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Regional estimation of daily to annual evapotranspiration with MODIS data in the Yellow River Delta wetland

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Abstract

Evapotranspiration (ET) from the wetland of the Yellow River Delta is one of the important components in the water cycle, which represents the water consumption by the plants and evaporation from the water and the non-vegetated surfaces. Reliable estimates of the total evapotranspiration from the wetland is useful information both for understanding the hydrological process and for water management to protect this natural environment. Due to the heterogeneity of the vegetation types and canopy density and of soil water content over the wetland (specifically over the natural reserve areas), it is difficult to estimate the regional evapotranspiration extrapolating measurements or calculations usually done locally for a specific land cover type. Remote sensing can provide observations of land surface conditions with high spatial and temporal resolution and coverage. In this study, a model based on the Energy Balance method was used to calculate daily ET using instantaneous observations of land surface reflectance and temperature from MODIS when the data were available on clouds-free days. A time series analysis algorithm is then applied to generate a time series of daily ET over a year period by filling the gaps in the observation series due to clouds. A detailed vegetation classification map is used to help identifying areas of various wetland vegetation types in the YRD wetland. Such information is also used to improve the parameterizations in the energy balance model to improve the accuracy of ET estimates.

This study shows that spatial variation of ET is significant over the same vegetation class at a given time and over different vegetation types in different seasons in the YRD wetland.

1 Introduction

The Yellow River run into Bohai Sea between the Bohai gulf and Laizhou gulf, coming to being the widest, the most integrated and the youngest natural wetland ecosystem. Recently, because of the decreasing supply of water and sediments, built-up of dikes

along the river, agriculture exploitation and urbanization, the wetland ecosystem in Yellow River Delta is under significant environmental stress. Rational exploitation of water resource becomes an important, hotspot problem now. Evapotranspiration (ET) from the wetland of the Yellow River Delta (YRD) is one of the important components in the water cycle, which represents the water consumption by the plants and evaporation from the water and the non-vegetated surfaces. Moreover, better understanding of wetland response under different water supply and consumption scenarios will help the water authority to release water amount in different seasons on a scientific basis.

Considerable efforts have been made by scientific community to develop algorithms for estimating spatially and temporally distributed evapotranspiration using land surface biophysical parameters provided by remote sensed spectral information. Widely used algorithms that utilize visible/near-infrared and thermal spectral measurements include energy balance based (single- and dual-source) models (Norman et al., 1995; Bastiaanssen et al., 1998a, b; Kustas and Norman, 1999; Jia et al., 2001; Jia, 2004; Su, 2002, 2005;), trapezoid or triangle methods (Nemani and Running, 1989; Moran et al., 1994; Gillies and Carlson, 1995; Jiang and Islam, 1999; Nishida et al., 2003), and simple image-dependent algorithms (Roerink et al., 2000).

Most recently, interest has been drawn back to the use of Penman-Monteith equation in combination of remote sensed plant growth information, i.e. LAI, and routine meteorological measurements to estimate actual daily evapotranspiration at regional scale (Cleugh et al., 2007; Mu et al., 2007; Leuning et al., 2008). Though surface thermal dynamics can be partly and indirectly reflected through introducing parameterization of soil evaporation by linking it to soil moisture status as measured from microwave spectral bands, the latter has rather coarse spatial resolution even with the most advanced sensor such as SMOS (with 50 km pixel size), which is not sufficient to identify water variability over wetland areas both due to complex vegetation types and various surface moisture status.

Different degrees of success in applying these methods over various land surface types are obtained in many applications, very rare applications have been reported

however over wetland environments. Due to the heterogeneity of the vegetation types and of canopy density over the YRD wetland (specifically over the natural reserve area), it becomes difficult to estimate the regional evapotranspiration by means of measurements done locally for a specific land cover type. Remote sensing can provide observations of land surface with high spatial and temporal resolution and coverage, monitoring of ET in the Yellow River Delta wetland (YRDW) using the remote sensing technology is a very important contribution to scientific water management in the wetlands area.

Optical remote sensing measurements are often hampered by clouds coverage which leads to limited numbers of efficient data continuously available over a year. Researchers have made efforts in developing algorithms to generate cloud-free time series of, for instance, vegetation index for land surface vegetation monitoring purpose (Menenti et al., 1991, 1993; Verhoef et al., 1996; Roerink et al., 2000 among others). The central idea is that a time series of irregularly spaced cloud-free observations can be modelled and reconstructed for each pixel independently, using time series analysis. This avoids any requirement for full cloud-free images and maximizes the number of useful observations. Similar idea was adapted recently by others to estimate daily or yearly evapotranspiration by filling gaps in the geostationary or polar-orbited satellites optical observations (Jia et al., 2007; Daamen, 2008; Jia and Daanmen, 2008), which has shown promising perspectives in dealing with clouds contamination.

A model based on the Energy Balance was developed to estimate regional ET using observations of reflectance and land surface temperature from satellites (Menenti and Choudhury, 1993; Su, 2002). This model has been evaluated over many experimental areas with different surface types (Jia et al., 2001, 2003; He et al., 2005 among others). In this study, we have used this method to calculate pixel-wise instantaneous evapotranspiration using instantaneous observations of land surface reflectance and temperature from MODIS (MODerate-resolution Imaging Spectroradiometer) when the data were available on clouds-free days. Daily values of ET are calculated based on the instantaneous ET values at each pixel assuming evaporative fraction remains constants over a clear day. A time series analysis algorithm, proposed by Verhoef (1996),

is applied to generate a time series of daily ET over a year period by filling the gaps in the time series due to clouds. A detailed vegetation classification map produced from high spatial resolution SPOT image is used to help identifying areas of various wetland vegetation types and their spatial distribution over the YRD wetland. Such information is also used to improve the parameterizations of roughness length for momentum in the energy balance based model to improve the accuracy of ET estimates.

2 Study area and data

2.1 Study area

The study area of the Yellow River Delta (YRD) Wetland is located in Dongying of Shandong province in China between the Bohai gulf and Laizhou gulf. The wetland is located between 118°10′ E and 119°15′ E, and 37°15′ N and 38°10′ N. The administrative districts include Dongying district, Hekou district, Guangrao county, Lijin county and Kenli county. This region has prominent monsoon climate characterized as warm temperate zone with typical rainfall season in June, July and August. The wetland area covered by this study starts at Yuwa and ends at Tiaohekou in the north and Songchunrong river in the south. The total area is about 2400 km^2 characterized by various wetland vegetation types, agricultural crops and other land cover types. Two nature reserve areas, currently recovering, have been identified by the national nature reserve and protection program in recent years. One is named Northern Nature Reserve (NNR) area located in the north of the YRD with an area about 35 km^2. The other one is named Southern Nature Reserve (SNR) area located in middle-east of the YRD with an area about 201 km^2.

2.2 GIS and satellite remote sensing data

2.2.1 Land cover map

A land cover map was generated based on one high spatial resolution (pixel size 2.5 m×2.5 m) SPOT satellite image (see Cao et al., 2007 for details of the methodology). Intensive field investigation was done in the summer of 2006 to collect geo-information and vegetation information in the YRD wetland area, which helped to have better classification of vegetation using SPOT images. The land covers are shown in Fig. 1. The original very detailed vegetation classes were grouped into seven major vegetation classes: reed-swamp, reed-meadow, Chinese tamarisk, Suaeda heteroptera and Black Locust Forest, Chinese tamarisk/Suaeda heteroptera (mixture of the two classes), agricultural croplands, and another seven classes dominated by intertidal/foreshore, bare saline soil, inland (open fresh) water, brine pond, shrimps pond and buildings/towns. Statistics of fractional area of each landsurface/vegetation type in the whole wetland area and in the two natural reserve areas are given in Table 1. The high spatial resolution vegetation map is then re-sampled to 1 km resolution to match the pixel size of MODIS images used in the estimation of evapotranspiration using the surface energy balance model described in Sect. 3.

2.2.2 MODIS data

Land surface temperature, vegetation cover and land surface albedo are three essential surface variables in determining heat and water exchanges between land surface and the overlying atmosphere and the partitioning of available energy between soil and vegetation. We have used data from MODIS for its optimal spectral bands, frequent re-visits and user-friendly data products. The utilized MODIS standard products in this study are listed in Table 2 which are available from the MODIS data distribution website (http://elpdl03.cr.usgs.gov/pub/imswelcome/index.html). Single band reflectance in each of the seven optical bands provided by MOD09A1 is converted to land surface

albedo using the algorithm proposed by Liang (2000).

The above MODIS products, land surface temperature data (MOD11A1) is daily products, while land surface reflectance (MOD09A1) and leaf area index (MOD15A2) are 8-day composite data. Because land surface status defined by LAI and surface reflectance or surface albedo does not change significantly in short periods, 8-day interval is sufficient to describe the land surface properties.

2.2.3 Meteorology data

Meteorological data needed by the surface energy balance model to estimate evapotranspiration include wind speed, air temperature, humidity, air pressure, solar radiation, etc. In this study, meteorological data at Dongying and Kenli meteorological stations were collected. Other data, like Pan evaporation, precipitation, daily solar hours, daily clouds amount, are collected as well. There were two types of Pans used in evaporation measurements, standard Class-A Evaporation Pan (model E601) and small Pan with diameter of 20 cm. Pan size has influence on the evaporation from the pan, pan evaporation measured by small Pan is therefore converted to the Class-A Evaporation Pan measurements by multiplying a conversion factor. The conversion factor is obtained by regression measurements made by the two types of pans in a period between 1994 and 2000 when both measurements were available. The conversion factor is found to be 0.65, i.e. ET(Pan_A)=0.65 ET(small pan).

3 Methodology

3.1 Energy balance based model for evapotranspiration estimate

Only a brief description is given in this paper, readers are referred to Menenti and Choudhury (1993), Su (2002) and Jia et al. (2003) for the details of the model SEBS.

The surface energy balance is commonly written as

$$R_n = G + H + \lambda E \tag{1}$$

where R_n is the net radiation; G is the soil heat flux; H is the turbulent sensible heat flux, and λE is the turbulent latent heat flux.

The net radiation flux is the difference between downwards and upwards radiation fluxes at the land surface both in shortwave length and longwave length, and is calculated by

$$R_n = (1 - \alpha)R_{swd} + R_{lwd} - \varepsilon_s \sigma T_s^4 - (1 - \varepsilon_s)R_{lwd} \tag{2}$$

where α is the land surface albedo, R_{swd} is the downward solar radiation flux, R_{lwd} is the downward longwave radiation flux, ε_s is the emissivity of the surface, T_s is the surface temperature; σ is the Stefen-Bolzmann constant.

Soil heat flux is the heat flux into soil or water. Generally, it is determined by a relationship with net radiation as the following

$$G = R_n[\Gamma_c + (1 - f_c)(\Gamma_s - \Gamma_c)] \tag{3}$$

We assumed the ratio of soil heat flux to net radiation Γ_c=0.05 for full vegetation canopy and Γ_c=0.315 for bare soil. An interpolation is then performed between these limiting cases using the fractional canopy coverage f_c. The ratio is set as 0.5 for water surface where fractional vegetation cover is zero.

Sensible heat flux is calculated using Monin-Obukhov Similarity (MOS) theory knowing atmospheric conditions and surface conditions. The atmospheric conditions are characterized by windspeed, air temperature and humidity at a reference height in the near surface layer or at the blending height of atmospheric boundary layer. The surface conditions are characterized by surface or canopy roughness length both for momentum and for heat transfer, fractional vegetation coverage, land surface albedo and temperature. Equations are not given here, instead we will give a brief description on the determination of some crucial surface parameters for the wetland in Sect. 3.2.

Latent heat flux is then calculated as the residual of the energy balance equation Eq. (1). Latent heat flux is converted to evapotranspiration ET in mm.

After all the terms in the energy balance are determined, the evaporative fraction, i.e. the energy used for the evaporation process divided by the total amount of energy available for the evaporation process, is then calculated by

$$\Lambda = \frac{\lambda E}{R_n - G} \tag{4}$$

3.2 Determination of roughness length

Among the parameters needed by SEBS model, roughness length of the surface ($z_{0\,\mathrm{m}}$) is the most crucial one which determines the height of momentum exchange between the land surface and the atmosphere, in turn the source/sink height of heat and water in the land surface and the atmosphere interaction through the factor kB^{-1} (Brutsaert, 1982 among others). Physically detailed models have been developed to estimate roughness length for momentum with consideration of canopy structure (Raupach, 1992, 1994; Massman, 1997), difficulties are however encountered due to lack of detailed canopy structure information needed by the models for regional scale application. Remote sensing measurement made by laser altimeter is suitable to estimate effective roughness length of a heterogeneity land surface (Menenti and Ritchie, 1994). Such measurements, however, were not available over the experimental sites used in this study. In many remote sensing models for ET estimate over regional scale, estimation of z_{0m} is often related to NDVI which can be derived from remote sensing observation. In deed, both the density and height of surface canopy affect the roughness length. We have considered the two factors. The vegetation map together with vegetation growth information provided by LAI and the canopy height collected in the field survey has helped in estimating both the height and density of the various wetland vegetation canopies. The equations used to estimate z_{0m} for short canopies are taken from Zhang (1996). For forest, water, bare soil, resident area, $z_{0\,\mathrm{m}}$ is taken as

0.5 m, 0.0005 m, 0.001 m and 0.5 m, respectively (Brutsaert, 1982; Basstiaanssen et al., 1998b; Gao et al. 2002).

3.3 Total daily ET

Since all the terms in the energy balance equation are estimated using instantaneous observations by MODIS, the calculated instantaneous ET must be integrated to a daily total ET. This is based on the assumption that evaporative fraction remains constant approximately though the sensible and latent heat fluxes fluctuate strongly during a day. This leads to the equation for total daily ET,

$$\mathrm{ET}_{\mathrm{daily}} = 8.64 \times 10^{7} \cdot \Lambda \cdot \frac{R_{n\mathrm{daily}} - G_{\mathrm{daily}}}{\lambda \rho_w} \quad (\mathrm{mm\,d^{-1}}) \tag{5}$$

where R_{daily} is the daily net radiation, G_{daily} is daily soil heat flux, ρ_w is density of water; λ is the latent heat of water taken as 2.47×10^{6} J/kg. For a clear day, the daily average soil heat flux cancels out for positive fluxes occur during night and negative during daytime.

3.4 Annual ET by gap-filling method

Satellite based methods to estimate evapotranspiration often encounter the problem of clouds contamination so that limited numbers of images are available for the ET calculation during a year cycle. To fill the gaps on the missing days due to clouds, a time series analysis algorithm HANTS (Verhoef, 1996; Roerink et al., 2000) is used to generate a gap-filled new set of ET maps based on a certain number of clouds free observations. The algorithm involved in HANTS allows the use of irregularly spaced observations over a certain period and allows the user to choose the frequencies of the periodic functions used to model the observed time series. As such, it is possible to follow to a certain extent the fluctuations of the water exchange between land surface and the atmosphere due to changes in weather and surface water conditions.

4 Results and discussions

4.1 Method evaluation

4.1.1 Evaluation of the modeled evapotranspiration

Since there were no direct measurements of latent heat flux or actual evapotranspiration over the wetland in 2005, we have proposed alternative methods to evaluate the calculated ET. The principle of the evaluation is based on the assumption that evapotranspiration of wet vegetated surfaces should be very close to the reference evapotranspiration (denoted as ET_{ref}) derived from FAO56 Penman-Monteith equation (Allen et al., 1998). In the YRD wetlands the ideal wet vegetated targets are "reed swamp" and "Suaeda heteroptera". Soil water conditions may vary due to less water flow to the wetland or less precipitation for a certain period, "reed swamp" or "Suaeda heteroptera" may not be all the time under water unlimited condition. To select pixels which were under wet conditions, pixels with "reed swamp" standing perennially in water and pixels with "Suaeda heteroptera" near to the inter-tidal areas are identified first by checking the vegetation classification map (Fig. 1). As second step, land surface temperature of pixels classed as "reed swamp" and "Suaeda heteroptera" is plotted against albedo. Wet pixels are identified by both lower LST and lower albedo (figure is not shown). The evaluation of the model estimated evapotranspiration is done using these wet targets pixels.

4.1.2 Gap-filled ET on cloudy-days by time series analysis

The time series analysis algorithm HANTS is used to fill gaps in the modeled evapotranspiration. After preliminary clouds check on the MODIS images, 153 images are selected as quasi cloud-free images though there might still be some pixels contaminated by clouds in the images on different days. The estimated daily ET maps using MODIS observations on the 153 quasi-clouds-free days are taken as the basic dataset

to reconstruct time series of daily ET by applying HANTS to it.

Figure 2 shows examples of the time series of daily ET values in 2005 estimated by the SEBS model and the gap-filled ET values after using HANTS for one pixel of wet "reed swamp". The reference ET estimated from FAO56 equation (ET_{ref}) is also given in Fig. 2. The gap-filled curve of ET have followed the ET_{ref} during the year cycle indicating that the algorithm HANTS is efficient to re-produce the time series of ET values with acceptable errors. Outliers (outliers mean that estimated ET is far below the gap-filled curve) are supposed to be from pixels with clouds. It appears that the frequency and duration of the gaps is limited and not sufficient to degrade the information on the temporal evolution of vegetation cover and surface temperature contained in the irregularly spaced observations retained after pixel-wise clouds screening.

To have a better comparison, a smaller dataset was made out of the 153 quasi-clouds-free images by meeting the criterion "daily amount of clouds measured at Dong Ying meteorological station is zero". There are 67 days that meet this criterion over the year 2005. Figure 3 shows the values of the estimated ET by SEBS, the gap-filled ET by HANTS, reference ET and Pan evaporation on the 67 clouds-free days. It is apparent to see that some outliers remain still (outliers mean that estimated ET is far below the ET_{ref}) after the clouds-screening procedures.

4.1.3 Relationship between vegetation potential ET and reference ET

Commonly, maximum ET of a vegetation canopy is calculated from ET value of a reference crop, i.e. reference ET as mentioned earlier, by multiplying a "crop coefficient" K_c,

$$ET_{max\_veg} = K_c ET_{ref} \tag{6}$$

Our analysis on the regression between the estimated ET (both before and after applying HANTS) of two wet target (reed-swamp and Suaeda heteroptera) and the ET_{ref} are shown in Table 3. The actual ET of the two wet target vegetation types can be considered as their maximum ET since there was no water limits. The modeled actual ET

values shown in Table 3 are the average over selected wet pixels corresponding to the "reed swamp" and "Suaeda heteroptera", respectively for each of the 67 clouds-free days. When the regression was forced through the origin, the slope of the regression line can be interpreted as the bulk "crop" coefficient for the corresponding crop. After applying HANTS to the estimated ET, the annual total ET are much closer to the ET_{ref}.

Different slopes are indeed found in different growing seasons (Table 3). Since the selected pixels are supposed to be well watered throughout the year (except in the winter months when it might be frozen for some days), changes in slope in different seasons are likely due to changes in leaf area index. Such changes are significant in the growing season when leaf area is increasing dramatically (April to June). However, a big shift is observed between the phase of daily ET and the phase of vegetation growth presented by LAI over the year (Fig. 3). Weather condition is another possible cause of the phase shift between daily ET and LAI. July and August are in rainfall season in the YRD wetland, heavy rainfall and low solar radiation resulted in low ET due to too high atmospheric moisture and low available energy for evapotranspiration. The combination of canopy growth and atmospheric conditions may lead to the consequence that simple empirical relationship as defined by a constant "crop coefficient" for each crop, or in general each vegetation type, may be not sufficient for actual ET calculation for the wetland vegetation canopies.

Experimental study on reed beds ET over Ramsar wetland in UK (Peacock and Hess, 2004) showed that ET from reed bed is generally smaller than ET_{ref}. Only on the days with a combination of greater cloud cover, lower radiation and high rainfall the ratio of the two are close to unity. We have also found smaller slope in regression between the estimated ET of reed-meadow and ET_{ref}. For reed-meadow class in the YRD wetland, reed plants were not in standing water perennially as reed-swamp. There is very rare information available, however, in the literature about "crop coefficient" for reed beds from measurements.

4.1.4 Spatial and temporal variability of daily ET

The full time series of the estimated daily ET after gap-filling by applying HANTS algorithm is analyzed for the three different vegetation types: reed-swamp, reed-meadow and Suaeda heteroptera (Fig. 4). For each vegetation type, the daily mean ET is averaged over all pixels with the same vegetation type in the YRD wetland in 2005. To show the spatial variation, the maximum and minimum values of each day's daily ET of the same vegetation type are also given in Fig. 4. Spatial variability is significantly large over the same vegetation type on the same day characterized by the difference between the maximum and the minimum values of the same vegetation type over pixels on the same day. This is particularly obvious for reed-meadow which has large spatial variations of soil water content and fractional cover (Fig. 4b).

In addition to the impact of growing season, large spatial variability in daily. ET over the same vegetation type makes the crop coefficient method difficult to use. Spatial variability in daily ET is caused by several factors, e.g. large spatial heterogeneity in vegetation density, spatial variation in soil water content, solar variation in space, ground water table variation in the wetland, etc.

4.2 Seasonality and spatial heterogeneity of ET in the YRD wetland

Evapotranspiration in the YRD wetland shows strong seasonality as illustrated by the integrated monthly ET maps over April-May-June and over July-August-September (Fig. 5). Along the course of the year 2005, monthly evapotranspiration followed the variations in annual meteorological conditions and vegetation growing seasons. As a consequence, larger values appeared in May, June and July with the peak of evapotranspiration about 130 mm in June (Fig. 6).

Except winter months in January–February and November–December, ET patterns over the entire wetland vary dramatically in the growing seasons, particularly during April, May and June (Fig. 5). Crops and grasslands were at the beginning stage of growth in April and May with lower LAI, the land surface was very close to bare soil

with sparser leaves. The major contributor to the total ET in the drylands (including croplands, grasslands and trees) was soil. With insufficient rainfall in April and May, cropland may have low soil water moisture comparing to the swamp areas. The ET distribution in turn shows smaller values in the drylands (croplands, Black Locust Forest, and Chinese tamarisk), while increasing in steps to swampland vegetations with wetter soil (e.g. reed-meadow), swampland vegetations in standing water (e.g. reed-swamp and Suaeda heteroptera) and inter-tidal zones which might be flooded by seawater or fresh water.

In June and July, a smaller difference in ET spatial variation between dryland and swampland vegetations is observed (monthly ET maps are not shown here). Vegetations in the drylands have developed during this period, implying that transpiration from well developed green plants is the major contributor to the total ET in dryland areas. Moreover, sufficient rainfall encountered in June and July ensured soil is in an optimal moisture condition both over dryland and swampland areas. Differences existed between vegetation in standing water (reed-swamp, Suaeda heteroptera), tideland, cropland vegetations and other wetland vegetations (Black Locust Forest, and Chinese tamarisk).

In September LAI of most vegetation species started decreasing due to senescence of leaves, which resulted in transpiration from vegetations, except those in standing water, to decrease sharply.

During the winter months, i.e. January/February and November/December, ET from the entire wetland area is quite uniform (maps are not shown).

4.3 Annual ET and wetland water requirements

4.3.1 The whole YRD wetland

Figure 7 gives the spatial distribution of the annual ET in 2005 over the YRD wetland. The annual average of evapotranspiration over the whole study area of the YRD wetland is about 934 mm with a standard deviation of 452 mm. Large ranges of evap-

otranspiration are found between 400 mm on average observed in the class of towns and buildings and about 1400 mm on average in the tideland/foreshore areas along the coast and in inland open water surfaces (Fig. 7). The spatial distribution of evapotranspiration of various vegetations is also shown , with large heterogeneity as expected, in particular among dryland vegetation (e.g. croplands) and swampland vegetations in standing water (e.g. reed-swamp). Mean annual ET values of all major vegetations are listed in Table 4.

Areas of the classified land surfaces and amount of water used for evaporation or evapotranspiration are also given in Table 4. Among the vegetation classes, two wetland vegetations often in standing water, reed-swamp and Suaeda heteroptera, have the largest annual ET on average. The reed-swamp and reed-meadow have very close annual ET indicating that transpiration from plants is higher than from the interspersed water. Likely, water table is high enough for reed-meadow to pump ground water for transpiration, but this should be investigated in further studies.

Salty water bodies seem evaporating much more than open fresh water bodies in the YRD area in 2005.

The total amount of water evaporated by water bodies and soil lands and evapotranspiration from vegetation-soil/water canopies of the whole wetland area of about 277 100 hectares (2771 km^2) in 2005 was about 27×10^8 m^3 with a standard deviation about 5.7×10^8 m^3. Since this is the actual ET from the area, it can be considered as the minimum water requirement by the wetland system for vegetation growth and water loss due to evaporation process to remain in its current conditions.

The total water needed by vegetation canopies in 2005 in the YRD wetland was about 5.27×10^8 m^3, of which about 4.59×10^8 m^3 were consumed by natural wetland vegetations with an areas about 89 400 hectares (894 km^2).

4.3.2 Annual ET in the natural reserve areas

One of the objectives of this study was to provide a picture of how much water is needed by the two nature reserve areas in the YRD wetland, i.e. the Northern Nature Reserve

(NNR) and the Southern Nature Reserve (SNR). Such information is important both for water authority and Nature Reserve society.

Currently the NNR is defined as 3500 hectares (35 km^2) and has only three major types of wetland vegetations (many more vegetation types and species with very small and scattered areas were grouped into these three major classes). The annual total water consumed by these naturally vegetated surfaces in the NNR in 2005 was about 0.318×10^8 m^3 with a standard deviation of 0.055×10^8 m^3 (Table 5).

In the current definition of the two natural reserve areas, the area of SNR is much larger than the NNR with many more land surface and vegetation types than the NNR (Fig. 1). The annual total actual evapotranspiration from the SNR in 2005 was about 2.264×10^8 m^3 with a standard deviation about 0.3×10^8 m^3 (Table 6). Reed-swamp and reed-meadow among others are the major wetland vegetations to be protected and areas of reed-swamp and reed-meadow will be extended by replacing cropland in the future to recover the SNR wetland area for the purpose of protection of wetland birds. In 2005, water consumed by reed beds in the SNR was about 0.5×10^8 m^3. Under the similar meteorological conditions as in 2005, one can estimate how much water would be evaporated in a year by the perspective reed beds assuming all or part of current croplands would be replaced by reed beds. By analyzing the monthly actual evapotranspiration from each vegetation type, water supply planning can be scheduled according to the water needs in the growing seasons of the major vegetation types in the nature reserve area.

Water supply to the natural reserve areas can be scheduled according to the consumed water by the wetland vegetations on the basis of estimated daily and monthly ET.

5 Conclusions

Through this study, the following conclusions can be drwan:

– Evapotranspiration over the YRD wetland was estimated using remote sensing

observations of land surface parameters. The calculation was first done using instantaneous MODIS observations by taking into account the detailed vegetation classifications to improve the parameterizations in the model used. Daily values of evapotranspiration were obtained by integrating the instantaneous values assuming a constant evaporative fraction during daytime. Comparison of the estimated daily ET over wet targets showed consistent trends with the reference ET values from FAO56 formula using meteorological measurements indicating that the model performance in simulating daily ET is acceptable. A method was proposed to fill the gaps in ET estimate on cloudy days when the satellite observations, in particular the land surface temperatures, were not available. Though the method needs to be carefully evaluated using in-situ measurements of land surface fluxes or actual evapotranspiration in the wetland, the comparison between the trends in the time series of the gap-filled daily ET over wet targets during the year 2005 and the reference ET from FAO56 using meteorological data showed good consistency. The gap-filled daily ET might still be with relatively larger errors, while the monthly and yearly values of ET are expected to achieve good accuracy, since random errors are filtered out by averaging.

– In the YRD wetland area, spatial variability in daily, monthly and annual ET is significant due to various wetland vegetations, their heterogeneity in space and different growing seasons, and variation in soil water content. Seasonal variation in the ET of the YRD wetland is very strong and varying among different vegetations, which leads to the fact that water requirement by different wetland vegetations and agricultural crops are changing with vegetation phenology and the wetland weather conditions.

– Classical "crop coefficient" method may not be suitable for wetland ET estimates due to the complications of land surface properties characterized both by various wetland vegetation types and by varying soil water content over the YRD wetland. Method for regional ET estimates using remote sensing observation as demon-

strated in this study is a promising and powerful tool for wetland ET monitoring.

– Further study should focus on detailed analysis on the relationship between ET from different vegetation and ground water table, and vegetation conditions (e.g. LAI). The latter will need to use remote sensing images with higher spatial resolution. Moreover, careful evaluation of the parameterizations in the model used and the method used for gap-filling should be in the consideration in the further study.

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Table 1. Fractional areas of the major vegetation classes and other land surface types in the whole YRD wetland and in the northern and southern natural reserve areas (in percentage).

Classification	Whole YRD wetland (%)	NNR (%)	SNR (%)
Reed-swamp	3.8	–	16.0
Reed-meadow	10.3	42.9	7.0
Chinese tamarisk	7.4	51.4	7.5
Chinese tamarisk/ Suaeda heteroptera	4.3	5.7	4.0
Black Locust Forest	2.7	–	10.4
Suaeda heteroptera	2.2	–	2.5
Cropland	30.1	–	10.9
Tideland/Foreshore	16.5	–	33.8
Bare soil	3.8	–	0.5
Saline soil	1.7	–	–
Inland (open fresh) water	4.3	–	5.0
Shrimp pond	3.8	–	1.5
Brine pond	3.0	–	–
Buildings/Towns	2.7	–	–
Others	1.6	–	1.0

Table 2. MODIS standard products and land surface parameters.

MODIS standard products	Land surface parameter	Spatial resolution	Temporal resolution
MOD09A1	Land surface reflectance, NDVI	Bands 1–2: 250 m Bands 3–7: 500 m	8 days
MOD11A1	Land surface temperature	1000 m	1 day
MOD15A2	Leaf area index (LAI)	500 m	8 days

Table 3. Regressions of estimated ET with reference ET over "reed-swamp" and "Suaeda heteroptera" over clouds-free days in 2005 in the YRD wetland.

	Reed-swamp		Suaeda heteroptera	
	Before HANTS	After HANTS	Before HANTS	After HANTS
Whole year	ET_{est}=0.8755 ET_{ref}, R^2=0.72	ET_{est}=1.1193 ET_{ref}, R^2=0.81	ET_{est}=0.8069 ET_{ref}, R^2=0.46	ET_{est}=1.0224 ET_{ref}, R^2=0.62
Jan–Mar	–	ET_{est}=1.2409 ET_{ref}, R^2=0.74	–	ET_{est}=1.1775 ET_{ref}, R^2=0.72
Apr–Jun	–	ET_{est}=0.5007 ET_{ref}+2.954, R^2=0.81	–	ET_{est}=1.609 ET_{ref}+3.6048, R^2=0.08
Jul–Sep	–	[a]	–	[a]
Oct–Dec	–	ET_{est}=1.2409 ET_{ref}, R^2=0.74	–	ET_{est}=0.5826 ET_{ref}+1.1541, R^2=0.46

[a] Means too few points for regression.

Table 4. Annual mean ET and water requirements in the YRD wetland in 2005. ET_std denotes the standard deviation over space among the same class.

Whole wetland	Areas (km^2)	ET (mm/year)	ET_std (mm/year)	ET (10^8 m^3)	ET_std (10^8 m^3)
Reed-swamp	99	1036.6	195.3	1.026	0.193
Reed-meadow	315	934.2	171.1	2.943	0.539
Chinese tamarisk	198	822.8	197.3	1.629	0.391
Chinese tamarisk/Suaeda heteroptera	127	889.1	215.7	1.129	0.274
Black Locust Forest	102	773.4	174.2	0.789	0.178
Suaeda heteroptera	53	1099.4	236.4	0.583	0.125
Cropland	825	833.8	164.8	6.879	1.360
Tideland/ Foreshore	455	1433.8	291.0	6.524	1.324
Bare soil	107	716.6	206.1	0.767	0.221
Saline soil	46	910.2	271.7	0.419	0.125
Inland (open fresh) water	138	1188.6	299.1	1.640	0.413
Shrimp pond	96	1273.0	170.8	1.222	0.164
Brine pond	84	1332.2	221.0	1.119	0.186
Buildings/Towns	82	470.2	187.8	0.386	0.154
Others	44	858.9	158.3	0.378	0.070
Total	2771			27.432	5.715

Table 5. Annual mean ET in the Northern Nature Reserve (NNR) area of YRD wetland in 2005. ET_std denotes the standard deviation over space among the same class.

Northern NR	Areas (km^2)	ET (mm/year)	ET_std (mm/year)	ET (10^8 m^3)	ET_std (10^8 m^3)
Reed-meadow	15	1024.5	247.0	0.154	0.037
Chinese tamarisk	18	833.9	90.0	0.150	0.016
Chinese tamarisk/Suaeda heteroptera	2	727.2	105.2	0.015	0.002
Total	35			0.318	0.055

Table 6. Annual mean ET in the Southern Nature Reserve (SNR) area of YRD wetland in 2005. ET_std denotes the standard deviation over space among the same class.

Southern NR	Areas (km^2)	ET (mm/year)	ET_std (mm/year)	ET (10^8 m^3)	ET_std (10^8 m^3)
Reed-swamp	32	1131.3	129.8	0.362	0.042
Reed-meadow	14	982.6	79.4	0.138	0.011
Chinese tamarisk	15	1019.0	135.3	0.153	0.020
Chinese tamarisk/Suaeda heteroptera	8	1018.1	142.0	0.081	0.011
Suaeda heteroptera	5	1099.4	0.0	0.055	0.000
Black Locust Forest	23	950.6	182.2	0.219	0.042
Cropland	22	986.7	153.1	0.217	0.034
Tideland/Foreshore	68	1295.1	210.3	0.881	0.143
Bare soil	1	716.6	0.0	0.007	0.000
Inland(open) water	10	1167.8	41.2	0.117	0.004
Shrimp pond	3	1153.6	146.1	0.035	0.004
Total	201			2.264	0.311

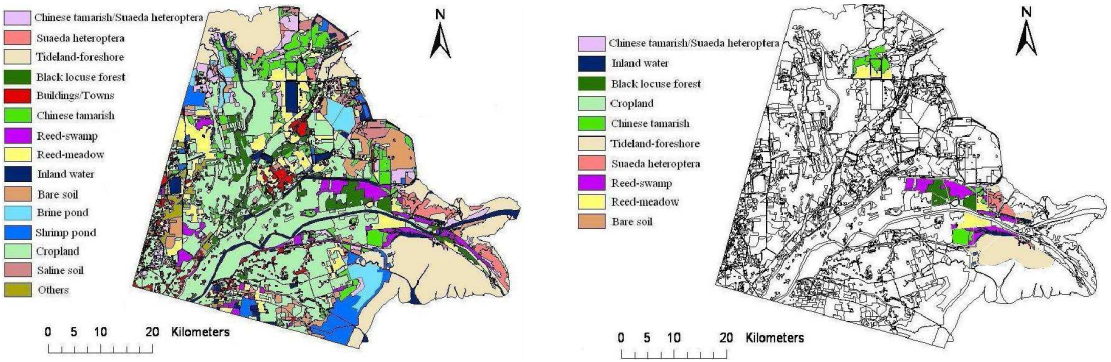

Fig. 1. **(a)** Land cover map of the study area of the YRD wetland; **(b)** Areas and vegetation classification of the northern and southern Natural Reserve Area of the YRD wetland.

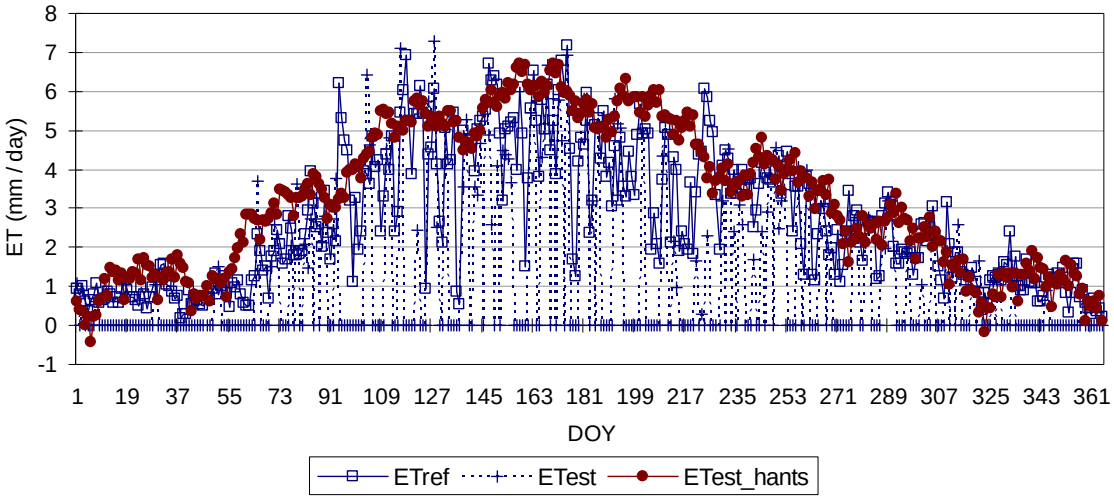

Fig. 2. Time series of estimated daily ET in 2005 (ETest, "+") and the gap-filled ET by using HANTS (ETest_hants, "•") in one pixel of "reed-swamp". ET_{ref} is given as a reference ("□").

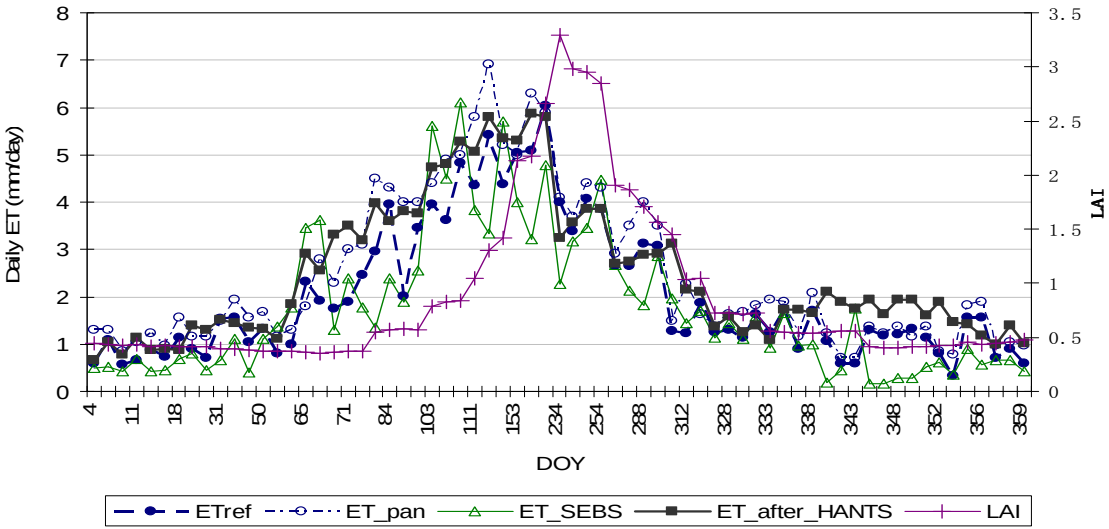

Fig. 3. Comparison between estimated daily ET, estimated daily ET after gap-filling by HANTS, reference ET and Pan evaporation measured in Dongying meteorological station over "clouds-free" days in 2005.

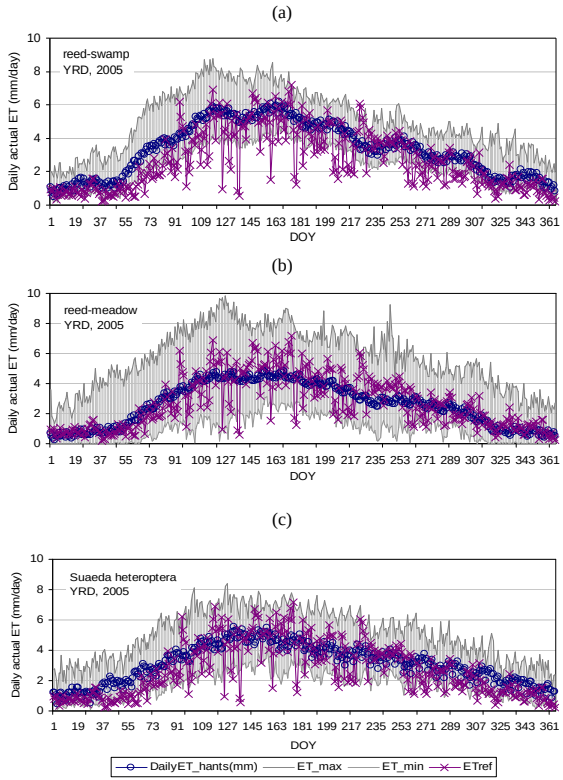

Fig. 4. After-HANTS daily ET averaged over all pixels corresponding to three vegetation types: **(a)** reed-swamp; **(b)** reed-pasture; **(c)** Suaeda heteroptera over the YRD wetland in 2005. Spatial variability is represented by the difference between maximum and minimum values of each day over the same vegetation type (shaded areas).

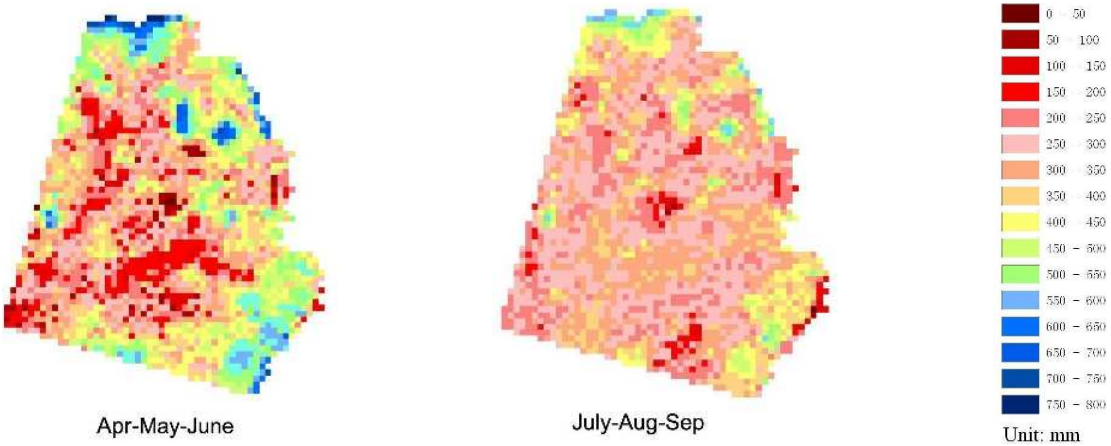

Fig. 5. Maps of evapotranspiration estimates integrated over **(a)** April-May-June; **(b)** July-August-September over the YRD wetland in 2005.

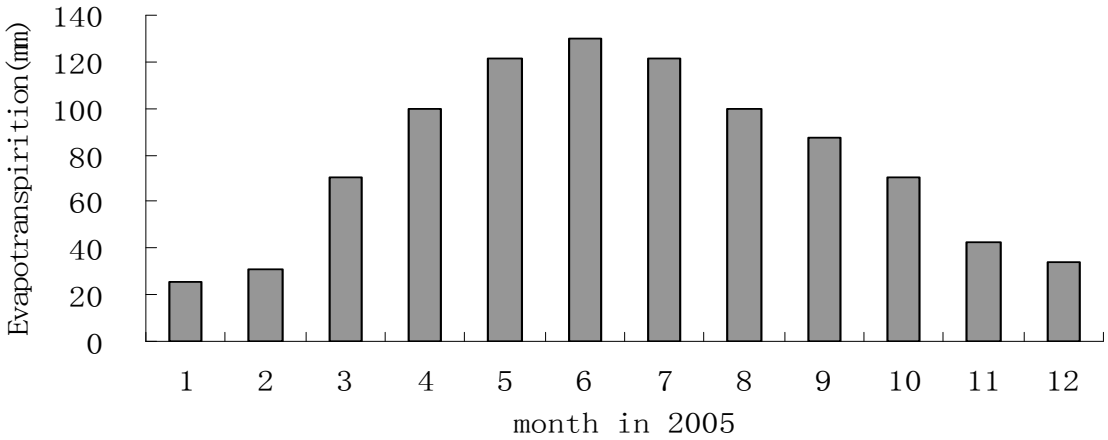

Fig. 6. Mean monthly ET in YRD wetland in 2005.

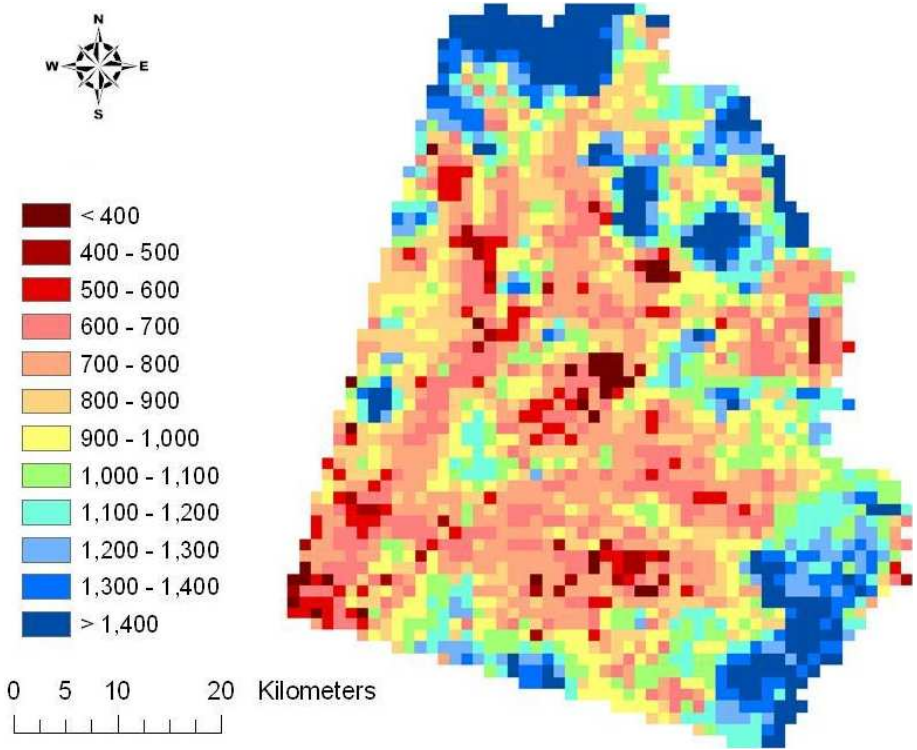

Fig. 7. Spatial distribution of annual ET in Yellow River Delta wetland in 2005 (unit: mm).