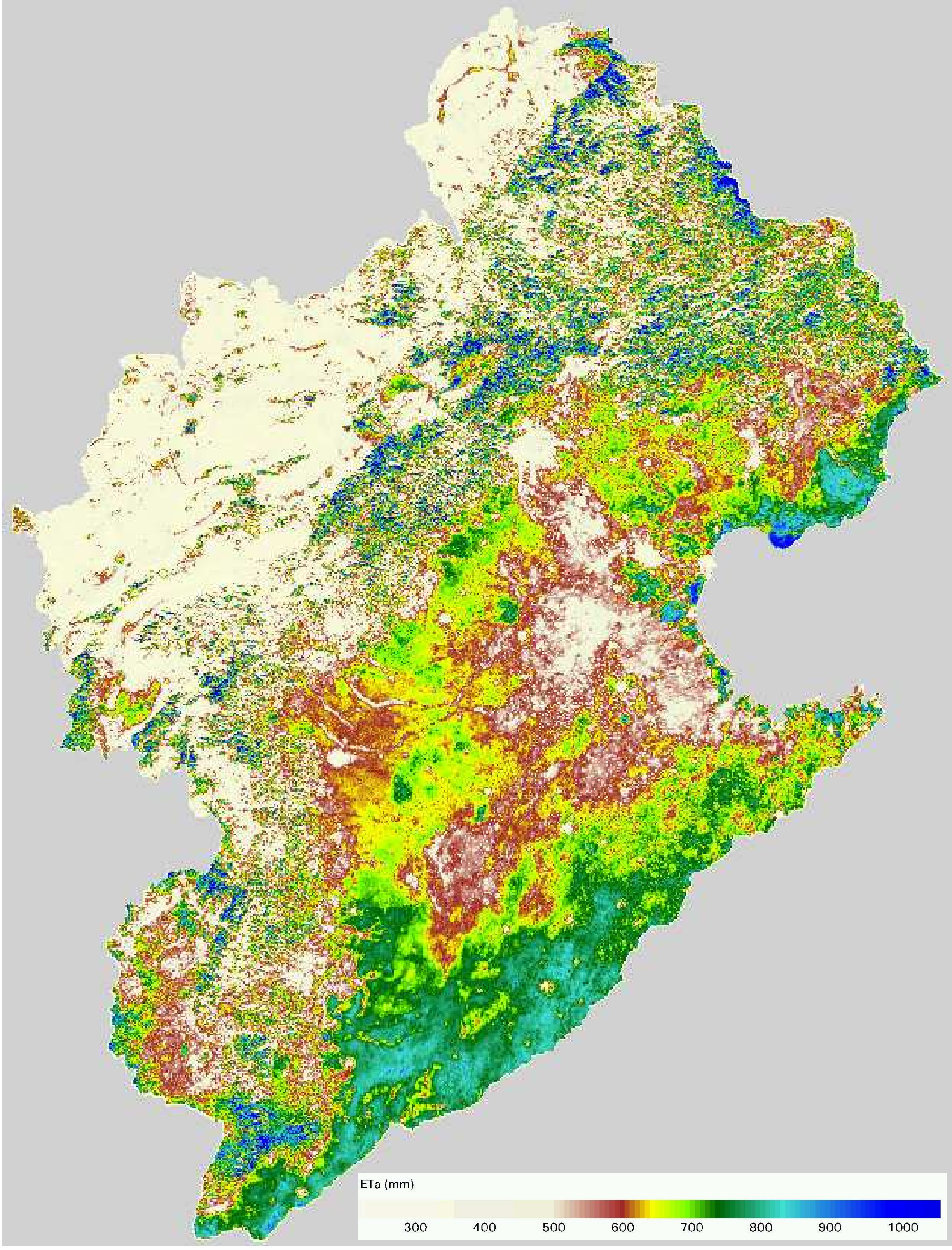

**Figure 7: Annual $ET_{act}$ for Hai Basin in 2003**

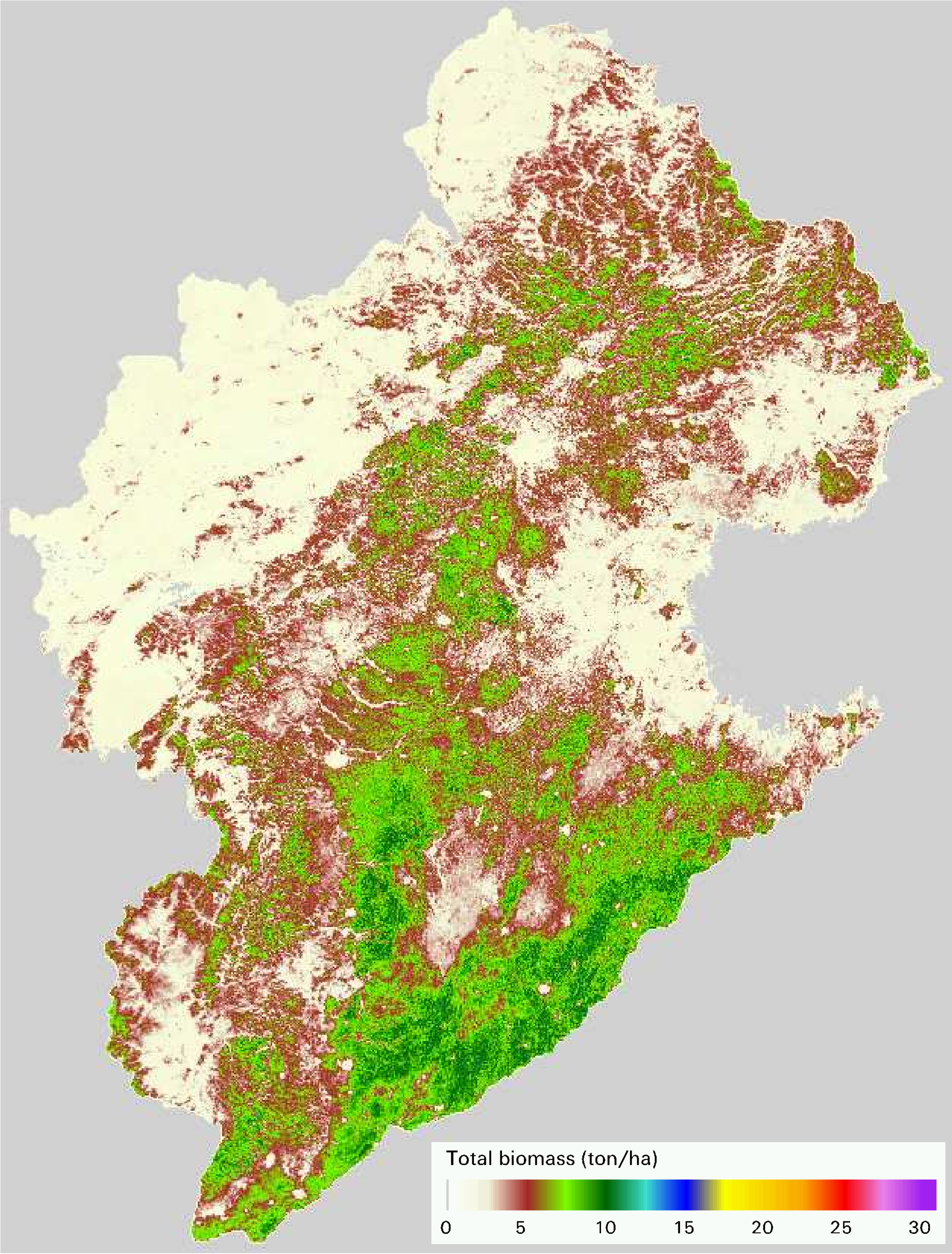

**Figure 8: Total biomass production from Oct 01 - June 15 (wheat)**

The area surrounded by the arms of the V-shape shows a very low biomass production during the wheat growing season. In discussions with Chinese experts from the Hai Basin Commission this area was indicated to have saline groundwater problems, thus limiting the amount of irrigation that is possible in the area. It is important to note that this same area shows a very high biomass production in the rest of the year, as shown in Figure 9. This shows the cumulative biomass production during the period where maize is the main crop grown in the basin. The areas with very high production compared to other areas in the basin, shown with by the red colors were indicated as areas with a different variety of maize crop by Chinese experts. This variety has a higher production, but a longer growing season. Due to the lack of the winter wheat, the maize crop can be sown earlier, thus lengthening the growing season.

This area without wheat and a longer-season maize consumes roughly 600 mm of water annually. Approximately 300-330 mm is consumed during the maize season, but approximately 280-300 mm is evaporated during the winter season, when barely biomass is produced.

On average, the wheat in the whole Hai basin has a total evapotranspiration of 369 mm in the winter. The average ET for maize during the summer months was 333 mm in 2003. A more detailed analysis of evapotranspiration during the two periods in the year is given in chapter 5 of this report.

Large cities like BeiJing, TianJin and ShiJiaZhuang are clearly visible in the biomass production image of the summer season as areas with low production. Note that the production is low, but not equal to zero, due to the presence of parks, trees and other urban vegetation. A high biomass production can also be observed in the forests populating the foothills and mountains surrounding the plane. Total biomass production is higher for maize than for wheat, despite the much longer growing season for wheat. This is partly due to the difference between summer and winter, but mainly due to the fact that maize is a C4 crop, and has a much higher light use efficiency than a C3 crop like wheat. Also note that to convert the total biomass production to harvested yields, a conversion factor (harvest index) is needed.

A separation of evapotranspiration per land use class will be presented in chapter 5. The link between land use and actual evapotranspiration is important for the division in consumptive use, beneficial ET and non-beneficial ET.

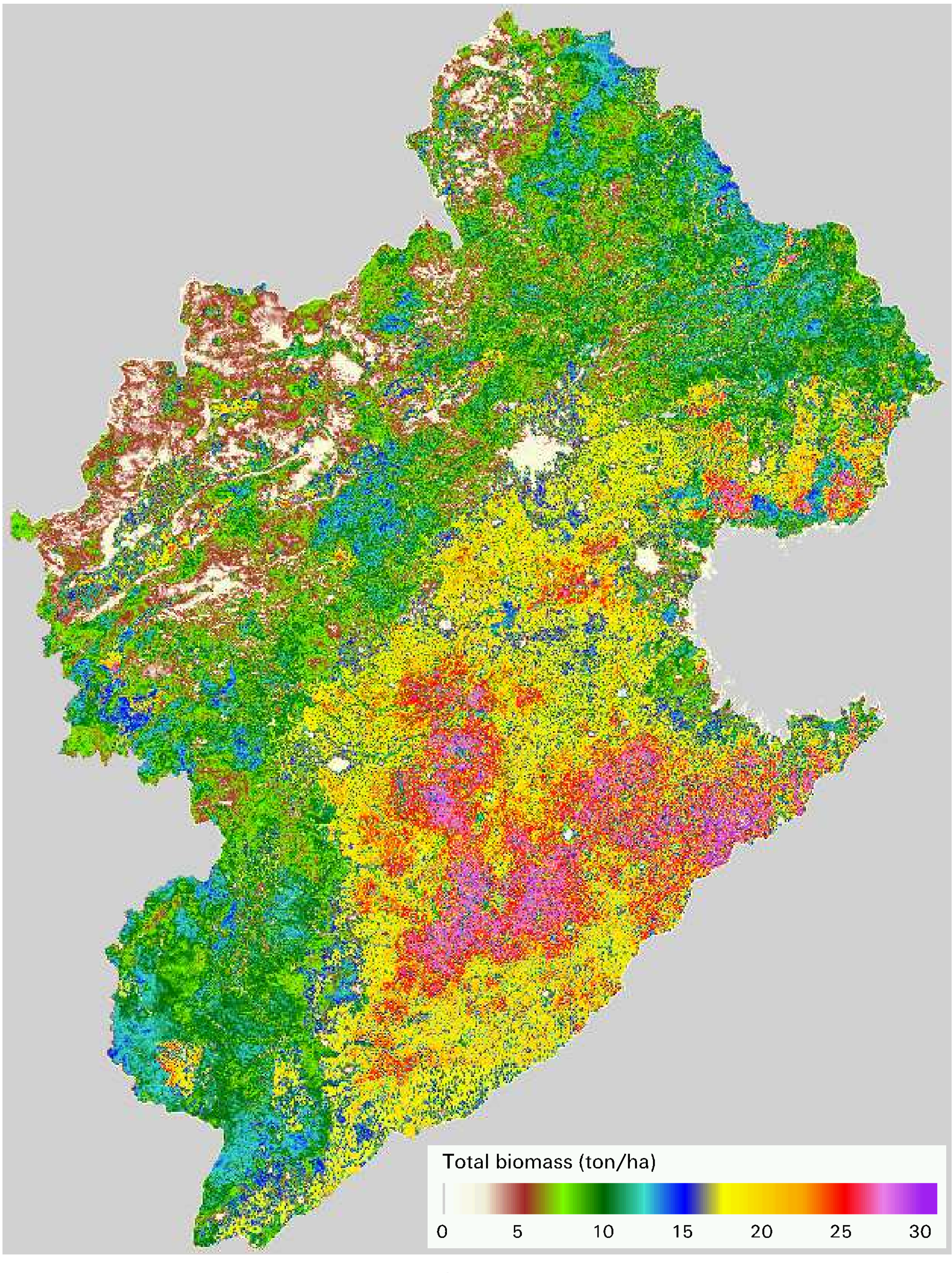

**Figure 9: Total biomass production from June 15 - Sept 30 (maize)**

## 4. Data validation

The two major crops in the Lower Hai Basin are a wheat-maize crop rotation. Wheat is usually a winter wheat, sown in early October and harvested in mid-June. Summer maize is sown in mid-June and harvested late September. Since precipitation is lower than the water requirement of this crop rotation, additional irrigation is needed. Since the precipitation mostly falls during the maize crop, supplementary irrigation is used mainly for winter wheat and early maize. The winter wheat is dormant during the winter period, but has a reviving stage around day of year (DOY) 70 (March 10). The harvest period is usually around DOY 150 (Zhang et al, 2002).

Zang et al (2002) compared ET of winter wheat using a weighing lysimeter and an energy balance for an experimental station in Luangcheng Agro-Ecological Station. They found, for the period between DOY 71 and DOY 155 in 1999, a total water use of 215 mm (Energy Balance) and 250 mm (Lysimeter). They note, however, that the lysimeter was slightly higher elevated than surrounding fields, and that advective energy could explain the higher measurements for the lysimeter. They measured a maximum daily ET of 6.5 mm, just before harvest. Shen (1998) gives a total ETact for the full growing season of 480 mm for winter wheat.

A review of several articles (Chen et al, 2003; Kendy et al, 2004; Zhang et al, 2002; Shen et al, 2004; Zhang et al, 2004; Liu et al, 2004; Zhang et al, 2003; Zhang et al, 1998; Wang et al, 2001; Zhang et al, 2003; Kang et al, 2000; Zhang et al, 2005; Wang et al, 2005; Zhang et al, 2001) on ETa for wheat and maize in the Hai Basin is summarized in Figure 10.

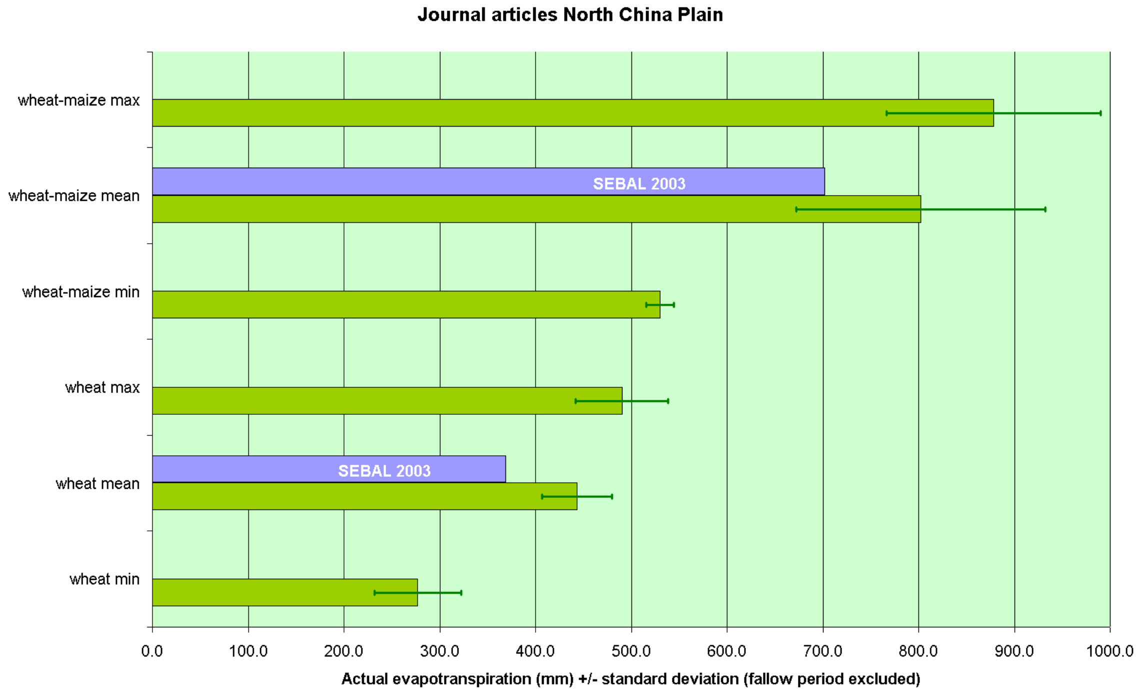

**Figure 10: Comparison between average literature values for wheat and maize in the Hai Basin and the SEBAL results for 2003.**

The purple bars in Figure 10 show the results of the SEBAL analysis. It is not surprising that the values of the MODIS analysis are less than the literature values that are often based on experimental field values. Since the resolution of MODIS is 250 m, field reflectances are averaged over 250 m. Experimental field measurements are usually based on point measurements. Since the spatial averaging over 250 meter usually also includes parts of field roads, pumping sheds, houses and canals it is expected that the average values are lower than actual field measurements. For the calculation of consumed water volumes, this spatial pixel integration of data has no major effect. The average evapotranspiration is lower than actual field measurements, but the area represented by the satellite image pixel is larger than the real area, thus offsetting the effect of spatial integration. On a basin scale, the computed values therefore appear very acceptable.

In addition to total evapotranspiration Zhang et al (2002) determined also the ratio between evaporation and transpiration, and found that 20-25% of ET was composed of (non-beneficial) soil evaporation. At the beginning of the reviving growing stage, this value was higher (70%) than just before harvest (15%). This separation is not included in the SEBAL model. Zhang et al (2002) show a day-time energy balance calculation for 6 individual clear days (Table 1). Note that there is a difference between day-time measurements and 24 hour measurements from SEBAL.

**Table 1: Daytime energy balance calculated for 6 individual clear days using Bowen Ratio measurements (Zhang,2002).**

| DOY | Rn W/m2 | ΛE W/m2 | H W/m2 | G W/m2 | EF (-) |
|---|---|---|---|---|---|
| 317 (1998) | 133.3 | 24.9 | 44.9 | 63.5 | 0.36 |
| 81 (1999) | 249.6 | 68.3 | 44.4 | 136.9 | 0.61 |
| 97 | 245.9 | 136.2 | 61.4 | 48.3 | 0.69 |
| 111 | 297.5 | 197.2 | 73.1 | 27.3 | 0.73 |
| 125 | 333.5 | 306.2 | 8.9 | 18.4 | 0.97 |
| 130 | 386.8 | 314.8 | 47.3 | 24.8 | 0.87 |

The 24-hr energy balance of the current SEBAL study for 2003 for selected clear days for the same location as the research of Zhang et al (2002) is shown in Table 2. LE data can be compared assuming that from 18:00 to 6:00 there is no latent energy transfer. A comparison based on these assumptions is shown in Fig 11

**Table 2: 24-Hour energy balance values for 6 dates analyzed with SEBAL**

| DOY | Rn W/m2 | λE W/m2 | H W/m2 | G W/m2 | EF (-) |
|---|---|---|---|---|---|
| 295 (2003) | 64.5 | 39.5 | 34.2 | -9.2 | 0.54 |
| 50 (2003) | 89.0 | 56.5 | 31.6 | 0.9 | 0.64 |
| 104 | 156.5 | 137.8 | 7.6 | 11.1 | 0.95 |
| 120 | 201.1 | 191.4 | 7.3 | 2.4 | 0.96 |
| 121 | 224.0 | 197.8 | 22.8 | 3.4 | 0.90 |
| 145 | 216.9 | 137.9 | 67.4 | 11.6 | 0.67 |

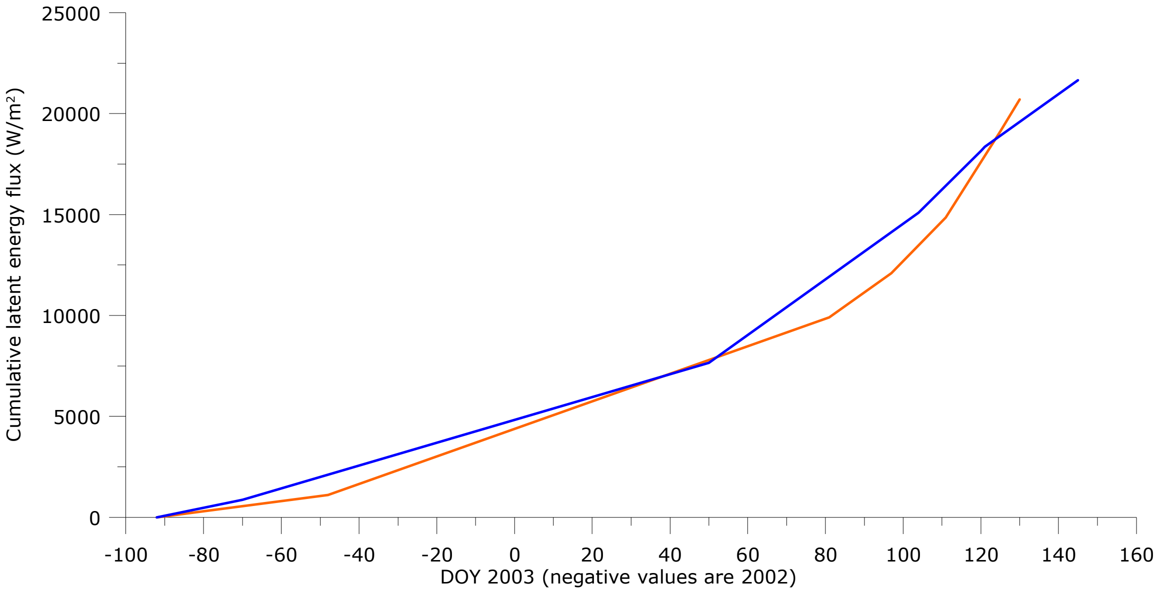

**Figure 11: Comparison between cumulative latent energy flux as measured by Zhang et al and SEBAL.**

Shen et al (2004), using the same methods at the same experimental station in LuangCheng, calculated the evaporative fraction (EF) for the period between 10:00 and 15:00 in 1999, 2000 and 2001. An averaged curve was developed based on these three years, and compared with the instantaneous value of SEBAL calculations for 2003. This comparison is shown in Fig 12. Note that the SEBAL values are area-averaged for the LuangCheng agricultural area (4 x 2 km; 16 x 8 pixels), while the measurements of Shen et al (2004) are point measurements.

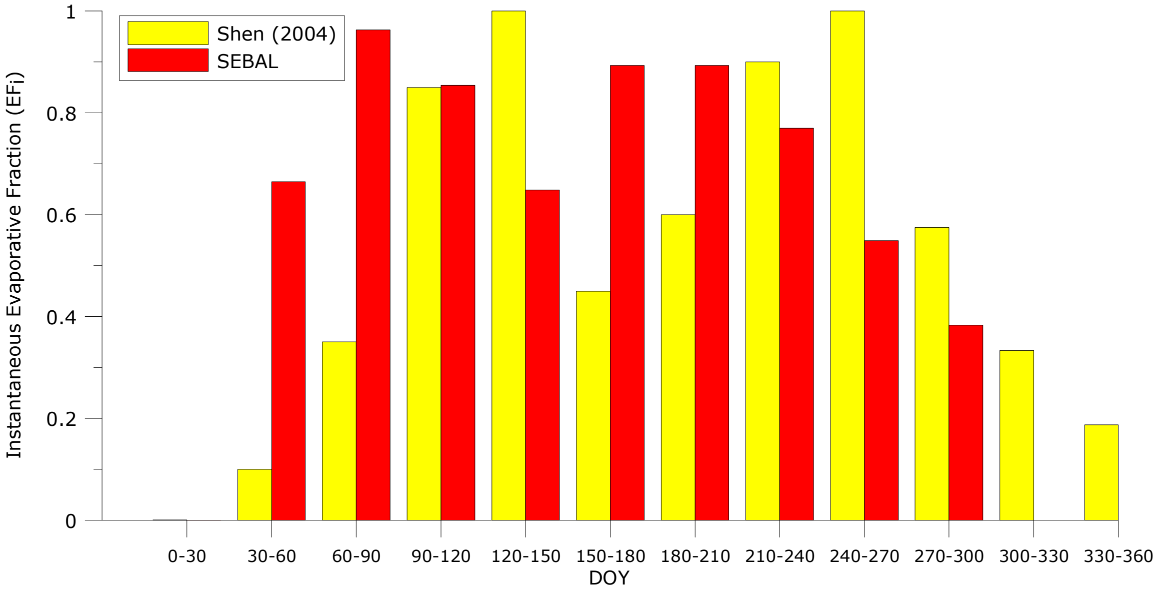

**Figure 12: Comparison of evaporative fraction over the year between Shen et al (2004) and the current SEBAL study for the Hai Basin.**

Kendy et al (2003) show that on average, approximately 400-500 mm/yr of additional irrigation is applied in area of LuangCheng. The use a long-term average rainfall of 460 mm, and a long-term average ET of 660 mm. The long-term average ET is similar to the current SEBAL study, where the wheat/maize rotation uses a total of 700 mm.

## 5. Data Analysis

While in Chapter 3 the main results of the SEBAL analysis are presented, this chapter will discuss what the implications are of the SEBAL 2003 results. The monthly and annual water are important to know, as well as the spatial distribution of evapotranspiration and biomass production, but it is even more important to know how water can be managed to reduce water shortages. For this reason, the analysis in this chapter will focus on small political units within the Hai Basin, namely the counties. The county map was obtained from Chinese experts at the Hai Basin. All analyzed data will be presented as county-averaged values, unless specified differently. Figure 13 shows the same results as Figure 7, but now presented as county averages.

The spatial distribution of the rainfall in the Hai basin is shown in figure 14. A clear gradient of rainfall can be distinguished, with a low amount in the north west of the basin, and a high amount of rainfall in the south part of the basin. The higher ET in the southern part of the Hai basin can likely be explained by a higher availability of surface water.

Figure 15 shows the annual deficit calculated from measured rainfall data using the Tropical Rainfall Measurement Mission (TRMM) and the calculated $ET_{act}$ values using SEBAL. It can be seen that the northerly counties show a deficit, which is not expected, since there does not appear to be intensive agriculture. However, TRMM measurements do not include measurements of snow, and in the northerly counties there is snow for large parts of December, January and February. In SEBAL, the evapotranspiration in the presence of snow cover is slightly overestimated (see box 1), since there is no inclusion for Latent Energy of fusion (energy needed to transfer snow into water). However, since the total amount of energy during these winter months is low (see Figure 5), the error introduced by this overestimation is small.

It is unlikely that the underestimation of rainfall and the slight overestimation of evapotranspiration will result in the deficit as shown in the northerly part of the basin. As discussed before, the spatial distribution of rain and evapotranspiration is variable over the basin, and it is clear that the rainfall in the north of the basin is much lower than in the south of the basin. The water resource for the excess evaporation in the northerly part of the basin is likely snow that was carried over from the previous year, which was not included in the rainfall measurements of 2003.

In the low plain of the Hai Basin, an annual water deficit can be found in the counties near the mountain range. These are counties with a high wheat production. The counties with high wheat production in the south east of the plain have a much higher rainfall in 2003 (figure 14), and do therefore not show a water deficit. However, the annual distribution shows larger water deficits.

During the irrigation period of wheat and the beginning of the maize season (between March and June; Figure 16), almost the complete Hai plane shows water deficit. Groundwater pumping complements the demand for water for agriculture during this period. In the wheat growing areas, most of the counties show a deficit of between 100 and 150 mm water in 2003. This is lower than the average annual groundwater abstraction of 200 mm for Luangcheng County given by Kendy et al (2003), but they looked at a long-time average abstraction, while the current study calculated for a single year. The deficit analysis as shown in Figure 15 and 16 also do not include any runoff across the county boundaries.

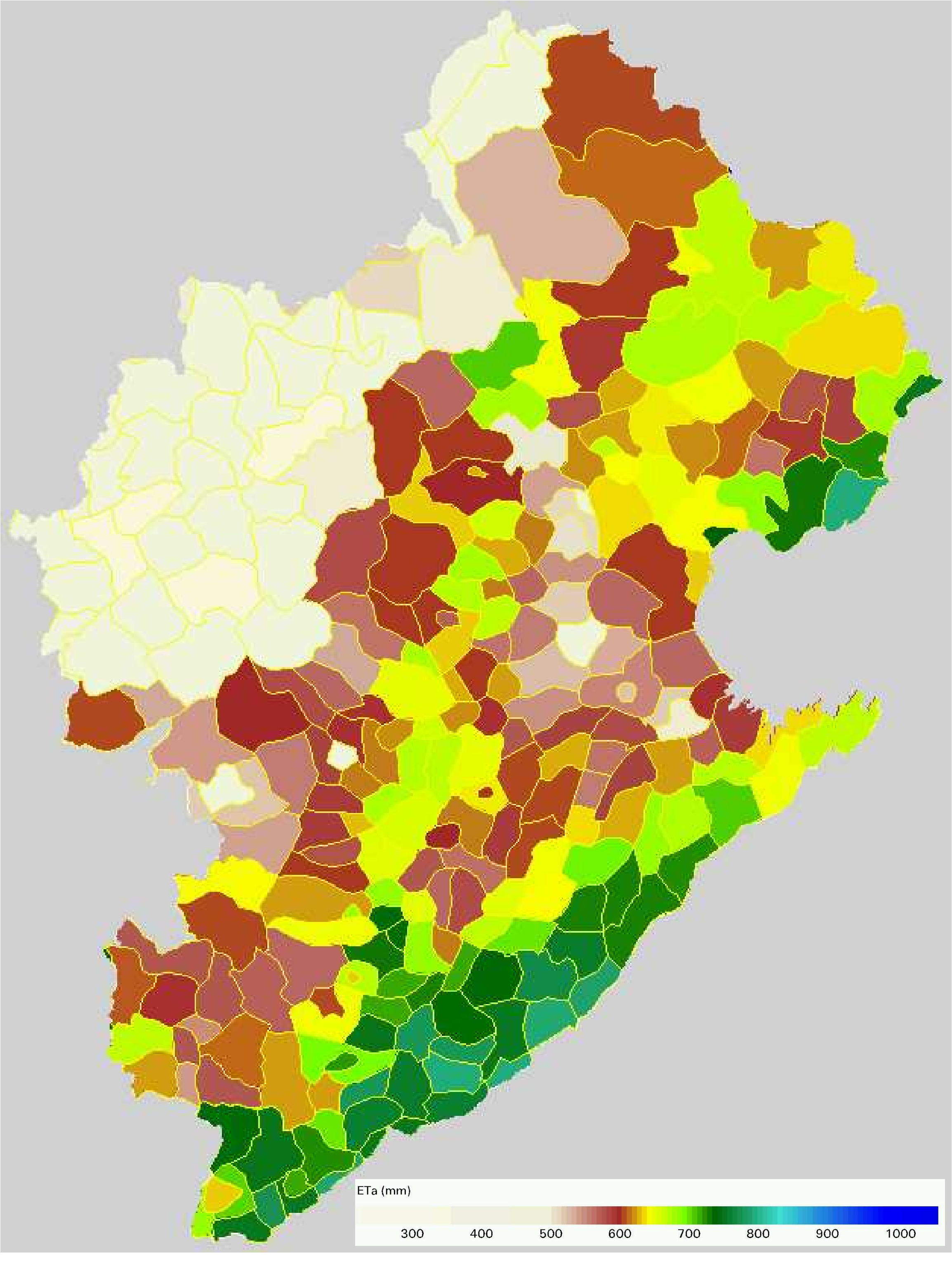

**Figure 13: ETa averaged by county in Hai Basin in 2003.**

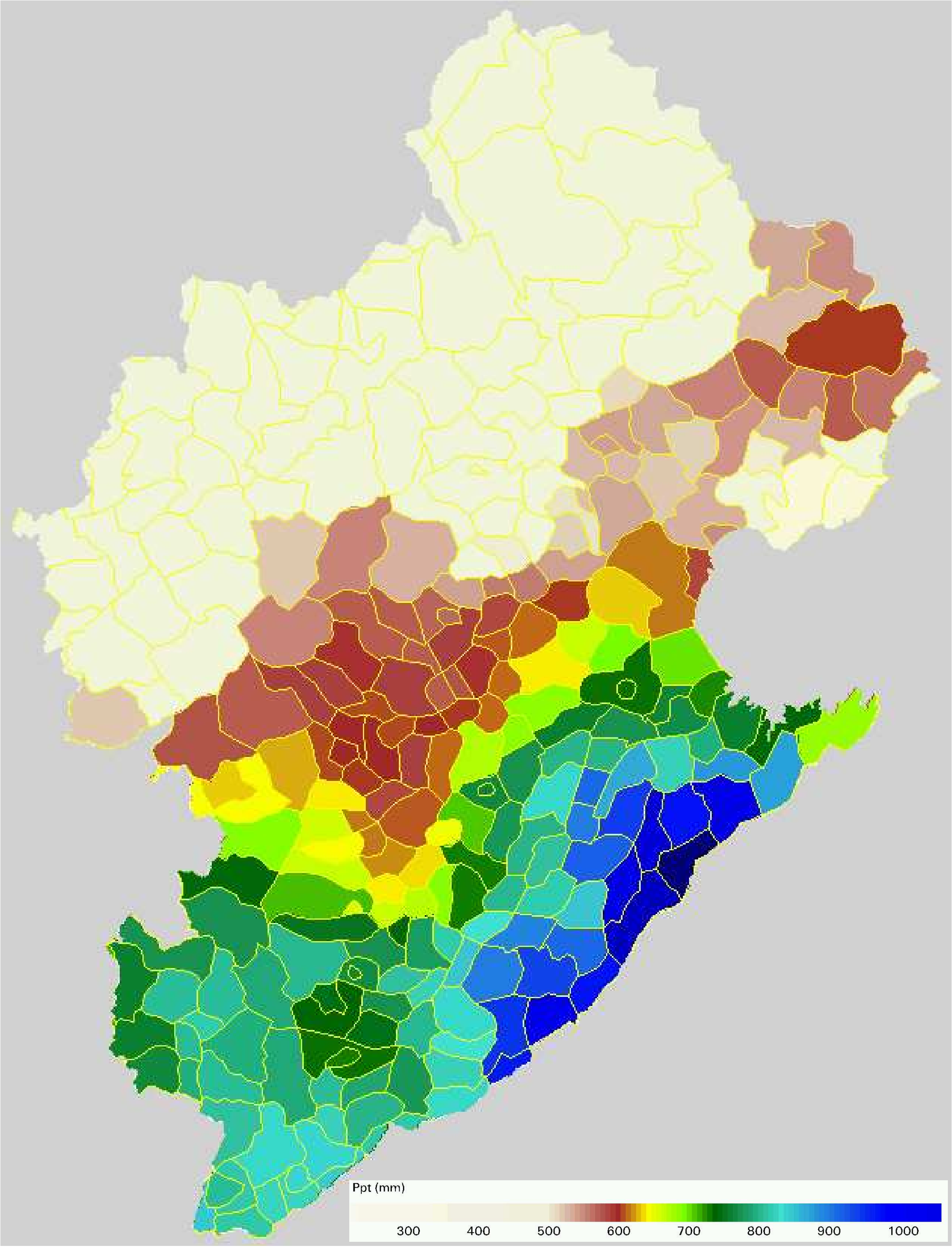

**Figure 14: Rainfall in Hai Basin for 2003 as measured by the Tropical Rainfall Measurement Mission (TRMM).**

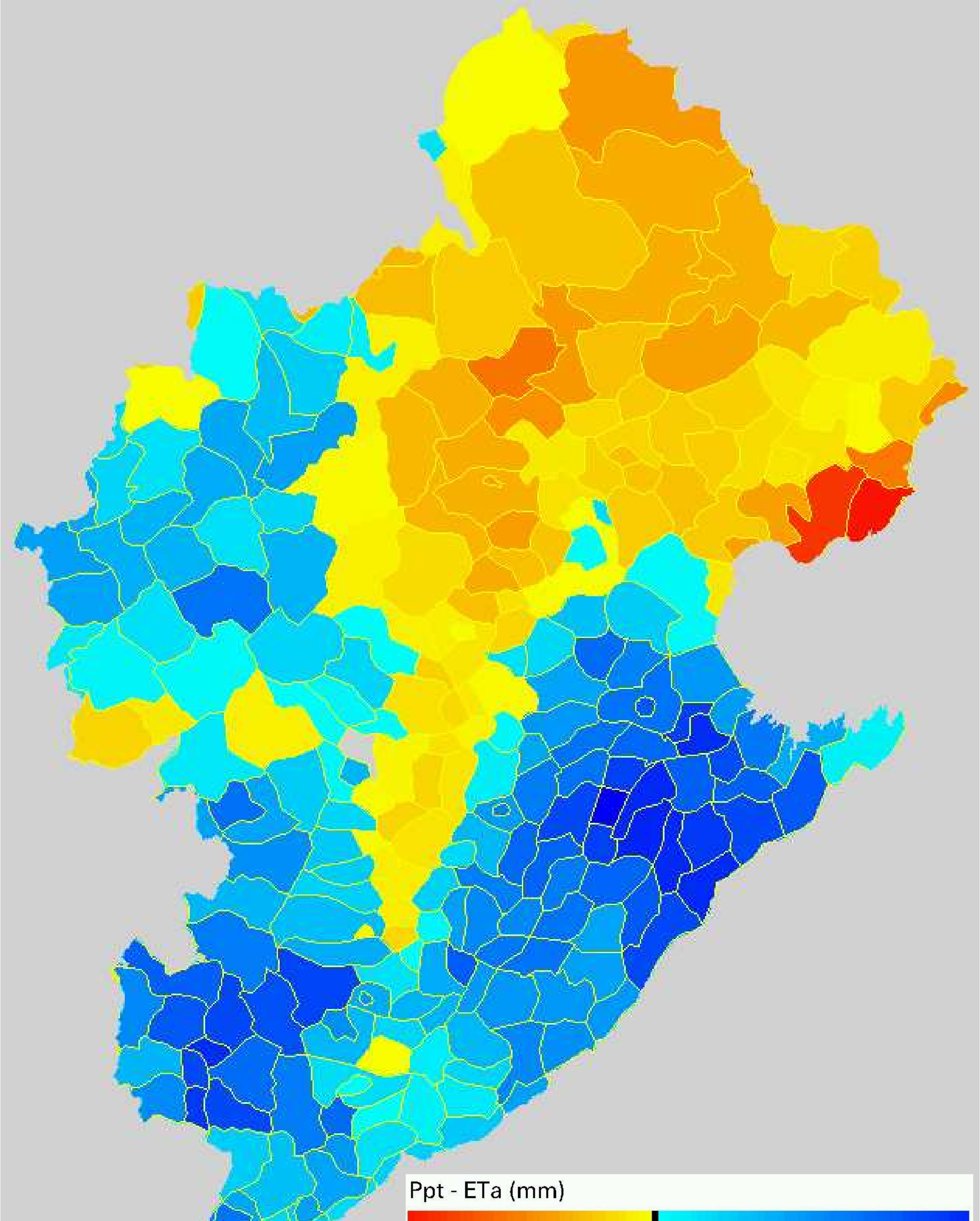

Figure 15: Rainfall (TRMM) minus ETact (SEBAL) for 2003 in Hai Basin

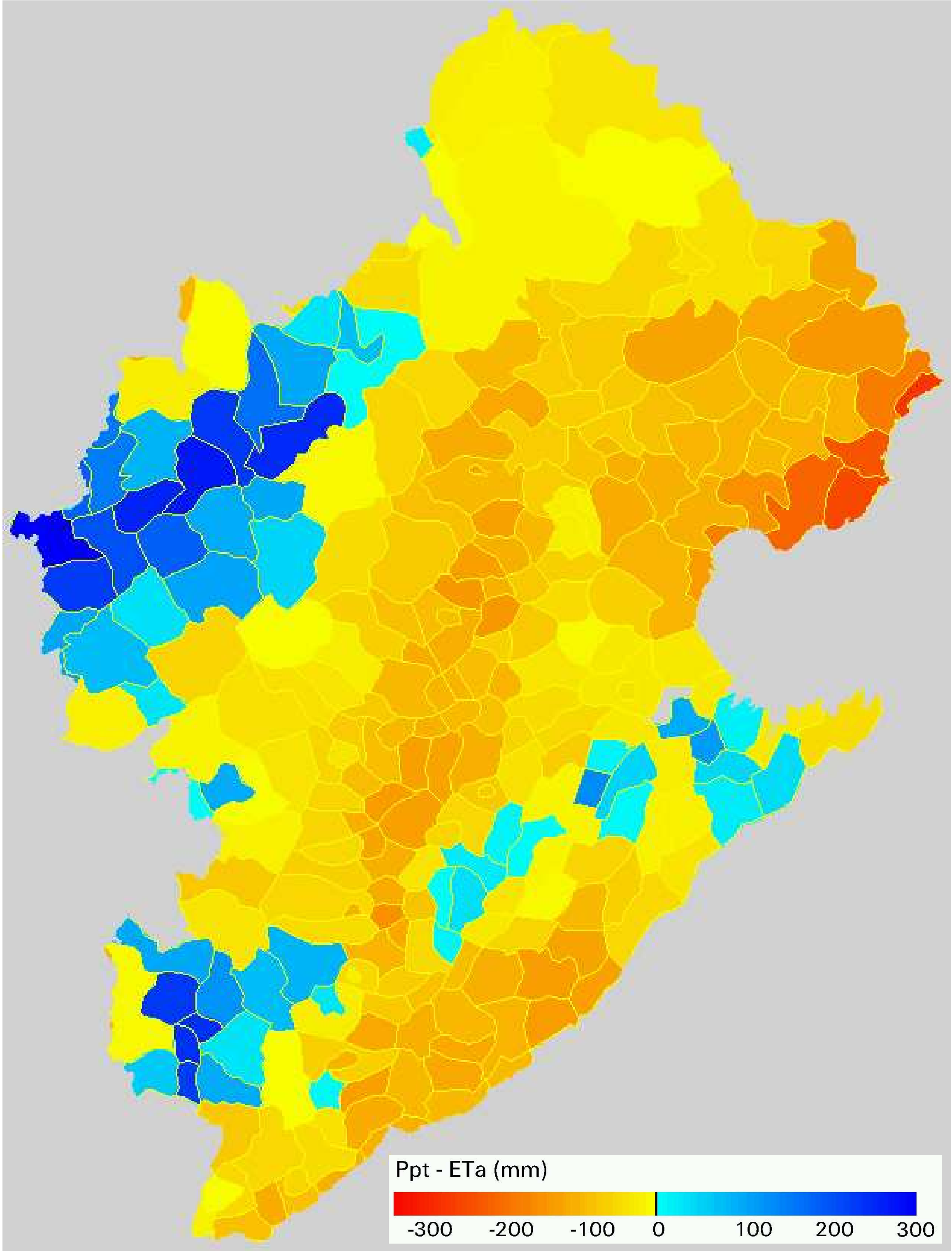

**Figure 16: Rainfall (TRMM) minus ETact (SEBAL) for March, April, May and June 2003 in Hai Basin.**

**Box 1: TRMM and the lack of snow measurements**

Although TRMM does not measure the snow fall, an estimate can be made on the amount of snow that fell based on rough calculations. Snow is visible on satellite images, and the energy balance for different periods in the year is also known. The melting of snow needs a certain amount of energy, similar to the phase change of water when it evaporates. The energy to melt snow is the latent energy of fusion, equal to $3.34 * 10^8$ J/m$^3$ of water.

Available energy is measured from the energy balance. It can be seen that the latent energy available in December and January is on average for the basin 20 W/m$^2$. Thus, energy available in J/m$^2$ can be calculated from

$$LE_{available} * Days * 24 * 3600$$

Where days is the number of days that snow can be observed on the ground.

Depth of water from snow can then be calculated as

$$Depth_{water} = \frac{LE_{available} * Days * 24 * 3600}{LE_{fusion}}$$

For a situation where available latent energy is 20 W/m$^2$, and snow is visible for three days continuously, the equivalent depth of precipitation is

$$Depth_{water} = \frac{20 * 3 * 24 * 3600}{3.34 * 10^8} = 0.0155 \text{ m or } 16 \text{ mm}$$

A reverse calculation can also be made. The most northerly county in the Hai Basin (Hexigten Qi in Nei Mongol Zizhiqu County (Inner Mongolia) shows an annual deficit of 61 mm between calculated ET and measured rainfall. This means that over the year, with available Latent Energy of 20 W/m$^2$, a total of 12 days should have snow cover. These are not unrealistic values; it is even likely that there were more than 12 days of snow cover.

A review of MODIS quicklooks shows that for approximately 90 days a snow cover were existent in Hexigten Qi county. Assuming that there is no runoff out of the county, and that the snow in these 90 days represents the 61 mm of rainfall deficit, the latent energy available for this period was 2.6 W/m$^2$. It is highly likely that the latent energy available for snow melt is far lower than the average latent energy available for the whole basin (20 W/m$^2$), since the albedo of snow is high, and the available net radiation thus lower than for bare soil. On the other hand, the actual rainfall deficit is likely less than the calculated 61 mm, since this is based on the assumption that all the latent energy calculated for the area was used for evapotranspiration. In the case of melting snow, the actual ET will be lower, since some of the energy was used for the phase change of water from crystalline to liquid (melting).

## 6. Water Balance Analysis

The Hai Basin currently exists in a non-sustainable water situation. Groundwater overdraft results in dropping groundwater levels, and river outflow (environmental flow) to the sea is in some months non-existing. This means that water consumption is larger than renewable water resources. Renewable water resources and consumptive water use in the Hai Basin are summarized in box 2.

**Box 2: Water balance components and indications of magnitude for the Hai Basin**

| | | |
|---|---|---|
| IN: | | |
| Long-term average rainfall[a]: | 550 mm | 175 $km^3$ |
| Yellow River water diversion[a]: | | 5 $km^3$ |
| 1998 Groundwater over-exploitation[b]: | | 5 $km^3$ |
| OUT: | | |
| 2003 – basin wide actual evapotranspiration[c]: | 590 mm | 188 $km^3$ |
| River discharge to the sea[b] | | 4 $km^3$ |
| STORAGE: | | |
| Reservoir storage capacity[a]: | | 26 $km^3$ |

[a] GEF, 2002
[b] GEF, 2003
[b] SEBAL, 2005

From box 2 it can be seen that there is a deficit between rainfall and ET of 13 $km^3$ (188-175 $km^3$). A total deficit in the water balance exists of 7 $km^3$ (192-185 $km^3$), which is caused by a variation in the rainfall, $ET_a$, diversions of the Yellow River, the groundwater exploitation and the river discharge to the sea over the years.

The objective of obtaining a sustainable water situation means that at least the groundwater overexploitation should be reduced to 0 $km^3$ overdraft. Note that using the example values from box 2 this would result in a total volume of needed water savings of 12 $km^3$ (5+7 $km^3$), since there is a shortage of 7 $km^3$ in the water balance. This volume of water savings would not increase the environmental flow of the rivers to the BoHai Sea. Water savings of 12-13 $km^3$ are therefore the minimum savings needed to stop the decline of the groundwater levels.

A water balance can also be calculated for the high elevated areas and the low elevated areas within the Hai Basin. Figure 17 shows the separation based on the DEM for the area. A monthly water balance was calculated using the SEBAL calculated ETa values, and the TRMM measured rainfall data. The lowland covers in this analysis 135,000 $km^2$ and the highland cover 183,700 $km^2$ (similar values as indicated in GEF, 2002). These data are summarized in table 3.

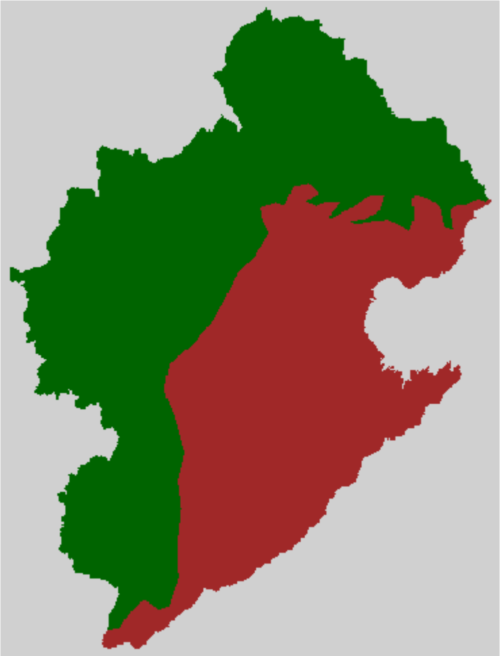

**Figure 17: Separation of Hai Basin in lowland (brown) and highland (green) for water balance analysis.**

**Table 3: Monthly ETa and rainfall for lowland and highland in Hai Basin in 2003**

| | ETa lowland (km$^3$) | ETa highland (km$^3$) | Rainfall lowland (km$^3$) | Rainfall highland (km$^3$) | Water surplus lowland (km$^3$) | Water surplus highland (km$^3$) |
|---|---|---|---|---|---|---|
| January | 1.7 | 4.9 | 0.5 | 0.9 | -1.2 | -4.0 |
| February | 3.2 | 2.2 | 1.0 | 1.3 | -2.2 | -0.9 |
| March | 5.0 | 6.1 | 2.8 | 3.9 | -2.2 | -2.1 |
| April | 9.7 | 9.3 | 6.9 | 5.6 | -2.7 | -3.7 |
| May | 8.7 | 8.0 | 5.4 | 9.5 | -3.3 | 1.6 |
| June | 13.7 | 14.2 | 9.9 | 14.0 | -3.9 | -0.2 |
| July | 13.9 | 17.0 | 24.0 | 22.9 | 10.1 | 5.9 |
| August | 13.3 | 14.7 | 19.1 | 19.3 | 5.7 | 4.6 |
| September | 9.5 | 10.4 | 0.9 | 0.5 | -8.6 | -9.9 |
| October | 3.9 | 5.1 | 18.3 | 13.3 | 14.4 | 8.3 |
| November | 3.5 | 4.1 | 4.7 | 5.8 | 1.2 | 1.7 |
| December | 2.4 | 3.1 | 0.9 | 0.5 | -1.4 | -2.6 |
| ANNUAL | 88.7 | 98.9 | 94.4 | 97.5 | 5.7 | -1.4 |

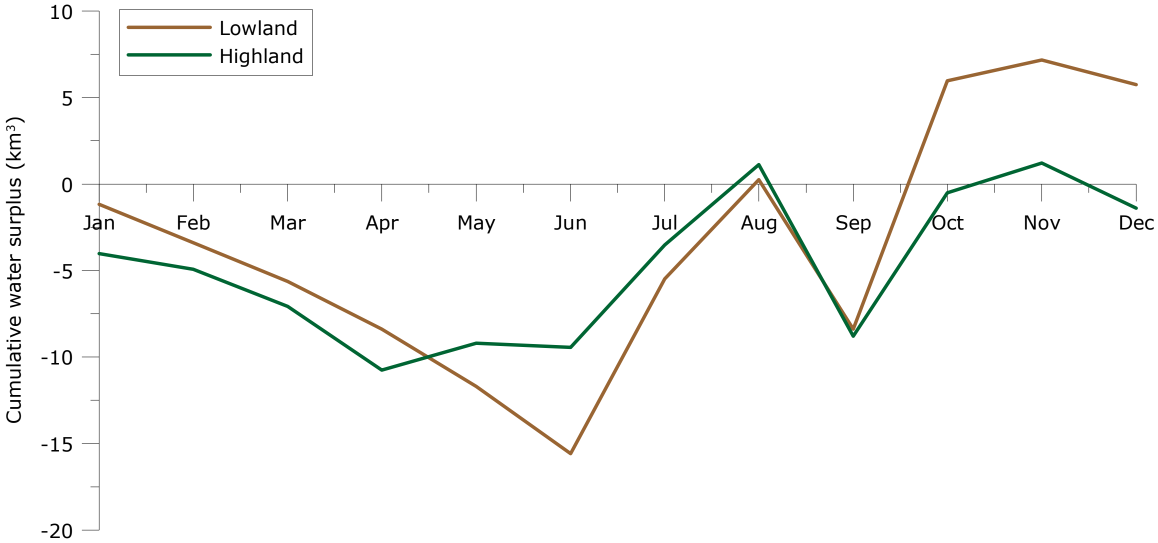

**Figure 18: Cumulative water surplus in 2003 for highland and lowland area in Hai Basin.**

Figure 18 shows the cumulative water surplus for the two areas, based on the table with ETa and rainfall data. It can be seen that the largest recharge of water took place in July, August, and October in 2003. It is not expected that water balance for the highland area results in a water shortage in 2003, since surface irrigation water (not groundwater irrigation) for the lowlands is mainly obtained from reservoirs in the mountains. This may indicate that the source of water for surface water irrigation is obtained from a smaller area than used in this analysis and that the agriculture and forestry in the highland area also consume more water than available from rainfall. A total storage capacity of 26 km$^3$ exists in the Hai Basin through reservoirs (GEF, 2002).

The water surplus in the lowlands is also unexpected, and occurs mainly during the summer season. Figure 15 already showed that most of the annual rainfall surplus can be found on the east side of the lower Hai Basin, and should therefore likely be considered as runoff to the BoHai Sea.

A more detailed water balance analysis was done using the model SWAT. This water balance model divides the Hai Basin in hydrological sub-basins, and uses more detailed water balance categories. Since the model defines its own hydrological basins based on the DEM of the area, the boundaries of the model do not fully overlap with the boundaries of the Hai Basin. The modeled area is actually larger than the Hai Basin, which resulted in a spatial average ETa that is smaller than calculated using SEBAL. The different monthly water balance components simulated with SWAT are shown in Figure 19.

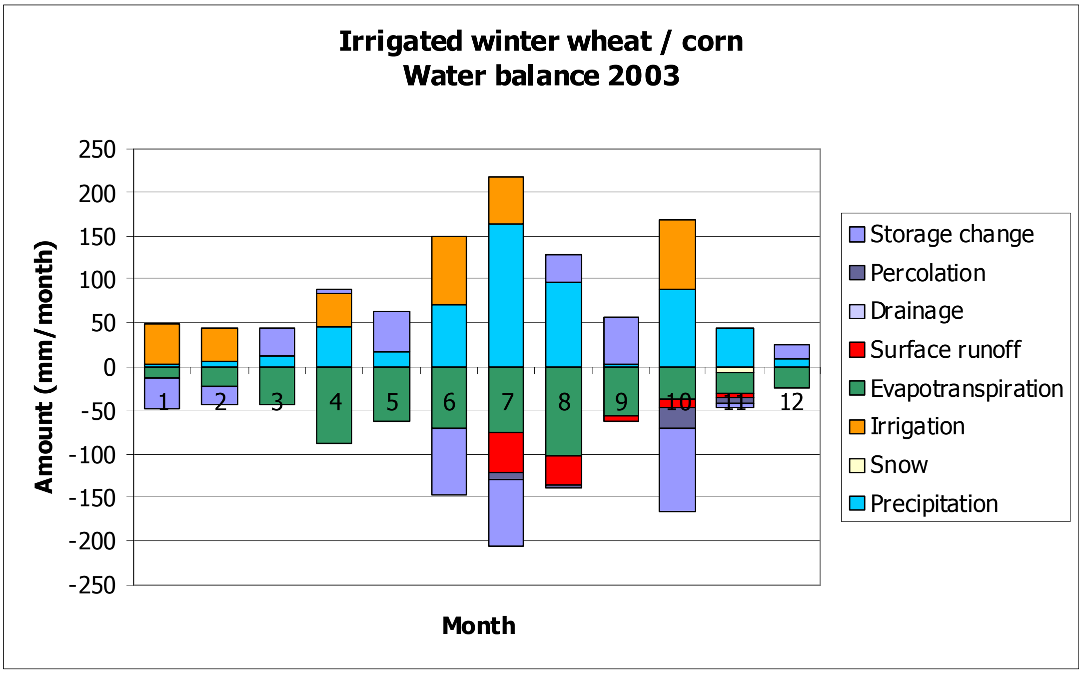

**Figure 19: Water balance components as modeled with SWAT for the Hai Basin 2003.**

From Figure 19 it can be seen that a considerable amount of the outflow in July and August is comprised of surface runoff out of the basin (red color), totaling 70 mm.

Figure 20 shows the average depth of irrigation applied in the sub-basins used in the simulation of SWAT. It can be seen that the applied irrigation varies between 0-350 mm annually, with the lower Hai basin having the most intensive irrigated areas. Comparison with the calculated groundwater extraction (Figure 21) shows that areas with intensive irrigation are mostly affected by groundwater decrease. This is similar to the area indicated in figure 16 where a water deficit exists between the months of March and June.

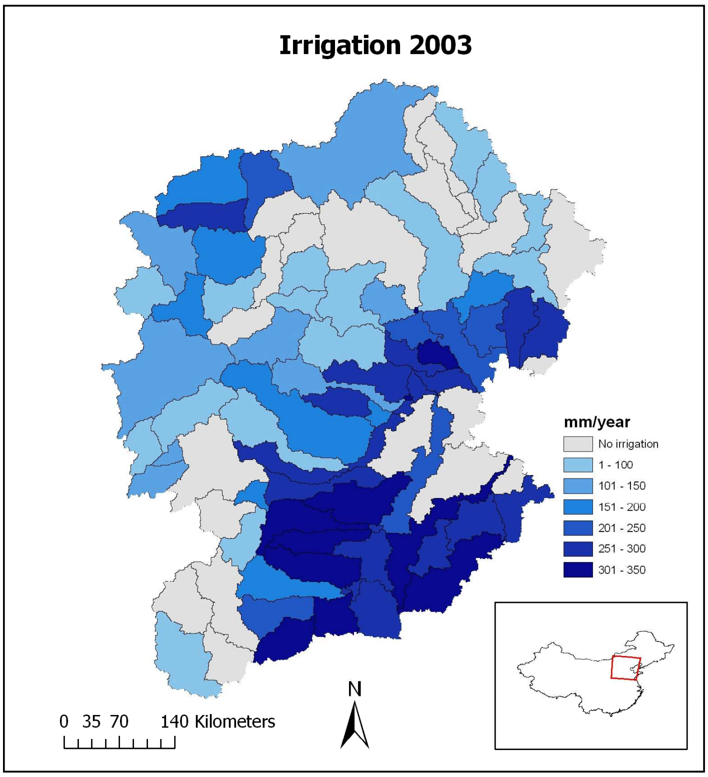

**Figure 20: Irrigation depths as calculated by SWAT simulation for Hai basin in 2003**

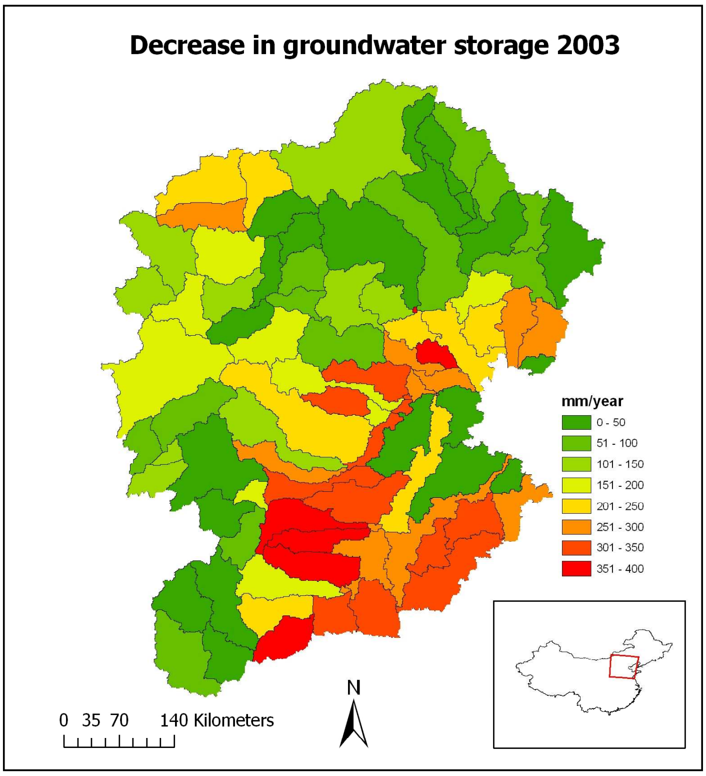

**Figure 21: Decrease of groundwater storage as calculated with the SWAT model for Hai Basin in 2003.**

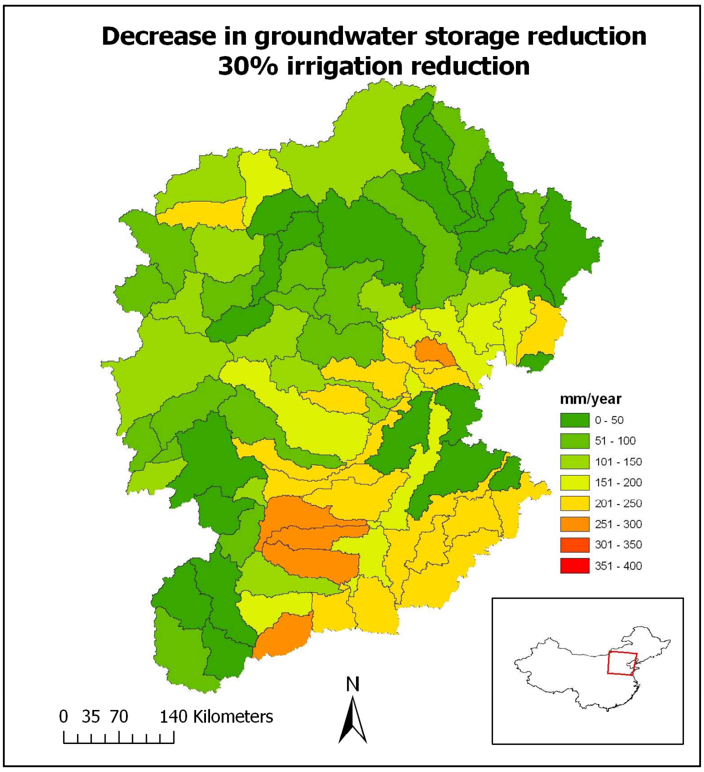

**Figure 22: Decrease of groundwater storage as calculated with the SWAT model for a simulation with 30% less irrigation applied in the Hai Basin 2003**.

The SWAT model was also used to simulate a 30% overall reduction of irrigation application, in all the sub-basins indicated in Figure 22. This simulation results, not unexpectedly, in less reduction of groundwater storage. It is important to note, however, that under the conditions of the simulation there are still major areas in the lower Hai Basin that have a considerable decrease in groundwater storage, even with 30% less irrigation application. This results shows the importance of the earlier statement that the "wet" savings are more important than the "dry" savings, and that the focus of water savings need to be in reduction of actual evapotranspiration.

Currently, about one third of the irrigation water applied is obtained from surface water, and two third of the total irrigation water is obtained from groundwater extraction. Reduction of groundwater extraction is one important objective in reaching a sustainable water situation. However, increasing the environmental flow is also an important element in reaching a sustainable situation. To obtain higher environmental flows in the rivers, not only the groundwater exploitation should be reduced, but also the volume of water used from surface runoff.

## 7. Water Management Implications

In 2003, an average annual $ET_{act}$ of 589 mm was calculated using SEBAL, and an average annual rainfall of 603 mm was measured using TRMM. When there is no runoff out of the basin, there would be no water deficit for the year. However, the highest rainfall is measured in the southerly counties, and part of the southerly area drains to the Yellow River. In addition, some runoff from the Hai River exists during parts of the year, thus it is likely that there is an overall water deficit. This deficit was limited in 2003, but this year had an above average rainfall. A deficit situation in an average year indicates that the water situation is not sustainable.

It was suggested in chapter 1 to reduce the evapotranspiration, and obtain "wet savings" of water. An analysis of water productivity for the two main crops in the basin can give an indication where the likeliness for wet savings is high. A low water use productivity for the same crop in the same region means that better crop management could result in higher yields using the same amount of water, or, in other words, that the same amount of yield can be obtained using less water. One should be careful, however, that without outside intervention, the first situation (more yield with the same amount of water) is commonly preferred by growers, while this is not reducing water consumption.

A classification of agriculture in winter and summer was made based on the NDVI, albedo and evapotranspiration calculations from the remote sensing images. The total Hai Basin was first filtered using the albedo and the NDVI to eliminate cities and forested areas. An unsupervised classification was then applied to the ETact results from the SEBAL calculations to make use of the temporal information, and select the crop development signatures for wheat and maize.

Figure 23 shows a histogram of crop water productivity, crop yield and evapotranspiration for wheat classified pixels in the Hai Basin in 2003. It shows an average water use productivity of 1.0 – 1.1 kg grain yield per $m^3$ of evapotranspired water, using a harvest index for wheat of 0.43. Figure 24 shows a histogram of crop water productivity, crop yield and evapotranspiration for maize classified pixels in the Hai Basin in 2003. It shows an average water use productivity of 2.0 kg grain yield per $m^3$ of evapotranspired water, using a harvest index of 0.36. Both graphs show a normal distribution of the crop water productivity, although the graph for wheat appears slightly lobbed on the low-productivity side, and the maize graph appears to show some effect of the long-season maize with a slightly higher number of high crop water productivity pixels.

The same yield with less water can only be obtained if the water productivity in increased. The highest potential for water savings is in the region where the water productivity is below the mean values. Since groundwater is mainly used for supplemental irrigation during the wheat growing season, and less during the maize season, the analysis will first focus on the water use productivity of wheat. A reduction in water use for wheat will reduce groundwater pumping, while a reduction in water use for maize will increase recharge to the groundwater. Reduction of groundwater pumping has priority over recharge of the groundwater.

Figure 25 shows the average crop water productivity for wheat per county. Only pixels that were classified as wheat were included in the calculations, and only counties with more than 25% of their area under wheat are shown. Although the crop water productivity values for the Hai Basin appear lower than regions in India, Egypt, the US and Mexico, water productivity could at least be improved in the counties that have a value below the region-average crop water productivity.

Assuming that the total yield is the same as calculated for 2003 in this analysis, but the water productivity for the counties below the region-average is increased to 0.87, the total water savings can be calculated.

Based on the SEBAL calculations, a total of 22.5 * $10^6$ ton of wheat was produced in the 127 selected counties (on 5.9 * $10^6$ ha), and 22.0 $km^3$ water was consumptively used. Note that another 3 $km^3$ of water is consumed by wheat on an additional 8000 $km^2$ in the Hai basin. However, this agriculture is not concentrated in an area, but spread over the counties that are grey in Figure 25.

When 114 counties that currently have a crop water productivity of less than 1.1 kg/$m^3$ will improve to the average cwp, the same amount of wheat can be produced with 20.4 $km^3$. This is not enough yet to reduce the targeted ET-reduction of 13 $km^3$, but could contribute to a total water saving of 1.6 $km^3$ without a loss in yield. This is not an unrealistic target, since there are already 13 counties in the Hai basin with high intensity wheat growth that obtain cwp values higher than 1.1 kg/$m^3$.

The above analysis means that only a small part of the minimal water savings target can be obtained during the wheat season. These savings are however very effective, since they will actually reduce the volume of pumped groundwater. To reduce the volume of pumped groundwater not only results in "wet" savings, but will also reduce the energy demand by agriculture.

It is clear that reduction of evapotranspiration of wheat alone is not enough to obtain a targeted minimum 13 $km^3$ reduction in consumptive use. The maize, although grown largely on rainfall, is grown on a much larger scale than the winter-wheat, and relative smaller reductions in evapotranspiration will therefore result in large volumetric savings. A similar analysis as for wheat is done for maize.

Figure 26 shows the average crop water productivity for maize per county. Only pixels that were classified as wheat were included in the calculations, and only counties with more than 25% of their area under maize are shown.

Assuming that the total yield is the same as calculated for 2003 in this analysis, but the water productivity for the counties below the region-average is increased to 2.0 kg/$m^3$, the total water savings can be calculated.

Based on the SEBAL calculations, a total of 64.8 * $10^6$ ton of maize was produced in the 175 selected counties (on 9.6 * $10^6$ ha), and 32.2 $km^3$ water was consumptively used. Note that another 6 $km^3$ of water is consumed by wheat on an additional 8000 $km^2$ in the Hai basin. However, this agriculture is not concentrated in an area, but spread over the counties with a grey color in Figure 25.

When 81 counties that currently have a crop water productivity of less than 2.0 kg/$m^3$ will improve to the average cwp, the same amount of maize can be produced with 30.8 $km^3$, thus saving 1.4 $km^3$ water.

Improving the crop water productivity for wheat and maize to the current region average will not be sufficient to obtain water savings to reach a sustainable water situation. This means that the regional production of wheat and maize would have to be increased for the whole region. Water savings can be calculated when a target of 95% of the current county-average maximum cwp is selected. For wheat this would result in a target cwp of 1.14 kg/$m^3$ and for maize a target cwp of 2.39 kg/$m^3$. For wheat this would result in a maximum saving of water (without yield reduction) of 2.8 $km^3$, and for maize this would result in a maximum water ("wet") saving of 5.1 $km^3$.

The above analysis of agriculture shows that the targeted 13 $km^3$ (as a minimum saving only to prevent groundwater overdraft) can not be obtained only from improvements in agricultural production. Other sources of water savings need to be found to obtain a sustainable water situation in the Hai Basin.

From the agricultural analysis it can be seen that the total area of wheat grown is smaller than the total area under maize. In addition to the areas classified as wheat and maize, there is additional agriculture that appears less intensive in the satellite images. Especially the area that is left fallow during the winter season is considerable. These fallow agricultural lands have the advantage over other land use classes that the land is manageable. These fields are at least part of the year under agricultural management, thus making them accessible for evaporation reducing management in the non-productive periods.

To identify the fallow fields during the winter and the summer, an analysis was done using a land use classification map indicating the areas used for agriculture, combined with the map developed from the SEBAL model results indicating wheat and maize pixels. The difference of these two datasets are an indication of fields that are either fallow or have low agricultural production during either the winter season or the summer season (Figures 27 and 28). A county average percentage was calculated, indicating the percentage of fallow lands over the total agricultural area within the county. Note that this percentage is not comparable with the percentage of wheat cover used in figures 25 and 26, since these indicate the area of wheat cover within the total area of the county. This last indicator was selected because the objective was to find the largest potential for water volume reduction. The indicator used for the fallow land is used to find the largest percentage of manageable non-agriculture in the county.

The areas shown in red are counties with a high percentage of non-producing agricultural lands. It is clear that there are more of these lands during the winter season (Figure 27) than during the summer season (Figure 28).

The average water consumption of these fallow and low-producing lands can be calculated from the SEBAL results, and is for the winter season 21 $m^3$ and for the maize season 8 $km^3$. The high volume during the winter is mainly due to the large area of non-producing agriculture. The equivalent depths for the winter season and the summer season are 250 and 208 mm respectively.

The land use map provided by Chinese experts can be used to calculate an average evapotranspiration per land use class. Table 4 shows the average annual evapotranspiration per class, and the percentage of consumed volume per land use class. Table 5 shows the results of a similar analysis done separately for summer and winter. From this table it can be seen that the land use class "bare ground" has the minimum evapotranspiration in the winter, with a value of 203 mm. There are 109 $km^2$ identified as bare ground in the Hai Basin.

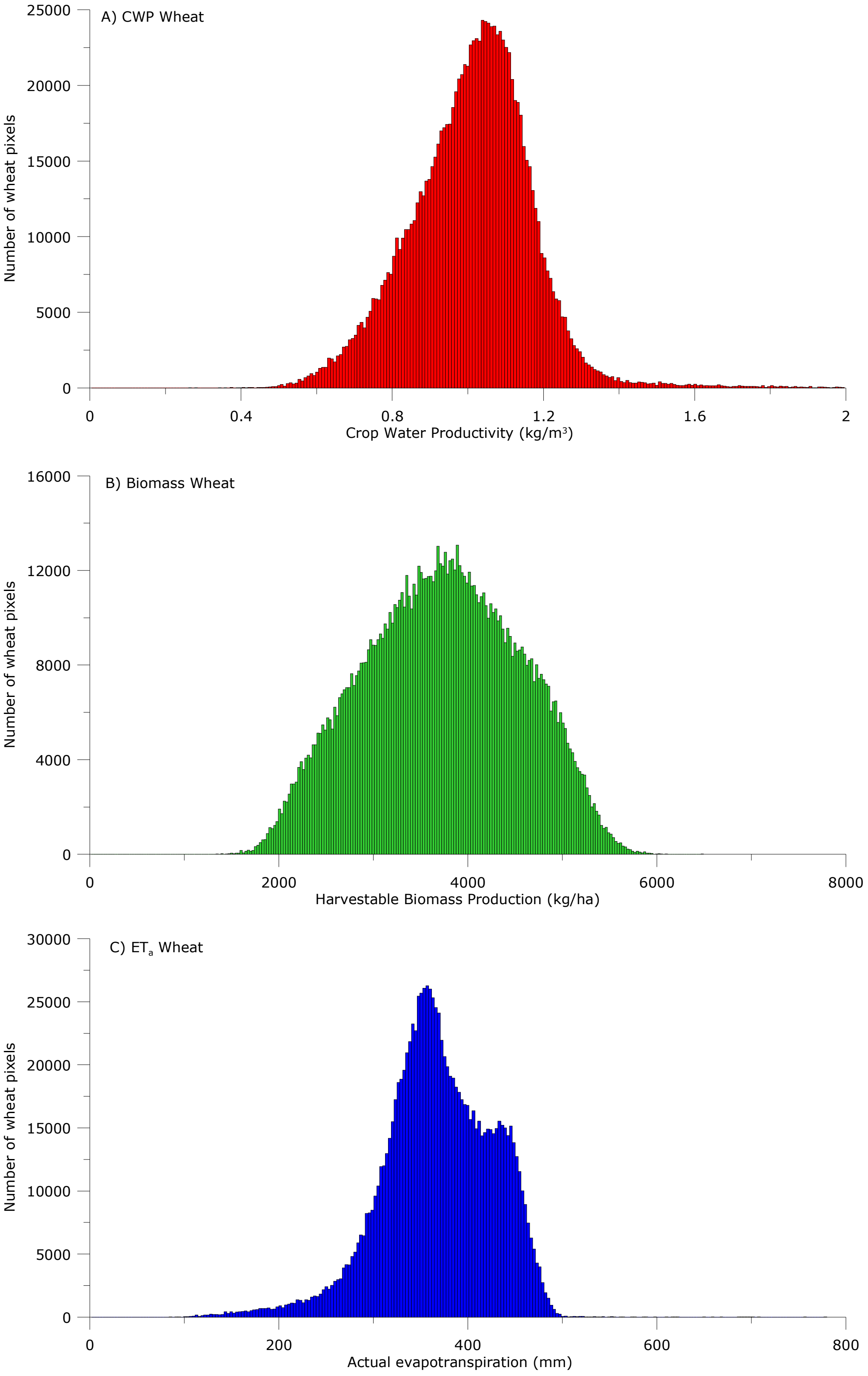

**Figure 23: Histogram of (A) crop water productivity (kg/m3), (B) Crop yield, (C) Actual evapotranspiration for wheat classified pixels in the Hai Basin in 2003.**

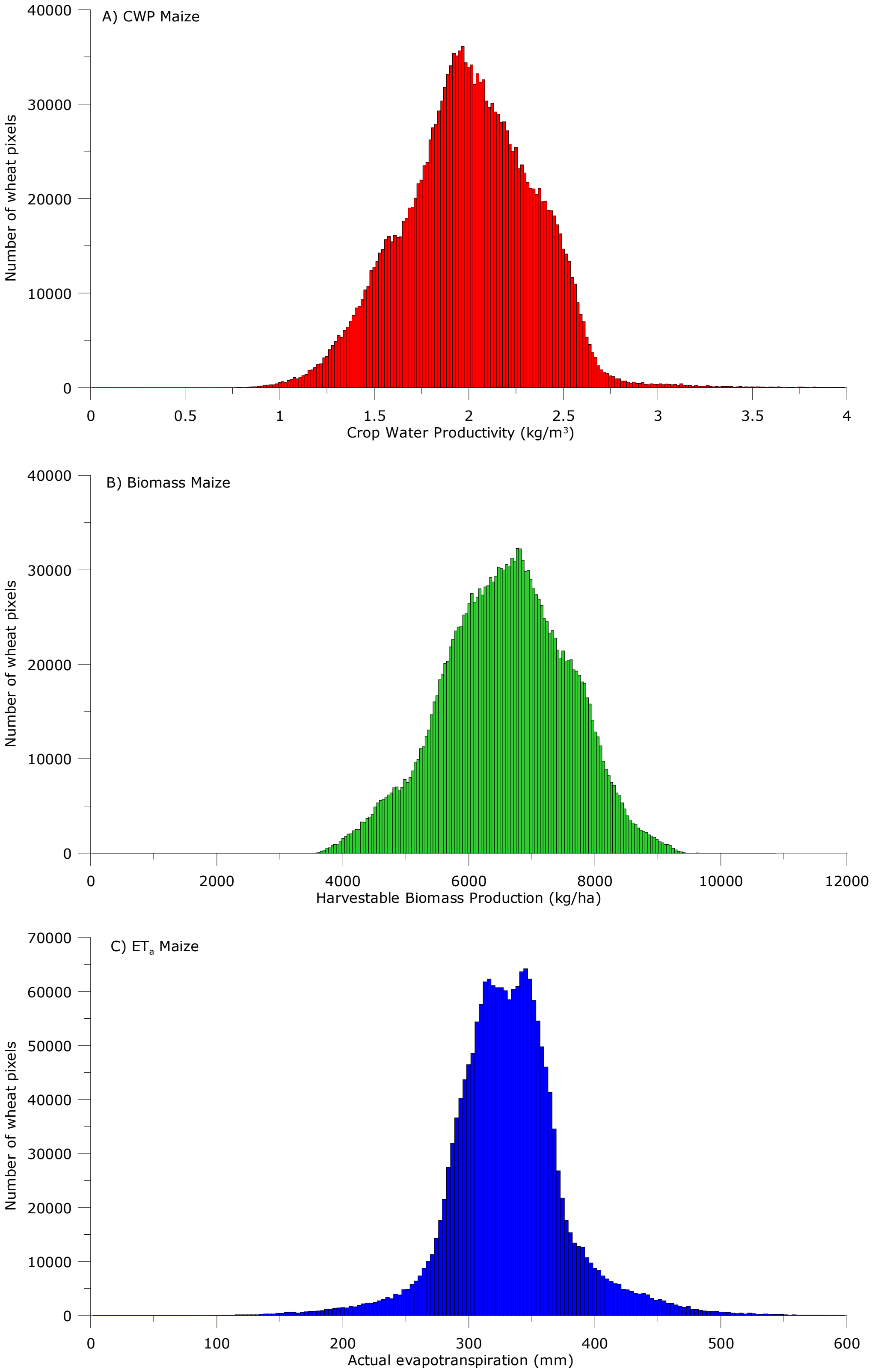

**Figure 24: Histogram of (A) crop water productivity (kg/m3), (B) Crop yield, (C) Actual evapotranspiration for maize classified pixels in the Hai Basin in 2003.**

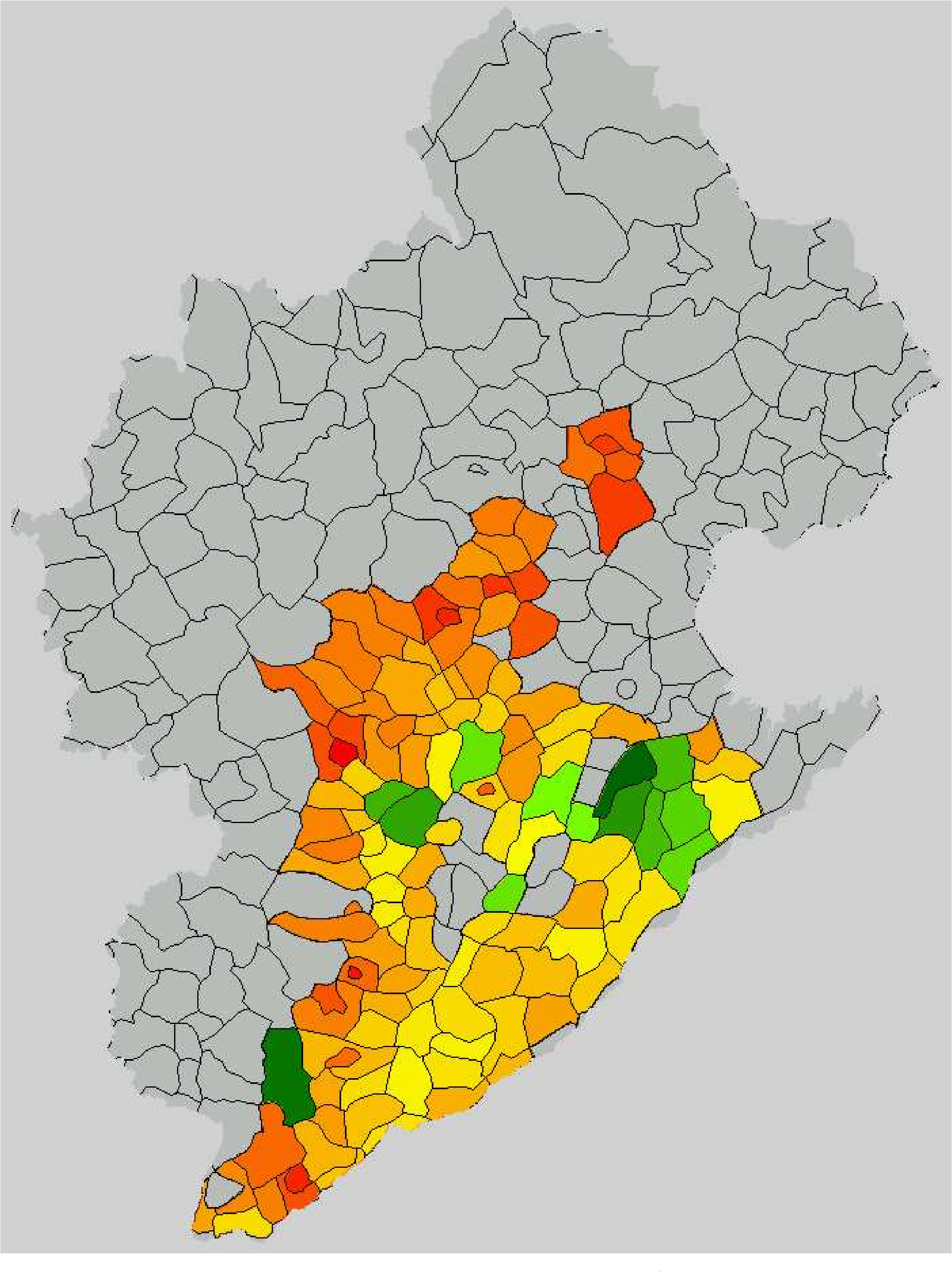

**Figure 25: County-averaged crop water productivity for counties with more than 25% wheat in the Hai Basin, 2003.**

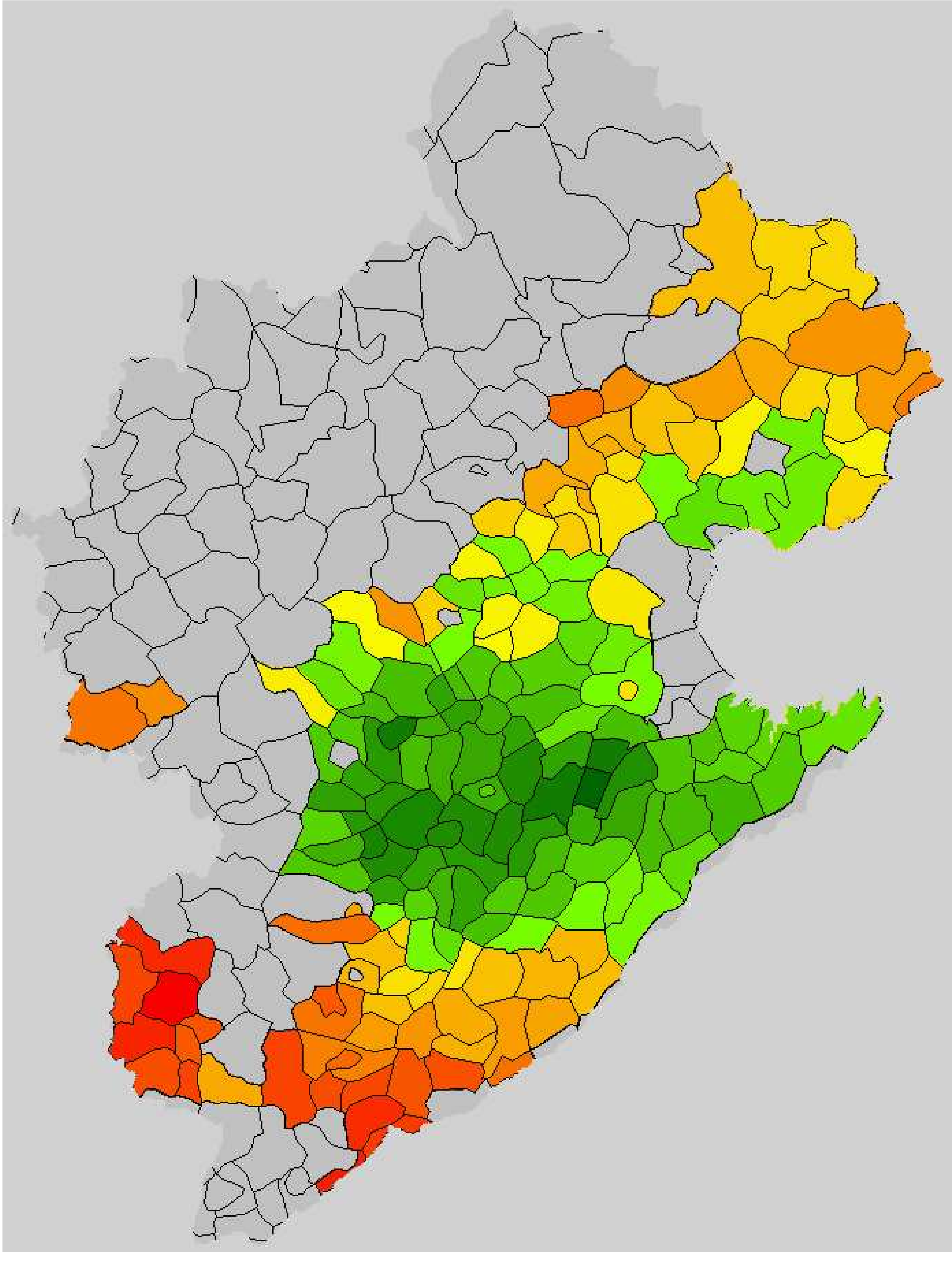

**Figure 26: Crop water productivity for Hai basin in 2003 for counties with more than 25% maize cover**

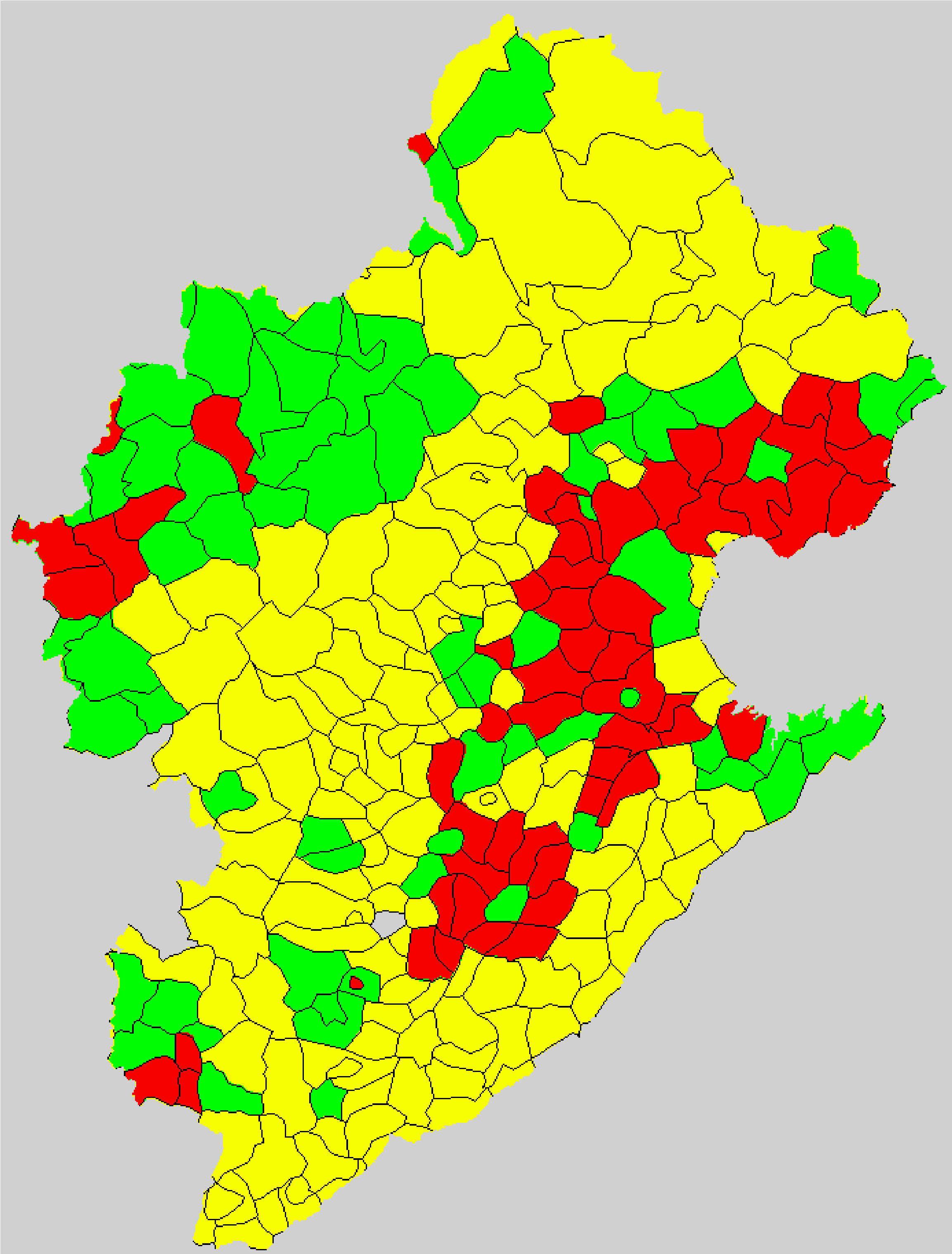

**Figure 27: Percentage of non-wheat agriculture per county in winter 2003. Yellow < 30% non-wheat agriculture; 30% < green < 50% non-wheat agriculture; 50% < red <80% non-wheat agriculture.**

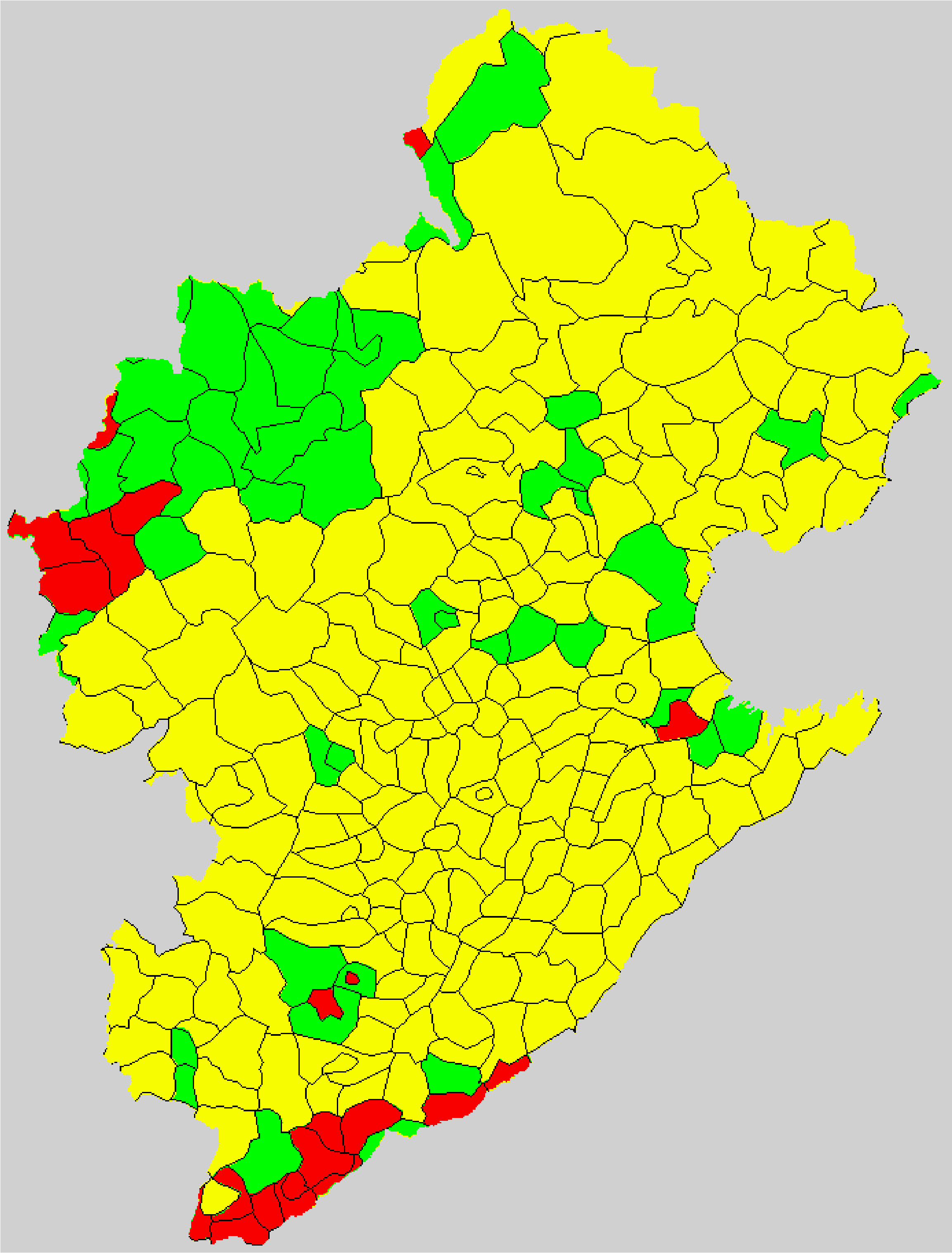

**Figure 28: Percentage of non-wheat agriculture per county in winter 2003. Yellow < 30% non-wheat agriculture; green < 50% non-wheat agriculture; red <80% non-wheat agriculture.**

Based on the measurements on bare ground the value of 200 mm is used as the lower limit that evapotranspiration can be reduced through land management during the winter. This means that through improved fallow-land management during the winter the evapotranspiration can be reduced by 50 mm. This is equal to a volume of 4.2 $km^3$.

During the summer season, when it rains more frequently, the land use class "bare ground" shows an average evapotranspiration of 225 mm. The non-maize agricultural fields show an average ET of 208 mm. This is an indication that management of fallow agricultural fields already are reducing evapotranspiration. This is likely caused by a good infiltration rate on these fields, and a top layer of these fields that, when dry, provides a mulching layer, thus reducing the amount of available water for evaporation. During the summer season, the land use classes "sandy land" and "exposed rock" show lower ET values. However, it is not likely that ET from land suitable for agriculture can be compared to ET from sandy land or exposed rock. The potential water savings during the summer from fallow lands is therefore negligible.

Based on table 4, the annual ET of the Hai Basin can be subdivided into three classes: consumptive use, beneficial ET and non-beneficial ET. Consumptive use is the total of all agricultural land, thus for the Hai basin the total of paddy, irrigated and non-irrigated land. Beneficial use is evapotranspiration of forests, woodlands and homesteads, while non-beneficial evaporation can be found from fallow land, weeds, and waste land. A classification of land uses into consumptive, beneficial and non-beneficial ET is shown in table 6. This would result in a total consumptive use of 92 $km^3$, beneficial use of 67 $km^3$ and non-beneficial use of 29 $km^3$. Especially this last category could be targeted to obtain more water savings. However, it is not known if these lands are manageable.

## Table 4: Annual evapotranspiration (volume and percentage) for land use classes in the Hai Basin in 2003.

| ET(mm) | ET (km3) | ET (%) | Area (km2) | Area (%) | Land use class |
|---|---|---|---|---|---|
| 630 | 75.6 | 40.4 | 120072 | 37.7 | plain irrigated field |
| 540 | 17.4 | 9.3 | 32135 | 10.1 | middle grassland with cover between 20-50% |
| 624 | 16.4 | 8.8 | 26273 | 8.2 | forest dominated by trees with a canopy cover >30% |
| 611 | 16.1 | 8.6 | 26346 | 8.3 | closed shrublands |
| 611 | 10.4 | 5.6 | 17059 | 5.4 | industrial and mining land |
| 485 | 9.1 | 4.8 | 18671 | 5.9 | low grassland with cover between 5-20% |
| 565 | 9.0 | 4.8 | 15940 | 5.0 | forest dominated by trees with a canopy cover between 10-30% |
| 537 | 6.9 | 3.7 | 12758 | 4.0 | mountain non-irrigated field |
| 456 | 6.6 | 3.5 | 14368 | 4.5 | hill non-irrigated field |
| 485 | 3.0 | 1.6 | 6131 | 1.9 | high grassland with cover >50% |
| 644 | 3.0 | 1.6 | 4605 | 1.4 | plain paddy |
| 587 | 2.5 | 1.4 | 4342 | 1.4 | other forest |
| 487 | 2.2 | 1.2 | 4598 | 1.4 | urban and town land |
| 671 | 2.0 | 1.1 | 3026 | 0.9 | reservoir and pond |
| 657 | 1.9 | 1.0 | 2867 | 0.9 | other construction land |
| 599 | 1.9 | 1.0 | 3132 | 1.0 | saline-alkali land |
| 576 | 1.6 | 0.8 | 2721 | 0.9 | bottomland |
| 619 | 0.8 | 0.4 | 1355 | 0.4 | river and channel |
| 432 | 0.4 | 0.2 | 837 | 0.3 | exposed rock |
| 533 | 0.3 | 0.2 | 598 | 0.2 | marshes |
| 389 | 0.1 | 0.1 | 310 | 0.1 | sandy land |
| 604 | 0.1 | 0.0 | 124 | 0.0 | slope non-irrigated field |
| 772 | 0.0 | 0.0 | 62 | 0.0 | tidal flat |
| 434 | 0.0 | 0.0 | 109 | 0.0 | bare ground |
| 710 | 0.0 | 0.0 | 45 | 0.0 | other land |
| 529 | 0.0 | 0.0 | 48 | 0.0 | mountain paddy |
| 578 | 0.0 | 0.0 | 40 | 0.0 | lake |
| 616 | 0.0 | 0.0 | 6 | 0.0 | hill paddy |

## Table 5: Summer and winter evapotranspiration (volume and percentage) for land use classes in the Hai Basin in 2003.

| ET summer (mm) | ET (%) | ET winter (mm) | ET (%) | Land use class |
|---|---|---|---|---|
| 313 | 40.6 | 320 | 40.6 | plain irrigated field |
| 260 | 9.0 | 281 | 9.5 | middle grassland with cover between 20-50% |
| 290 | 8.2 | 333 | 9.2 | forest dominated by trees with a canopy cover >30% |
| 284 | 8.1 | 331 | 9.2 | closed shrublands |
| 325 | 6.0 | 264 | 4.8 | industrial and mining land |
| 265 | 5.3 | 218 | 4.3 | low grassland with cover between 5-20% |
| 274 | 4.7 | 287 | 4.8 | forest dominated by trees with a canopy cover between 10-30% |
| 254 | 3.9 | 202 | 3.1 | hill non-irrigated field |
| 269 | 3.7 | 265 | 3.6 | mountain non-irrigated field |
| 320 | 1.6 | 329 | 1.6 | plain paddy |
| 230 | 1.5 | 256 | 1.7 | high grassland with cover >50% |
| 310 | 1.5 | 265 | 1.2 | other forest |
| 215 | 1.1 | 257 | 1.2 | urban and town land |
| 311 | 1.1 | 289 | 1.0 | saline-alkali land |
| 317 | 1.0 | 358 | 1.1 | reservoir and pond |
| 286 | 0.9 | 365 | 1.1 | other construction land |
| 285 | 0.8 | 292 | 0.8 | bottomland |
| 304 | 0.4 | 318 | 0.5 | river and channel |
| 195 | 0.2 | 237 | 0.2 | exposed rock |
| 260 | 0.2 | 281 | 0.2 | marshes |
| 152 | 0.1 | 234 | 0.1 | sandy land |
| 304 | 0.0 | 298 | 0.0 | slope non-irrigated field |
| 225 | 0.0 | 209 | 0.0 | bare ground |
| 321 | 0.0 | 441 | 0.0 | tidal flat |
| 295 | 0.0 | 428 | 0.0 | other land |
| 273 | 0.0 | 262 | 0.0 | mountain paddy |
| 280 | 0.0 | 327 | 0.0 | lake |
| 321 | 0.0 | 301 | 0.0 | hill paddy |

## Table 6: Classification of land use categories in ET categories

| Land use class | ET-category | ET (km3) |
|---|---|---|
| middle grassland with cover between 20-50% | Beneficial Use | 17.4 |
| forest dominated by trees with a canopy cover >30% | Beneficial Use | 16.4 |
| closed shrublands | Beneficial Use | 16.1 |
| forest dominated by trees with a canopy cover between 10-30% | Beneficial Use | 9.0 |
| high grassland with cover >50% | Beneficial Use | 3.0 |
| other forest | Beneficial Use | 2.5 |
| urban and town land | Beneficial Use | 2.2 |
| tidal flat | Beneficial Use | 0.0 |
| plain irrigated field | Consumptive Use | 75.6 |
| mountain non-irrigated field | Consumptive Use | 6.9 |
| hill non-irrigated field | Consumptive Use | 6.6 |
| plain paddy | Consumptive Use | 3.0 |
| slope non-irrigated field | Consumptive Use | 0.1 |
| mountain paddy | Consumptive Use | 0.0 |
| industrial and mining land | Non-Beneficial Use | 10.4 |
| low grassland with cover between 5-20% | Non-Beneficial Use | 9.1 |
| reservoir and pond | Non-Beneficial Use | 2.0 |
| other construction land | Non-Beneficial Use | 1.9 |
| saline-alkali land | Non-Beneficial Use | 1.9 |
| bottomland | Non-Beneficial Use | 1.6 |
| river and channel | Non-Beneficial Use | 0.8 |
| exposed rock | Non-Beneficial Use | 0.4 |
| marshes | Non-Beneficial Use | 0.3 |
| sandy land | Non-Beneficial Use | 0.1 |
| bare ground | Non-Beneficial Use | 0.0 |
| other land | Non-Beneficial Use | 0.0 |
| lake | Non-Beneficial Use | 0.0 |
| hill paddy | Non-Beneficial Use | 0.0 |

## 8. Conclusions and Recommendations

A summary of results of this study is shown in box 3

**Box 3: Summary of values obtained in this study**

| | |
|---|---|
| - Hai Basin Surface Area[a]: | 318.650 km$^2$ |
| **2003** | |
| - Basin average ET actual in 2003 (SEBAL) | 589 mm |
| - Basin average rainfall in 2003 (TRMM) | 603 mm |
| - Long term average rainfall in Hai Basin | 550 mm |
| - Total ET consumption (all land use classes) | 188 km$^3$ |
| - Total ET consumption by agriculture[b, c] | 92 km$^3$ |
| - Total area classified as agriculture[c] | 151.981 km$^2$ |
| **Winter Crop** | |
| - Season from 1 Oct to 15 Jun | 258 days |
| - Basin average ET in wheat season (SEBAL) | 297 mm |
| - Basin average rainfall in 2003 (TRMM) | 293 mm |
| - Total ET consumption (all land use classes) | 95 km$^3$ |
| - Total ET consumption by class "agriculture" | 46 km$^3$ |
| - Total area classified as wheat in 2003[d] | 67.564 km$^2$ |
| - Total ET consumption by wheat | 25 km$^3$ |
| - Total ET consumption by non-wheat agriculture | 21 km$^3$ |
| - Average ET for wheat | 369 mm |
| - Average ET for non-wheat agriculture class | 250 mm |
| **Summer Crop** | |
| - Season from 16 Jun to 30 Sep | 107 days |
| - Basin average ET in maize season (SEBAL) | 291 mm |
| - Basin average rainfall in 2003 (TRMM) | 309 mm |
| - Total ET consumption (all land use classes) | 93 km$^3$ |
| - Total ET consumption by class "agriculture" | 46 km$^3$ |
| - Total area classified as maize[d] | 114.779 km$^2$ |
| - Total ET consumption by maize | 38 km$^3$ |
| - Total ET consumption by non-maize agriculture | 8 km$^3$ |
| - Average ET for maize | 333 mm |
| - Average ET for non-maize agriculture class | 208 mm |

---

[a] Based on shape file obtained from Hai Basin Commission

[b] Includes irrigated and non-irrigated agriculture

[c] Based on land use classification file obtained from Hai Basin Commission

[d] Based on land use classification using results of SEBAL calculations

- ETa values obtained by the present study are in the range of values reported in literature for the Hai Basin. The area under wheat is smaller than the area under maize. The area classified as agriculture in the land use map was not fully covered by maize or wheat in 2003. These areas are likely covered by less intensive agriculture, or are left fallow. The volumes of water manageable through wheat and maize is therefore 17 and 36 km$^3$ respectively. The evapotranspiration of the non-wheat and non-maize agriculture (including fallow fields), 29 km$^3$ and 10 km$^3$ respectively, are also manageable, however, and could possibly be reduced without a loss of total crop yield.

- Both winter crop (wheat) and summer crop (maize) use similar volumes of water. The winter crop has a season that is more than twice as long as the summer crop. Based on the seasonal water balance in 2003, as well as the annual water balance in 2003, it appears that no additional groundwater extraction would be necessary. However, the temporal distribution of ETa and precipitation over the season is such that supplemental irrigation is needed. The winter crop usually is irrigated during the months of March, April, May and June, while the summer crop may receive supplemental irrigation in June and July. Figure 10 shows that there is a water deficit for these months in almost the complete Hai Basin.

- The long term average rainfall for the Hai Basin is 550 mm. This is 53 mm below the TRMM measurement for 2003. Assuming that consumptive use (ETa) is constant over the years, there would be a structural groundwater overexploitation of 40 mm, equivalent to 13 km$^3$. To maintain a sustainable use of groundwater, and to develop healthy rivers with an outflow to the sea, more than 13 km$^3$ is required to be saved, or added to the water resources through a south-north transfer of water. This is a somewhat lower deficit than assumed in previous reports (ET of 660 mm and rainfall of 460 mm in LuangCheng County, deficit of 200 mm/year [Kendy et al, 2003]; 700 mm ET and rainfall of 550 mm in 2002, deficit of 150 mm [Bastiaanssen, 2005]) possibly indicating a lower than average basin-ET in 2003. Increased rainfall and a higher annual cloud cover would result in a lower annual ET.

- A reduction of 11 km$^3$ could be obtained by eliminating the water use by the wheat crop. However, this would likely result in a non-acceptable loss of yield and income. Eliminating the wheat crop would just be sufficient for the minimal reduction, since the difference between a cropped area and a fallow area is less than 100% of the crop evapotranspiration. More likely it will only reduce 50-60% of the crop ETa. Improvements in the water use of the wheat and maize crop will however contribute to the reduction of evaporation and implementation of water saving techniques. The non-intensive agriculture and fallow land during the winter period however contribute to 21 km$^3$ of consumed water. Since it has been classified as agricultural land in the land use cover, it can be assumed that this evapotranspiration occurs from manageable fields. Mulching, zero tillage and other methods to reduce evaporation from fallow fields can be applied to these areas. Counties with a high percentage of areas classified as "agriculture" but without high density agriculture as measured using remote sensing are shown in Figure 27.

- A summary of potential water savings using different approaches is shown in box 4. It can be concluded that no single water management implementation will be sufficient to obtain the minimal savings required to obtain a sustainable groundwater extraction (12-13 km$^3$). To reach this more sustainable situation, several parallel water savings programs will need to be implemented. A combination of improving the regional crop water productivity and a reduction of evaporation from non-productive agricultural fields can result already in savings of 12 km$^3$ without reduction of agricultural production. Increasing environmental flows of rivers should also be part of reaching a sustainable water situation. This would result in higher savings of water than indicated above.

**Box 4: Summary of potential water savings**

Increase crop water productivity in areas with lower than region average cwp (no reduction of total yield)

| | |
|---|---|
| - for wheat | 1.6 km$^3$ |
| - for maize | 1.4 km$^3$ |
| - annually | 3.0 km$^3$ |

Increase crop water productivity for all agriculture to 95% of max regional cwp (no reduction of total yield)

| | |
|---|---|
| - for wheat | 2.8 km$^3$ |
| - for maize | 5.1 km$^3$ |
| - annually | 7.9 km$^3$ |

Eliminating winter crop, assuming a fallow field evaporation of 200 mm (100% reduction of yield)

| | |
|---|---|
| - for wheat | 11.4 km$^3$ |

Managing non-productive agricultural fields to reduce ET to 200 mm

| | |
|---|---|
| - for winter season | 4.2 km$^3$ |
| - for summer season | 0.3 km$^3$ |
| - annually | 4.5 km$^3$ |

- This current study has focused on agricultural water savings, and has used the crop water productivity as an indicator to select areas where water could be saved. Water savings and policy implementations can also be applied based on other indicators, for example an indicator based on the distribution of rainfall, or based on the levels of groundwater levels. This could possibly result in a different ET-quota than indicated in this report.

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# Appendix 1: Technical Report on SEBAL analysis

## 1. General Information

**a.** Satellite sensors used

MODIS

**b.** Location of study area

Hai Basin, P.R. China

**c.** Image acquisition dates /times

| Image Date | Local Time | GMT time |
|---|---|---|
| 01/08/2003 | 12:50 | 04:50 |
| 02/12/2003 | 13:22 | 05:22 |
| 02/19/2003 | 13:27 | 05:27 |
| 03/09/2003 | 13:15 | 05:15 |
| 03/25/2003 | 13:15 | 05:15 |
| 04/14/2003 | 12:52 | 04:52 |
| 04/30/2003 | 12:50 | 04:50 |
| 05/01/2003 | 13:35 | 05:35 |
| 05/25/2003 | 12:45 | 04:45 |
| 06/04/2003 | 13:20 | 05:20 |
| 06/10/2003 | 12:45 | 04:45 |
| 06/24/2003 | 12:57 | 04:57 |
| 07/04/2003 | 13:35 | 05:35 |
| 07/29/2003 | 13:27 | 05:27 |
| 08/07/2003 | 13:20 | 05:20 |
| 08/11/2003 | 12:57 | 04:57 |
| 08/30/2003 | 13:27 | 05:27 |
| 09/10/2003 | 13:10 | 05:10 |
| 09/20/2003 | 13:45 | 05:45 |
| 09/24/2003 | 13:20 | 05:20 |
| 10/03/2003 | 13:15 | 05:15 |
| 10/15/2003 | 13:40 | 05:40 |
| 10/22/2003 | 13:47 | 05:47 |
| 10/28/2003 | 13:10 | 05:10 |
| 11/22/2003 | 13:05 | 05:05 |
| 12/13/2003 | 13:22 | 05:22 |
| 12/20/2003 | 13:27 | 05:27 |

**d.** SEBAL processing period

August - November 2005

**e.** Names of staff involved and divisions of tasks

Dr R.W.O. (Richard) Soppe: computing and reporting of results
Dr. W.G.M. (Wim) Bastiaanssen: supervision

## 2. Data Sent

**a.** File names
- bio_maize
- bio_wheat
- et_period
- et_ss_alper
- etp_ss_alper
- h2oprod_maize
- h2oprod_wheat
- et_sum
- etp_sum
- etr_sum

**b.** File contents

Each file contains ArcView GRID coverages for the dates analyzed.

**c.** Format and projections used

Arc/INFO-Grid coverages;
Projection:
Alberts Conical Equal Area
Speroid/Datum: WSG84

## 3. Meteorological pre-processing

**a.** Weather stations used

Meteorological data were provided by the client.
Rainfall was obtained from the Tropical Rainfall Measurement Mission (TRMM)

**b.** Meteorological parameters measured

Air temperature
Relative humidity
Solar radiation
Wind speed

## 4. SEBAL decisions made

**a.** Type of Digital Elevation Model used

SRTM data, 90 m resolution

**b.** Specifications of hot and cold pixels

Hot and cold pixels were selected for each image. The table below shows the UTM-coordinates of these pixels. Cold pixels were chosen over water bodies.

| Date | Cold pix X | Cold pix Y | Hot pix X | Hot pix Y |
|---|---|---|---|---|
| 01/08/2003 | 752527 | 2362005 | 727158 | 1937923 |
| 02/12/2003 | 1080789 | 2375404 | 648293 | 2593911 |
| 02/19/2003 | 1068410 | 2357469 | 756876 | 2483757 |
| 03/09/2003 | | | | |
| 03/25/2003 | | | | |
| 04/14/2003 | 1147848 | 2412297 | 731230 | 2131637 |
| 04/30/2003 | 855279 | 2231729 | 675094 | 2427907 |
| 05/01/2003 | 633072 | 2587979 | 817599 | 2562196 |
| 05/25/2003 | 942749 | 287360 | 768653 | 2494592 |
| 06/04/2003 | | | | |
| 06/10/2003 | | | | |
| 06/24/2003 | 1151886 | 2304313 | 619059 | 2463794 |
| 07/04/2003 | 949622 | 2858323 | 852464 | 2813326 |
| 07/29/2003 | 915027 | 2131756 | 736837 | 238786 |
| 08/07/2003 | 950258 | 2857743 | 821928 | 2836039 |
| 08/11/2003 | 948019 | 2859252 | 867274 | 2821887 |
| 08/30/2003 | 950592 | 2856245 | 804562 | 2823812 |
| 09/10/2003 | 951639 | 2856492 | 835926 | 2809170 |
| 09/20/2003 | 1062226 | 2357519 | 684847 | 2522338 |
| 09/24/2003 | | | | |
| 10/03/2003 | | | | |
| 10/15/2003 | | | | |
| 10/22/2003 | | | | |
| 10/28/2003 | | | | |
| 11/22/2003 | | | | |
| 12/13/2003 | | | | |
| 12/20/2003 | | | | |

Advection-correction has been applied.

## 5. Additional comments

In 2003, it was possible to obtain 27 MODIS images that could be used for the SEBAL analysis. However, not all the 27 images were cloud free. The daily analysis of images were done using a cloud mask to eliminate areas under cloud cover.

For the period integration (from 1 daily image to a 10 or 15 day period), the areas masked in the daily image were calculated using an average value from images before and after the missing data. This is the same methodology as if for an area the period integration is to a 15 day integration instead of a 10 day integration, or a 30 day integration instead of a 15 day integration.

The cumulative normalized cloud mask shown in Figure 1 is an indication in what area clouds most often occurred. It can be seen that in most of the Hai Basin, more than 90% of the images were cloud free. Only in the southern part of the basin a small area exist with 60% of the images cloud free. The SEBAL analysis is still valid for this area (16 images were still used for the annual evapotranspiration calculations).

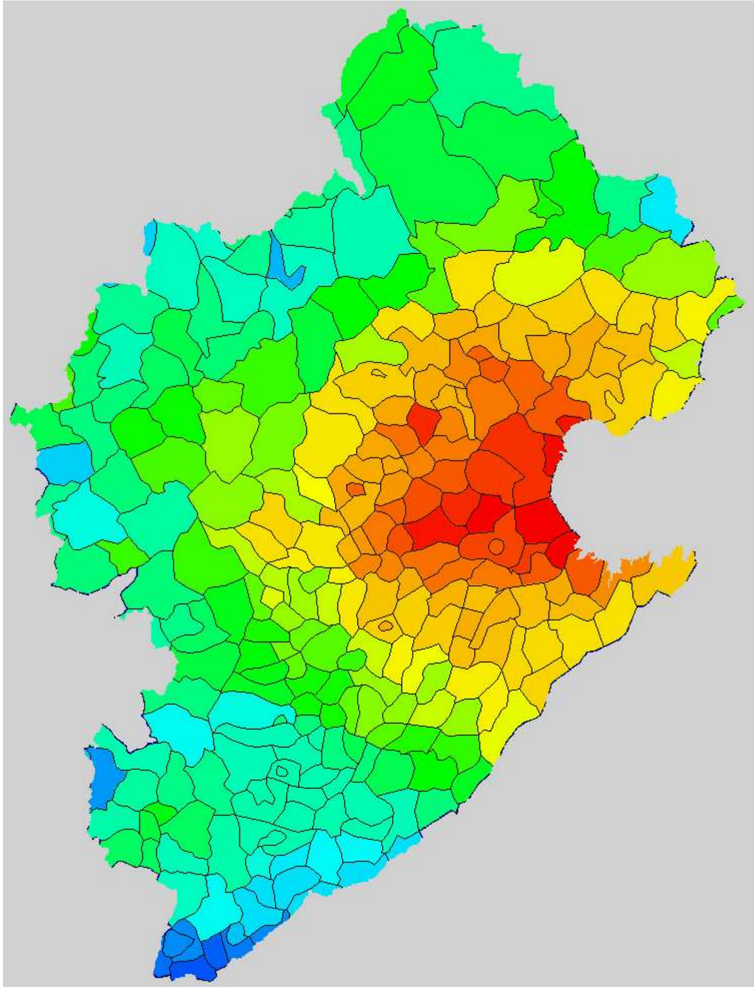

**Figure 1: Normalized cloud free areas for 27 images used in analysis**