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Improving spatial resolution of ET seasonal for irrigated rice in Zhanghe, China

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ABSTRACT

Recently, advances have been made to obtain estimates of evapotranspiration (ET) through remote sensing. A problem still persists to get ET over a longer time period. Orbiting satellites supply with images answering the need for water consumption data, but due to technical limitations have either high spatial resolution restricted to low revisit frequency, or frequent revisit cycle but low spatial resolution. Remote sensing technicians are facing this problem when trying to provide regular and fine resolution information about water consumption of crops in irrigation systems. The solution would be to combine the high spatial resolution with the high temporal resolution satellite images.
In this study, actual evapotranspiration images from NOAA AVHRR acquired at various dates in Zhanghe irrigation district are used together with meteorological daily reference evapotranspiration data to simulate daily evapotranspiration. A temporal integration for the May – September rice cropping season provides the seasonal actual evapotranspiration map. This information, collected at a pixel size of 1.1 km is merged together with a Landsat 7 ETM+ image acquired at a strategic moment of the cropping season. The result is a more detailed redistribution of seasonal evapotranspiration to finer resolutions, while keeping the actual evapotranspirated global volume constant, before and after the merging. This provides a better located estimation of water consumption, especially for rice. Irrigated rice fields are of particular interest to the water managers, since these fields are the main cash crop of the irrigation district. In the discussion that follows, it is shown that the remote sensing limitations can be overcome using meteorological data and combined information from two satellites, providing detailed results of low cost.

1. INTRODUCTION

Balancing the limited water resources to match the human needs is a challenge to be faced in the coming years. Water resources have to be managed very clearly from the water basin to the irrigated crops, eventually reaching to smaller areas and users. Measuring the evapotranspiration is of highest importance for understanding and eventually intervening into the water cycle of natural systems. Especially in the water balance of the different critical users of water, like irrigated areas. Remote sensing has come out, over the last decade, with methods for calculating the actual evapotranspiration (ETa) (Vidal and Perrier 1989; Bastiaanssen 1998).

A main limitation of the models used in remote sensing, is that they are based on a satellite image, representing the calculation of a daily evapotranspiration. It would be tempting to process images every day if the computation procedures were not so intensive, and if visible satellite data were always cloud free and cost was not a limitation. As it is not so, most of the time a limited amount of images processed into daily evapotranspiration maps are available to supplement studies. The issue of temporal integration is risen to fill in the missing data. Droogers and Bastiaanssen (submitted) improved the temporal and spatial variation of evapotranspiration from a water balance model by supplementing it with high-resolution satellite images of evapotranspiration. The satellite images provided the model with strategic calibration data to refine the seasonal estimation of the water balance for irrigated crops. Work performed by Bastiaanssen et al. (2001) and Bastiaanssen and Ali (submitted) uses meteorological data to integrate ETa and crop growth, respectively between satellite image data in the Indus Basin of Pakistan. Farah (2001) supplemented evaporation estimates from remote sensing over Kenya by coupled models of Penman-Monteith and Jarvis-Stewards to reconstitute evaporation under cloud conditions in the Navaisha Basin.

Despite the technological advance of remote sensors and the ability to detect finer objects on the ground, higher accuracy is always desirable. Technological restrictions confine satellite design to high resolution but low revisit frequency, or low resolution and high revisit frequency. A combination of both qualities would be preferred, and therefore, techniques to merge satellite images of different spatial resolutions have been developed. Welch and Ehlers (1987) have used an IHS transformation to merge SPOT panchromatic and Landsat multispectral satellite images, while Ambrosia et al. (1991) have used the same technique to merge airborne digital data with digitized aerial photography. Other techniques include the principal components transformation (Chavez, 1991), and merging of the spatial frequency content (Schowengerdt, 1980). Except for the need of spatial detail, another reason for this merge is that often high resolution images are costly, while low resolution are of low cost, or even are freely distributed.

It is possible that remote sensing work is performed using low-resolution satellite images that are later spatially enhanced using a high spatial resolution image. In this study, the free-of-cost NOAA AVHRR images provide a frequent source of data to calculate the volume of evapotranspirated water that has been consumed over the Zhanghe irrigation district during the 2000 rice cropping season. A methodology is developed to calculate the seasonal ETa, a component estimated with difficulty in water balance studies. Another objective is to show that enhancement of the spatial distribution of seasonal ETa is possible using a single Landsat ETM+ image. Finally, the last objective is to prove that the located estimations of water consumed for the whole season in rice fields can be enhanced through different scales.

2. METHODS

2.1 Study area

Situated in the Hubei Province, Central China, the Zhanghe irrigation district is situated North of the (Changjiang) Yangtze River. The net irrigated area reported is approximately of 160,000 ha, providing a large proportion of Hubei Province grain production. Rice production is widespread in the irrigation district, and the recent decline in water availability to agricultural purposes has not decreased much the global rice production due to a proportional increase of efficiency of water use by the farmers (Bin et al. 2001). Even though the system is running under the main operation of the Zhanghe reservoir, there are thousands of small sized reservoirs, small basins and pump stations in Zhanghe irrigation district partly incorporated in the irrigation system, but sometimes operating independently (Loeve et al. 2001). The complexity of the system brings up the difficulty to quantify the volumes of water used by traditional scientific methods.

2.2 Satellite images

NOAA AVHRR LAC images were ordered and downloaded from Satellite Active Archive. Five images of acceptable atmospheric conditions were acquired. These covered the rice-cropping season of 2000 with an average representation period of 32 days. The dates of the satellite images are May 10, June 21, July 9, August 12, and September 15. These are surrounding well the Landsat 7 ETM+ image acquired on July 10, that is in the full vegetative growth of rice crop. The satellites are having inherent characteristics and advantages linked to their spatial resolution and revisiting periods (temporal resolution), as shown in Table 1.

Satellite	Sensor	Spatial resolution	Temporal resolution	Acquisition dates
Landsat 7	ETM+	30 – 60 m	16 days	July 10, 2000
NOAA	AVHRR	1.1 km at nadir	1-2 days	May 10, 2000 June 21, 2000 July 9, 2000 August 12, 2000 September 15, 2000

Table 1: Details of satellites and images used in this study

2.3 SEBAL application in Zhanghe

The actual evaporation was estimated with the Surface Energy Balance Algorithm for Land (SEBAL), which was developed by Bastiaanssen (1998). SEBAL is a thermodynamically based model, looking towards finding the energy-balance terms at the land surface. While having a lot of empirically based steps, the physics of the core are robust thermodynamic equations. For insight of the practical procedure, Chemin et al. (2000) and Tasumi et al. (2000), provide extensive details of step-by-step considerations applied. It has been satisfactorily validated in many places and situations, from Spain (Bastiaanssen 1995) to Pakistan (Bastiaanssen et al. 2001).

Applying the SEBAL model to the Landsat ETM+ and NOAA AVHRR images of the Zhanghe irrigation district produces a set of intermediary products. These transitory layers of information are the normalized difference vegetation index (NDVI), surface emissivity, surface albedo, surface temperature, radiative/conductive/convective energy fluxes at the soil surface, daily potential ET, instantaneous evaporative fraction. Evaporation is calculated from the instantaneous evaporative fraction, and the daily averaged net radiation. The evaporative fraction is computed from the instantaneous surface energy balance at the moment of satellite overpass on a pixel-by-pixel basis. On the other hand, the daily averaged net radiation is mainly dependent on surface black body radiation and on the sun incoming radiation heating the Earth surface.

2.4 Temporal integration

Remote sensing calculation of ETa on certain sample dates during the cropping season gives a very good indication of its spatial distribution, but cannot be used directly in water balance studies. The reason behind is the wide fluctuation of ETa from day to day, depending on meteorological conditions and availability of water. Therefore, in order to obtain an accurate estimation of the seasonal ETa, daily values have to be simulated. A polynomial equation could describe the fluctuation of ETa, but a bigger sample of ET observations in time would be necessary to obtain an accurate result. The missing time component can be provided by daily calculation of ETo (reference evapotranspiration) as proposed by Tasumi and Allen (2000). ETo is calculated with the standardized Penman-Monteith method (Allen et al. 1998). Considering the fraction c_j = ETa/ETo constant for the time period j between two consecutive satellite images, the daily ETa can be simulated with the equation:

$$ETa' = c_j \, Eto \qquad (1)$$

where ETa' are the daily simulated ETa maps. Equation (1) is using the time component (ETo) to calibrate the spatial component of ETa calculation (c_j) in order to describe better the daily fluctuation, which is dependant on meteorological conditions. ETa also depends on the availability of water. Spatial variation of water availability can be described by the five ETa maps, which are assumed representative for each period j.

After the simulation of daily ETa', the values for the whole season are integrated and the seasonal ETa (ETs) is calculated on a pixel basis:

$$ETs = \sum_{t_1}^{t_2} ETa' \qquad (2)$$

where t_1 to t_2 is the period from May 01 to September 10, 2000.

The good spatial distribution of the satellite image is not matched with equally good meteorological data. Unfortunately there is only one meteorological station in Zhanghe, in the center of the irrigated area, and is not representative of the climatic conditions present in the area. Nonetheless, the measurements from the meteorological station where considered uniform across the Zhanghe irrigation district, due to lack of other data.

2.5 Resolution improvement

The spatial resolution of ETs estimated in the previous paragraph is limited by the resolution of NOAA AVHRR satellite images (1.1 km at nadir). Higher resolution could be desirable in Zhanghe irrigation district because of the size of the fields, and the texture of the cropping pattern (Alexandridis and Chemin, 2001). This can be achieved by using the higher spatial resolution of the available Landsat ETM+ satellite image (30m). The complex texture of the resulting ETa map is used as a weight to redistribute spatially the ETs calculated for each 1.21 km^2 pixel of the NOAA AVHRR satellite using the formula:

$$ETs' = ETs \cdot \frac{ET_{ETM+}}{\left(\overline{ET_{ETM+}}\right)} \qquad (3)$$

where $\overline{ET_{ETM+}}$ is the average of the values of ET_{ETM+} (Landsat) that occupy a pixel of ETs (NOAA).

Using this proportional distribution method, the total ETs value calculated for each area of 1.21 km^2 is preserved, but redistributed according to the detailed pattern of ETa derived from the ETM+ image. In this way, the influence of the high-resolution image induced in the methods found in literature (IHS and PC transformation) is avoided. Following Ambrosia et al. (1991), who suggest that a spatial resolution difference factor of 36 would be excessive (from 1.1 km to 30 m), factors of 2 and 4 have been used in order to redistribute the ETa values to spatial resolutions of 500m and to 250m, respectively.

3. RESULTS

Simulation of daily ETa raster maps was accomplished using the simple method described in the previous paragraphs. After the integration of the maps on a pixel-by-pixel basis, the seasonal ETa map (ETs) was produced. The ETs map describes the amount of water consumed (evapotranspirated) per unit area during the cropping season of rice (1 May 2000 – 10 September 2000), in the Zhanghe irrigation district (Table 2). Even with the 1.1 km spatial resolution (Figure 1a), the dryer non-irrigated areas (red color) can be differentiated from the areas where irrigated fields prevail (blue color).

Area	444300 ha
Global volume of water	2.0963 km^3
Mean ETs	472 mm/season
Min. ETs	299 mm/season
Max. ETs	649 mm/season

Table 2: Seasonal evapotranspiration (ETs) in Zhanghe irrigation district.

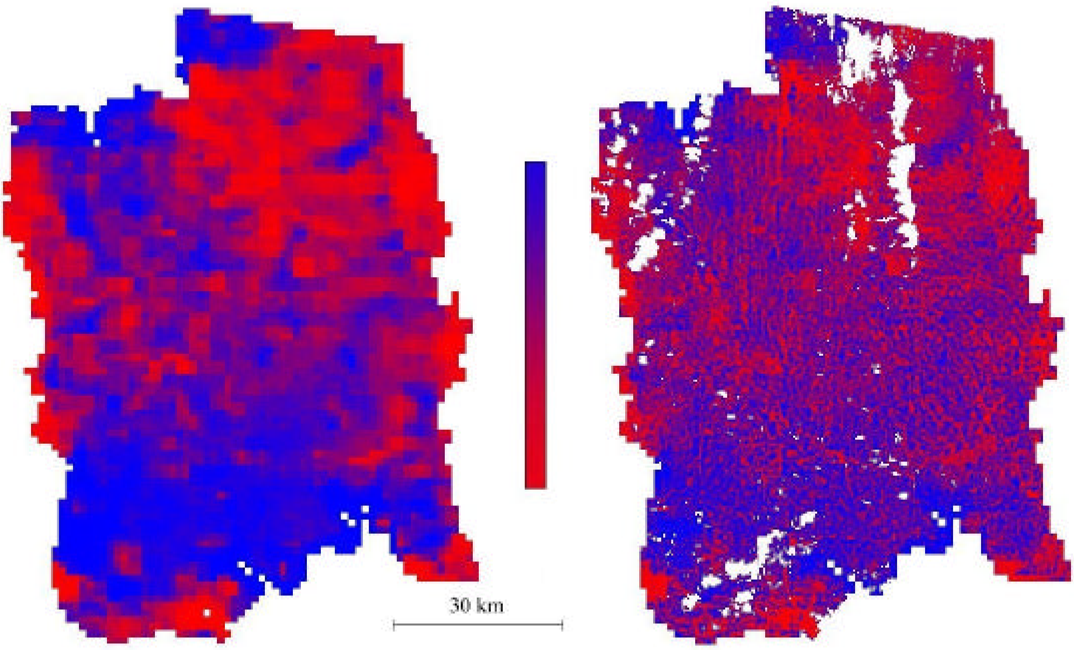

Figure 1: Seasonal actual evapotranspiration (ETs) map of Zhanghe irrigation district (1.1Km & 250m).

The spatial resolution of the ETs map is improved with the use of the high resolution ET_{ETM+} map. The 250 m pixel size map is presented in Figure 1b. Clearly, a different pattern is visible with interesting string type features that are the lowland rice cropping areas (blue). Lower ETs (red) is found in the natural vegetation interweaved between the rice features. White areas are clouds appearing in the Landsat ETM+ image, which were masked out in the improved ETs map. An enlarged detail from Zhanghe irrigation district is shown in Figure 2, where the pattern of irrigated areas (blue) is becoming gradually more visible.

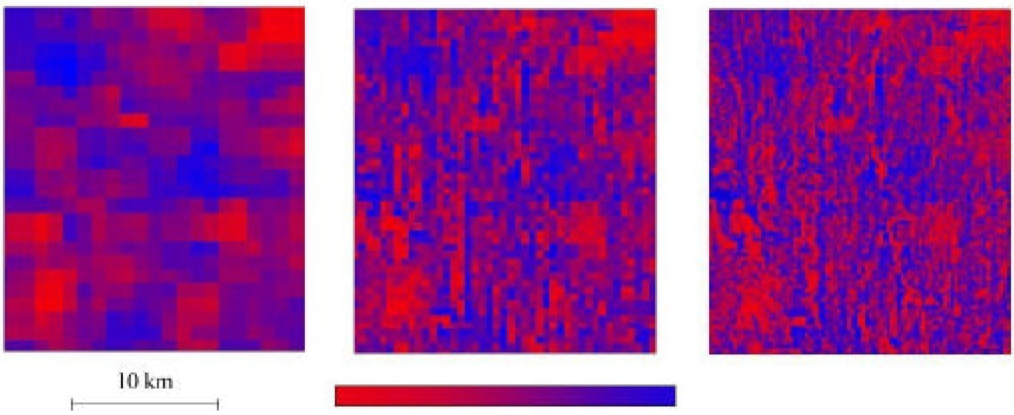

Figure 2: Area of ETs map in various spatial resolutions (1.1Km, 500m & 250m)

4. CONCLUSIONS

Simulation of daily ETa is a way to calculate the volume of water consumed during the rice cropping season (ETs). Temporal integration of the simulated ETa can produce a raster map of ETs, limited by the spatial resolution of NOAA AVHRR (1.1 km). Improving the spatial resolution of ETs map is possible by redistributing the pixel values proportional to a Landsat ETM+ ETa map. The global volume of water consumed in Zhanghe irrigation district is given in Table 3, calculated in different spatial resolutions. The mean value for the whole map is constant, as expected, since only the distribution of the values has changed to a more detailed pattern. For the same reason the standard deviation of the ETs map is increasing when moving to finer resolution. The global volume of water seems to change with the change of resolution, this is due to the appearance of clouds in the high resolution Landsat image. The mask for removing the clouds is changing slightly because of the change in pixel size. The cloud covered area is changing and influencing the remaining cloud-free area, and therefore, altering the global volume of water consumed.

Spatial resolution	Area (ha)	Global volume of water (km^3)	Mean ETs (mm/season)	Standard deviation (mm/season)
1.1 km	444300	2.0963	472	33
500 m	438225	2.0680	472	45
250 m	438737	2.0677	472	55

Table 3: ETs in Zhanghe at different spatial resolutions.

Apart from the cloud cover introduced by the Landsat ETM+ image, another problem is considered. The issue of representativity of a single day ETa map (10 July 2000) for the whole rice cropping season (1 May 2000 – 10 September 2000). The values of ETs measured for the whole season have been redistributed within each pixel proportionally to the use of water on a single day. The land use does not change within the same cropping season, and therefore variation of evapotranspiration between irrigated areas, natural vegetation, settlement areas and other land uses, can be correctly described. Within irrigated areas, a degree of inaccuracy in the redistribution of ETs is expected since the rate of evapotranspiration changes during the cropping cycle. Nevertheless, a degree of representation is provided since the chosen day is when rice is at full maturity and therefore fully evapotranspirating.

Spatial distribution of the water consumed is improved, leading to higher ETs accuracy per land class. The major irrigated crop in Zhanghe is rice, covering 33 percent of the area. Statistics for rice covered areas (Table 4) indicate a small increase in mean ETs when spatial resolution becomes finer. The improvement of the spatial distribution of the ETs through smaller pixel sizes, does separate more and more the low consumptive land classes from the highly consumptive irrigated rice areas. Therefore less influence from other land classes is input when calculating statistics for rice, and the refined result is reaching ideally towards pure rice pixels only. Still, the mean ETs for rice areas is not significantly higher than the mean of the total area, which leads to the conclusion that other features are equally high in water consumption as rice. These could be the open water bodies, which are numerous in the area, or other irrigated crops, such as cotton. The levels of standard deviations are smaller in the rice areas (Table 4) than the overall Zhanghe assessment (Table 3). This is expected because rice pixels are belonging to one homogeneous class of water consumer, reducing relatively the range of variations for a given pixel size.

Spatial resolution	Area (ha)	Volume of water (km^3)	Mean ETs (mm/season)	Standard deviation (mm/season)
1.1 km	142900	0.6768	474	24
500 m	144200	0.6915	480	36
250 m	144800	0.7048	487	44

Table 4: ETs in rice covered areas at different spatial resolutions.

The simulation of temporal detail and then the improvement of location accuracy of ETs, does bring a good trade off in low-cost water consumption monitoring of irrigation systems of medium areas. The redistribution of ETs is preserving the original estimated water volumes from NOAA AVHRR, but improves the allocation of water used between different land use classes, especially irrigated versus non-irrigated, since it is of first interest of water managers in an irrigation system *a priori*. The improved ETs of the highly water consuming irrigated crops (rice), can be further derived for primary and secondary canals if necessary. This is allowing the water managers to assess more accurately the performance and the water balance of irrigation sub-systems under operational constraints.

Improvement of the water efficiency at different levels of water supply and distribution can find suitable support in such technique for planning processes. The enhanced information content for low cost is very attractive for water managers and decision support system applications, especially in the sub-system level of irrigated areas where high resolution ET data is not spatially and temporally available simultaneously.

REFERENCES

Alexandridis, T., and Chemin, Y., 2001. Irrigation water consumption through remote sensing. Comparison at different scales in Zhanghe irrigation system, China. To be presented in First International Conference on Water Resources Management, Halkidiki, Greece, 10pp.

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO irrigation and drainage paper No 56. FAO, Rome, 300pp.

Ambrosia, V.G., Myers, J.S., Ekstrand, R.E., and Fitzgerald, M.T., 1991. Integration of Airborne Thematic Mapper Simulator (TMS) data and digitised areal photography via IHS. Geocarto International, 6 (2), pp.45-48.

Bastiaanssen, W.G.M., 1995. Regionalization of surface flux densities and moisture indicators in composite terrain. A remote sensing approach under clear skies in Mediterranean climates. Agricultural Research Department, Report 109, Wageningen, The Netherlands.

Bastiaanssen, W.G.M., 1998. Remote sensing in water resources management: the state of the art. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Bastiaanssen, W.G.M., Ahmad, M.D., and Chemin, Y., 2001. Satellite Surveillance of water use across the Indus Basin. Submitted to Water Resources Research.

Bastiaanssen, W.G.M., and Ali, S., 2000. A new crop yield forecasting model based on satellite measurements applied across the Indus Basin, Pakistan. Submitted to Agricultural Systems.

Bin, D., Loeve, R., Li, Y.H., Chen, C.D., Deng, L., and Molden, D.J., 2001. Water Productivity in Zhanghe Irrigation System: Issues of Scale. International Workshop on Water Saving Irrigation for Paddy Rice, Wuhan, China. Wuhan, China: China Rural Water and Hydropower. pp.76-93.

Chavez, P.J., Sides, S.C., and Anderson, J.A., 1991. Comparison of three different methods to merge multiresolution and multispectral data: Landsat TM and SPOT panchromatic. Photogrammetric Engineering and Remote Sensing, 57 (3), pp.295-303.

Droogers, P., and Bastiaanssen, W.G.M., 2001. Combining remote sensing and hydrological models to enhance spatial and temporal variability. Submitted to IAHS Red Books.

Farah, H.O., 2001. Estimation of regional evaporation under different weather conditions from satellite and meteorological data: a case study in the Navaisha Basin, Kenya. Doctoral Thesis Wageningen University and ITC, CIP-Data Koninklijke Biblotheek, Den Haag, The Netherlands, 170pp.

Loeve, R., Bin, D., and Molden, D.J., 2001. Operation of the Zhanghe Irrigation System. In International Workshop on Water Saving Irrigation for Paddy Rice, 23-25 March 2001, Wuhan, China. China Rural Water and Hydropower. pp.95-115.

Schowengerdt, R.A., 1980. Reconstruction of multispatial, multispectral image data using spatial frequency content. Photogrammetric Engineering and Remote Sensing, 46 (10), pp.1325-1334.

Tasumi, M., and Allen, R.G., 2000. Application of the SEBAL methodology for estimating consumptive use of water and streamflow depletion in the Bear River Basin of Idaho through Remote Sensing. Appendix A: The theoretical basis of SEBAL. Final Report. The Raytheon Systems Company, EOSDIS Project.

Tasumi, M., Bastiannssen, W.G.M., and Allen, R.G., 2000. Application of the SEBAL methodology for estimating consumptive use of water and streamflow depletion in the Bear River Basin of Idaho through Remote Sensing. Appendix C: A step-by-step guide to running SEBAL. Final Report. The Raytheon Systems Company, EOSDIS Project.

Vidal, A., and Perrier, A., 1989. Analysis of a simplified relation used to estimate daily evapotranspiration from satellite thermal IR data. International Journal of Remote Sensing 10 (8), pp. 1,327-1,337.

Welch, R., and Ehlers, W., 1987. Merging multiresolution SPOT HRV and Landsat TM data. Photogrammetric Engineering and Remote Sensing, 53 (3), pp.301-303.