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The response of terrestrial net primary productivity (NPP_T) in the Wujiang catchment (China) to the construction of cascade hydropower stations

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Abstract:

The damming of rivers results in hydrological modifications that not only affect the aquatic ecosystem but also adjoining terrestrial systems as well. Thirteen dams have been commissioned along the Wujiang River in the last century. These have induced ecological problems, including decreased water turbidity, land use change and biodiversity loss, all of which have the potential to influence ecosystem net primary production and hence the sequestration, transformation and storage of carbon. We used terrestrial net primary productivity (NPP_T) as a bio-indicator to assess the impact of dams on carbon storage in the Wujiang catchment. MODIS satellite and meteorological data were used as inputs to the CASA model to calculate annual NPP_T from 2000 to 2014. The calculation of NPP_T was carried out at both the catchment and landscape scale to quantify the impact of dams on surrounding terrestrial ecosystems. Mean NPP_T was calculated for concentric buffer zones covering a range of spatial extents (0-10 km) from the reservoir shoreline.

The results showed the impact of construction of a single dam on NPP_T at the catchment scale was negligible. In contrast, the impact of dam construction was scale-dependent at the landscape scale (<10 km), with a stronger effect observed at short distances (i.e. 0-1 km) from the reservoir. Decreases in NPP_T were mainly ascribed to the loss of vegetated land resulting from dam impoundment and subsequent urbanization of the surrounding area.

Keywords:

Dam; Terrestrial Net Primary Productivity (NPP_T); Catchment; Riparian vegetation; Land use change

Subject classification codes: Primary Production/Metabolism; Reservoir Limnology; Wetland Ecology; Carbon Flux

Introduction

Inland waters (e.g. lakes, reservoirs, rivers and streams) play vital roles as both sources and sinks in the global carbon cycle, and ultimately in climate regulation (Bastviken et al. 2011, Raymond et al., 2013). In many regions globally, extensive damming of rivers to enable social and economic development by generating electricity, providing irrigation water for agriculture and reducing flooding (Graf 2006) has resulted in significant change to catchment hydrology and land use practices. Such is the scale of dam construction globally, the reservoirs created upstream of impoundments are understood to intercept nearly one-fifth of the organic carbon being transferred from the land to the ocean (Maavara et al. 2017). In addition to the disruption to global carbon cycling, recent research has also highlighted other environmental impacts arising from dam construction such as forest decline (Wildi 2010), landslides (Yin et al. 2016) and habitat fragmentation (Qiu 2011, Emer et al. 2013).

The construction of a dam affects local climate and ecosystem function by altering evaporation and precipitation in a region (Degu et al. 2011). In aquatic systems, the dam-induced impoundment (i.e. increased surface water) promotes evaporation processes, subsequently altering precipitation, in addition to physically restricting the flow of water downstream (Gordon and Meentemeyer 2006). Moreover, dams impede the transport of dissolved and particulate nutrients (e.g. nitrogen, phosphorus and silicon) through the river network, ultimately affecting downstream wetlands, floodplain and coastal areas (Ling et al. 2016). The influence of dams also extends to terrestrial systems, through changes to riparian vegetation and land use (Silva et al. 2010, Grumbine and Xu 2011). Physically, riparian vegetation along the reservoir boundary contributes to the protection of water quality by reducing shoreline erosion and nutrients entering surface waters. Riparian vegetation is also important for sequestering atmospheric carbon in organic matter (Brown et al. 1996, Harms and Grimm 2008, Maraseni and Mitchell 2016). Dam construction has been shown to have a significant negative impact on the surrounding natural habitat and ecosystems (New and Xie 2008), largely through the loss of common riparian land cover types through the process of inundation (Kellogg and Zhou 2014); subsequently, the process of carbon sequestration within the riparian vegetations would be potentially changed.

Terrestrial Net Primary Productivity (NPP_T) is useful for identifying changes in ecosystem structure and function with implications for the exchange of carbon between the land and the atmosphere (Xu et al. 2011). NPP_T is the balance between the carbon accumulated through photosynthesis (gross primary productivity, GPP) and the loss by autotrophic respiration by plants during a given time interval (Lieth 1975, Likens 1975), reported in units of grams of carbon per unit area (gC/m^2) (Melillo et al. 1993, Apps and Peng 1998, Peng and Apps 1999). NPP_T is a sensitive ecological indicator to assess changes in vegetation carbon storage such as those due to land use alteration (Feng et al. 2007) and climate change (Pimm and Raven 2000). Studying the response of NPP_T to environmental disturbance is necessary for understanding the overall trend and dynamics of terrestrial carbon cycling at a regional or global scale (Fang et al. 2001, Luo et al. 2002). Moreover, NPP_T could be used to monitor the changes in natural resources (e.g. aquatic and terrestrial vegetation) across varied ecosystems, and together with a series of policy implications which might be useful for the Sustainable Development Goals (SDGs), particularly in fragile ecosystems such as dam-impacted freshwaters.

A range of methods can be used to estimate NPP_T including destructive measurements biomass, micrometeorology (e.g. eddy covariance fluxes) or model simulation (Melillo et al. 1993, Goetz et al. 1999, Liu et al. 1999, Alexandrov et al. 2002). The traditional methods such as ground-based biomass surveys have the advantage of high accuracy but are time consuming, labour intensive and providing limited coverage in both space and time (Jenkins et al. 2003). More recently, technologies such as remote sensing coupled with eco-physical models have been used to estimate NPP_T at regional and global scales (Potter et al. 1993; Ruimy et al. 1994, Xiao et al. 2011). Models can be classified into three types, including process-based models (e.g. TEM (Melillo et al. 1993), CENTURY (Parton et al. 1993), Biome-BGC (Running and Hunt 1993)), statistical models (e.g. Rathgeber et al. 2000), and light use efficiency models (LUE, e.g. Carnegie-Ames-Stanford-Approach (CASA), Potter et al. 1993). The CASA model is one of the most widely used and sophisticated models to estimate NPP_T (Prince 1991, Cramer et al. 1999). The coupling of remote sensing technology and the CASA model can be an efficient way to obtain extensive, synchronous and extended time series data on NPP_T (Julien and Sobrino 2012). Previous studies have typically looked at gross spatial or temporal patterns in NPP_T (Law et al. 2006, Xiao et al. 2011), but few studies have looked at specific event-driven changes in NPP such as those resulting from dam construction. One exception was Xu et al. (2011), who examined the impact of the Three Gorges Dam Project on the spatial distribution of NPP_T in the area surrounding the reservoirs during impoundment, in particular the effect of the dam-induced inundation of land and the resettlement of displaced residents on NPP_T. Given that a large proportion of the world's rivers are dammed, the implications of dam construction on land use and carbon cycling need further consideration. The impact of dam construction on NPP_T is required to understand at the different spatial extent (i.e. catchment or landscape) and magnitude in the future studies so that the wider carbon implications can be explored.

The aim of study was to use the CASA model, coupled with Moderate Resolution Imaging Spectro-radiometer (MODIS) and local meteorological data to investigate annual NPP_T in the Wujiang catchment for the period of 2000-2014. The Wujiang catchment is one of the most heavily impounded catchments in China, and previous studies have focussed on the geo-chemical process (Li et al 2013 etc.) in the reservoir and river ecosystem. While the vegetation impacts of these dams have not been considered in a spatially sensitive way. We proposed our hypotheses: (1) the construction of a single dam reduces mean NPP_T at a catchment scale, and that the impact is scale-dependent; (2) the construction of cascade dams results in a negative cumulative effect (both temporal and spatial) on NPP_T.

Methods

Study sites

The Wujiang River, located at E104°–110°, N26°–30° (Figure 1), is an upstream tributary of the Yangtze River in China. It is situated in the western regions of the Three Gorges Dam. The drainage basin is formed of Karst topography. The Wujiang river features a subtropical monsoon climate. During the investigation period (2000-2014) the annual temperature and precipitation measured by the local weather meteorological stations ranged from 15 to 27 °C and from 241 to 424 mm, respectively. The Wujiang catchment covers a total area of 57804 km^2, and shows a clear gradient feature in land use type according to topography, with farmland and construction land located in lowland while forest and unutilized land distributed in the upland. The construction of cascade dams plays a vital social and economic role, providing water supply, flooding control, irrigation and electricity supply to the region. Thirteen dams were presented in the study area, situated at elevations ranging from 215 m to 1145 m above sea level. The investigated dams could be classified into different types based on the slope of the dam, water residence time and the extent of the water fluctuation zone. The characteristics of the investigated dams are summarized in Table 1.

The digitized boundary for each investigated reservoir was obtained using the normal water level recorded as the theoretical value according to the reservoir operation scheme using a ε* (ArcGIS). Data frame Digital terrain model (DTM) at a 30 m × 30 m grid resolution were obtained from the Geospatial Data Cloud for China (GDEMDEM). The catchment boundary for each reservoir was digitized using Arc Hydro Tools in ArcGIS (v10.2) using the vectored reservoir boundary and DTM (Figure 1). The catchments of upstream reservoirs are nested within the catchment boundary for each downstream reservoir. Concentric buffers, at spatial distances of 0-1, 1-3, 3-5, 5-7 and 7-10 km from the reservoir shoreline were subsequently calculated using Buffer Tool in ArcGIS with overlaps between buffer zones removed.

Insert [Figure 1 near here]

Insert [Table 1. near here]

Estimation of NPP_T

The Wujiang catchment has a marked change of natural landscape over its elevation gradient. Historically, plant surveys and fieldwork have been confined to partial regions and do not cover the whole catchment due to the difficulty of access. To overcome the difficulties faced in surveying vegetation over the inaccessible terrain of much of the Wujiang catchment, in this study, we used remote sensing data combined with ecological modelling to monitor the spatial and temporal changes of NPP_T at the catchment scale. NPP_T in this study was calculated using the CASA model by the given function (1), which includes two terms, the absorbed photosynthetically active radiation (APAR) and a light use efficiency factor (ε) (Potter et al. 1993) as follows:

$$(NPP_T (x, t) = APAR (x, t) \times \varepsilon (x, t)) \quad (1)$$

$$(APAR (x, t) = FPAR (x, t) \times SOL (x, t) \times 0.5)) \quad (2)$$

Where NPP_T (x, t) is the total NPP_T of the given position, site x, during the given time t, in the units gC/m^2. APAR (x, t) is the total solar radiation absorbed by the pixel x, integrated over the month t, given in MJ/m^2, calculated using function (2). Where SOL (x, t) is the total solar radiation (MJ/m^2), and FPAR (x, t) is the fraction of the active photosynthetic radiation absorbed by the vegetation. The constant of 0.5 accounts for the proportion of the effective solar radiation present in the total solar radiation (wavelengths between 0.38 and 0.71 μm). Finally, ε (x, t) is the light use efficiency of APAR (x, t) in converting radiation into organic matter (gC/MJ), which is calculated by the function (3):

$$(\varepsilon (x, t) = T\varepsilon_1 (x, t) \times T\varepsilon_2 (x, t) \times W\varepsilon (x, t) \times \varepsilon^*) \quad (3)$$

In function (3), $T\varepsilon_1$ (x, t) and $T\varepsilon_2$ (x, t) represent the stress coefficients of the light use efficiency for low and high temperatures. Wε (x, t) represents the stress coefficient for moisture limitation. ε* is the maximal light use efficiency, which has a constant value of 0. 389 gC/MJ for global vegetation used in the CASA model (Potter et al. 1993). There is current debate over the correct value of ε*, which is believed to be affected by factors such as vegetation type and environmental conditions of temperature and water availability for example (Prince 1991, Paruelo et al. 1997, McCrady and Jokela 1998). This study used the ε* of ten vegetation types, typical of the vegetation found in the Wujiang catchment, as published by Zhu et al. (2006), shown in Supplemental Table S1. The value of ε* for these ten different vegetation types in China is reported to be lower than that simulated by the eco-physiological processing model BIOME-BGG (Running et al. 2000, Peng et al. 2000).

Data source and processing

Remote sensing data

Normalized Difference Vegetation Index (NDVI) was extracted from MODIS13Q1 time-series data (available from Modis Web; https://modis.gsfc.nasa.gov/). The data were provided at a 16-day interval with a 250 m spatial resolution in the study area for the period 2000-2014. Additionally, a yearly L4 dataset at 1 km × 1 km resolution on a global scale (i.e. MODIS17A3), was also obtained from https://modis.gsfc.nasa.gov/, and used to correct the simulated NPP_T value from the CASA model.

The remote sensing data were re-projected from sinusoidal grid projection (SIN) to UTM WGS84 using the MODIS Reprojection Tool (MRT), available from http://lpdaac.usgs.gov/tools/modis_reprojection_tool. The Savitzky-Golay filter was applied to reconstruct the NDVI long-term data, reducing noise created by clouds and atmospheric interference etc. A monthly NDVI value was derived from the 16-day MODIS-NDVI data using Maximum Value Compositing (MVC) (Bian et al. 2010).

Vegetation classification data were produced by the State Key Laboratory of Resources and Environmental Information System, Institute of Geography, Chinese Academy of Sciences. Vegetation data were resampled to a resolution of 250 m to match the resolution of the MODIS-NDVI data.

Meteorological data

The monthly meteorological data, i.e. precipitation, mean air temperature and total solar radiation, were observed at 23 field stations within the Wujiang Catchment from 2000 to 2014. Data were downloaded from the National Meteorological Centre (NMC) of China (http://data.cma.cn/). Precipitation, mean temperature and total radiation for each station were interpolated to cover the whole Wujiang catchment by applying an inverse distance weighted (IDW) method in ArcGIS. All raster data were projected with WGS84 and transformed into float format with a spatial resolution of 250 m, consistent with the NDVI data.

We evaluated the accuracy of the CASA-simulated NPP_T model by comparing the annual NPP_T value with the MODIS17A3 global NPP_T products from 2000 to 2014 (Supplemental Fig.S1). The comparison indicated that the simulated annual NPP_T values and the MODIS17A3 global NPP_T products were consistent, with an accuracy of 96%. Mean NPP_T was calculated at both the catchment and landscape (5 riparian buffer strips) scales for each study reservoir.

Land use data

Due to the rapid urbanization that often accompanies dam construction in China, the urban coverage in the Wujiang catchment increased from 343 km^2 in 2000 to greater than 435 km^2 in 2014. To capture the land use changes within the study area more accurately, six land use cover categories (urban, water, woodland, croplands, grassland and barren land) were defined using Landsat images (downloaded from https://earthexplorer.usgs.gov/) for the years 2000, 2005, 2010 and 2014. Among the simply aggregated classes from the Landsat data, cropland was consisting of improved grassland, arable cereals, and urban was combining suburban/rural developed land with designated urban areas. The area of each land-use class was calculated within a 1 km buffer zone (mentioned before) of each reservoir using ArcGIS. Land use information derived from Landsat images with a 30 m × 30 m resolution might not provide sufficiently detailed information on individual urban structures. Nevertheless, it is sufficient to represent the general changes in coverage of urban and rural land use for the purposes of this study.

Statistical analyses

The simulated time series NPP_T data for each reservoir were categorised into pre- and post-dam construction to compare the difference of mean NPP_T. All NPP_T time series datasets at both the catchment and landscape scales were found to be normally distributed using Shapiro tests and inspection of Q-Q plots. T-tests were used to test the significance of the difference between mean NPP_T pre- and post-dam construction for the whole Wujiang catchment, and for the sub-catchment of each individual dam. Only 10 dams constructed between 2000 and 2014, where NPP_T datasets were available to allow a pre- and post-dam comparison during the investigation period, were included in the statistical analyses.

At the landscape scale, mean NPP_T was compared over the 5 distinct buffer zones before and after dam construction for each reservoir. Initial analyses revealed that the construction of an individual dam has little influence on NPP_T at the catchment scale. Hence, this allowed changes in each buffer zone to be compared against the catchment-scale NPP_T as the control. This allowed us to account for the effects of local meteorological conditions and natural NPP_T changes over time. To isolate the effect of dam construction, normalized mean NPP_T was obtained by dividing the mean catchment-scale NPP_T by the NPP_T for each buffer strip (0-1, 1-3, 3-5, 5-7, 7-10 km). This normalized mean NPP_T was then tested for statistically significant differences between pre-and post-dam construction using a t-test and One-way Analysis of variance (ANOVA). A Tukey *post-hoc* test was used to determine in which buffer strip mean NPP_T differed at a 95% family-wise confidence level between the period of pre- and post-dam construction.

To investigate the temporal and spatial changes induced by the dam on the capacity of vegetation carbon sequestration in the area directly neighbouring the reservoir, four representative reservoirs were selected. Considering physical features of each dam, indicating slope, water residence time and water fluctuation zone extent, we selected reservoirs GPT, HJD, SL and YZD (Figure 1) to calculate further the local changes in land use classes and their corresponding mean NPP_T within a 1 km reservoir buffer (including the reservoir area). Depending on the year of dam construction, two representative Landsat images from before and after dam construction were chosen to represent each time period. Coverage of the six land use classes outlined earlier, and their corresponding mean NPP_T were compared and discussed. NPP data use NDVI as the proxy for biomass in this work but this index is only valid over fully or partial vegetated land surfaces. NDVI value over urban area and water bodies are meaningless and the calculation of NPP for water bodies requires an entirely different approach. Therefore, urban areas and water bodies were assumed to have zero NPP_T in the calculations. All the statistical analyses were conducted in R 3.3.3 (R development Core Team 2017) using the core stats package.

Results

Spatial patterns and temporal changes of NPP_T in the Wujiang catchment from 2000 to 2014

Total NPP_T in the Wujiang catchment fluctuated over time from 2000 to 2014, from a maximum of 55648 GgC (Gigagram of Carbon, 1GgC= 10^9gC) in 2002 and a minimum of 41946 GgC in 2011 (Figure 2). During this period, a total of 10 dams were constructed along the Wujiang River. Annual total NPP_T was not significantly related to precipitation nor to mean air temperature, with correlation coefficients of -0.344 and 0.323, respectively.

Mean NPP_T (Figure 3a) was highly correlated with the topography (Figure 3b) of the investigated region. High NPP_T values could be found in lowland regions, at elevations less than 500 m. Change in mean NPP_T from 2000 to 2014 was calculated using the standard deviation to detect the variability of NPP_T values over the study period. (Figure 3c). It can be found in Figure 3c, the time series of mean NPP_T showed a notable change over time in the downstream part of the catchment.

Insert [Figure 3 near here]

Comparison of NPP_T at a sub-catchment scale for individual reservoir after dam construction

Mean NPP_T was calculated before and after dam construction at a sub-catchment scale for each reservoir (Figure 4). The catchment-scale mean NPP_T was generally higher compared to the mean NPP_T after dam construction (the differences range from 23.08 to 47.01 gC/m^2, Table 2). The upstream catchments of three reservoirs, SFY, YZD and HJD, were an exception to this and exhibited the converse trend where NPP_T increased post-construction. However, these differences were not statistically significant ($p>0.05$; Table 2), indicating a negligible impact of individual dam construction on NPP_T at a catchment scale.

Insert [Figure 4 near here]

Insert [Table 2 near here]

Spatial patterns and temporal changes of NPP_T for individual reservoirs at a Landscape scale

ANOVA results suggested the modelled NPP_T significantly differed between distinct buffer strips both before and after dam construction for most of the reservoirs investigated ($p < 0.001$, Table 3). However, for two reservoirs, HJD and SL, there was no significant difference in mean NPP_T (HJD, $F=0.459$, $p=0.765$; ST, $F=0.385$, $p=0.818$) across the buffer strips during the pre-dam period. Interestingly, after dam construction both reservoirs did show a significant difference in NPP_T across buffers (HJD, $F=20.01$, $p<0.001$; ST, $F=2.635$, $p=0.058$).

Insert [Table 3 near here]

Insert [Figure 5 near here]

T-test results indicated in which buffer strip there was a significant difference in mean NPP_T prior to and after dam construction occurred (Figure 5). A significant reduction of the normalized mean NPP_T occurred after the construction of dams at GPT, HJD, PS, SL, SFY, YZD reservoirs. The impact of dam construction displayed a strong scale dependency with the greatest changes observed at small spatial scales (i.e. 0-1 km buffer zone; Figure 5). There was a reduction of NPP in all buffer zones at GPT and SL reservoirs. The normalized mean NPP_T in most reservoirs was greater than 1, indicating that the mean NPP_T across continuous buffer strips within 10km of the reservoir boundary was greater than the catchment-scale mean NPP_T, with the exception of three reservoirs, HJD, SFY and ST. These three reservoirs with a lower than catchment mean NPP_T value across the investigated buffer strips, also drained large areas of land, water fluctuation zones had lower than average slopes with a lack of vegetation cover (Table 4) which may have driven this difference.

The impact of land use on mean NPP_T

Land use data from Landsat showed that the whole Wujiang catchment underwent rapid urbanization from 2000 to 2014, with the area of urban land expanding from 343.8 km^2 to 953.7 km^2 in 2014 (Table 5). The contribution of cropland and woodland to the total NPP_T remained stable (about 29% and 53%), while grassland area coverage and NPP_T

contributions decreased by 0.75%.

Insert [Table 4 near here]

Insert [Figure 6 near here]

The dam construction coincided with the expansion of water cover and urban land in the region (Table 4). At reservoir GPT, for example, the coverage of water from 6.19 km^2 to 14.9 km^2 and urban land expanded from 0.0885 km^2 to 0.192 km^2 after dam construction. Most impounded areas came at the expense of grassland, cropland and forest, which showed a decrease in all four investigated reservoirs (Table 5). Total NPP_T reduced in all vegetated land use types after the dam construction. The degree of reduction for each land use category was reservoir-dependent (Table 4). The change in contribution of each vegetation land use to mean NPP varied between reservoir and vegetation type. However urban consistently increased in their contributions to mean NPP_T. The average NPP_T of all land uses within the 1 km buffer decreased after dam construction (Table 4). Take GPT for example, the mean NPP_T of the forest in the investigated area was decreasing from 657 gC/m^2 to 640 gC/m^2 after the construction of the dam.

Insert [Table 5 near here]

Discussion

A better understanding of the change in patterns of NPP_T in areas affected by dam construction will inform the management of land adjacent to impoundment reservoirs, to minimize the possible negative effects on vegetation and overall ecosystem function (Smith et al. 2012). This study has highlighted the specific areas most impacted by land cover and land use change under the pressure of cascade dam construction in the Wujiang catchment. These findings can help inform the targeted protection of those ecologically important vegetation communities and habitats that contribute disproportionally to carbon sequestration during dam construction.

The role of dam construction in NPP_T at Wujiang catchment/sub-catchment scale

Terrestrial NPP_T is vulnerable to climate and land use change driven variation. Changes in temperature, precipitation or land cover have been found to drive significant alterations in the biogeochemical process of the terrestrial carbon cycle (Jenkinson et al. 1991). We found the response of NPP_T specifically to dam construction to depend on the spatial scale considered, an important finding given the spatially variable nature of NPP within a landscape (Reich et al. 1999).

An impoundment reservoir is not isolated, but connected to a wider aquatic ecosystem. The topographical catchments of reservoirs drain surface and sub-surface water along with sediments and other materials to the receiving reservoir. The dam structure however influences the connectivity of river corridors by disrupting the flow of materials including nutrients, seeds and vegetative propagules, and thus it exerts major influence on the occurrence of riparian vegetation (Bornette et al. 1998, Bracken and Croke 2007, Oťaheľova et al. 2011). It is necessary to evaluate the impact of dam construction on the ecosystem at a catchment scale, because the dam as a disturbance not only has potential effects on the ecosystem along the river (e.g. riparian vegetation, soil property etc.), but also induces regional changes in climate and landscape. Many studies have evaluated the negative impact of dam construction in the upper catchment on agriculture productivity (Freden 2011), vegetation communities (Colonnello and Medina 1998, Azami et al. 2004, New and Xie 2008), and biodiversity of aquatic and terrestrial species (Gehrke et al. 2002) in the downstream. In this study, NPP_T of the whole catchment displayed a spatial pattern with high values of NPP_T distributed in downstream regions and low values in upstream regions (Figure 3a). The total NPP_T of the Wujiang catchment experienced a decrease, dropping to a low of 41946 GgC in 2011 (Figure 2), which might be explained by a short term and cumulative effect of the construction of 7 dams between 2008 and 2011. Although it seems that NPP_T have recovered again since 2012 when is the end of the dam building period. It might be explained by a change in the type of crop grown, more productive or more harvests plants, in the land water level fluctuated.

Previous studies suggest that global warming and land cover variation (Melillo et al. 1993, Cao and Woodward 1998) might induce an initial-change in NPP_T. However, total catchment NPP_T was not significantly correlated with either the annual total precipitation or the mean temperature in this study. The changes in land cover are at least partly responsible for the long-term decline in NPP_T. We hypothesized that the construction of ten dams along the Wujiang river was responsible for the annual-change in NPP_T, which result in the lowest total catchment NPP_T occurring in 2011. It was possible that NPP_T in 2011 is an anomaly. And it was difficult to elucidate the mechanism driving this spatial or temporal trend using the current dataset, which might require a more detailed study to identify the scope and causes of such dam-induced cumulative impact on material and energy flows through the catchment in the future study.

Our results revealed that individual dam construction only had a weak influence on mean NPP_T at the sub-catchment scale (Figure 4, Table 2). This conclusion is not consistent with previous studies, which found that dam construction contributed to the degradation of catchment forest cover and overall biodiversity due to the loss of this forest and other vegetation habitats through impounding (Dugan et al. 2010). Forest cover plays an important role in mitigating potential climate change caused by increasing atmospheric carbon dioxide (CO_2) concentrations (Schulze et al. 2000). In the Wujiang catchment, forest biomass often accounts for the majority of living terrestrial biomass within the sub-catchment of an individual dam (Dixon et al. 1994, Brown et al. 1996). However, in this study, the land use most affected by the impounded area such as in HJD and YZD was grassland and cropland (Table 4). We found that the loss of NPP_T from impounded grassland or cropland had a limited influence on total NPP_T, when compared to possible NPP_T changes resulting from the loss of forest cover. When considered at a sub-catchment scale for each reservoir, it is important in terms of biodiversity and carbon sequestration to minimize the loss of forest cover during dam construction.

The role of dam-induced land use change in reducing NPP_T at a landscape scale

As stated above, the construction of an individual dam had a limited impact on mean NPP_T at a sub-catchment scale, however mean NPP_T often decreased after dam construction in the region immediately surrounding the dam, especially within a 1 km riparian buffer. Lower values of NPP_T were observed at a landscape scale in a few reservoirs that were not evident at the catchment scale, for example HJD, SL and SFY (Figure 5 d, g, h). This was probably due to the loss of riparian vegetation, especially tree species from the riparian zone after the construction of the dam, presumably eventually riparian vegetation will re-establish except where large water level fluctuations occur (Kellogg and Zhou 2014).

T-test results indicated a significant reduction of mean NPP_T within the 1 km buffer (including both upstream and downstream of the reservoir) after dam construction (Figure 4 c, d, g, j). These findings are in agreement with other published reports revealing that dam construction causes a reduction in primary production near the new shoreline (Zhang et al. 2009, Xu et al. 2011).

The most obvious environmental impact of dam construction was found to be the loss of vegetated habitat and the expansion of the inundation zone (New and Xie 2008, Kellogg and Zhou 2014). In the Wujiang catchment, the impoundment of the reservoir invariably submerges surrounding land, often flooding areas of the Bermuda grass and other herbaceous plants, although it all depends on the nature of the vegetation surrounding the newly constructed dam. At HJD reservoir for example, the reservoir submerged productive agricultural land, which could adversely influence cultivated biodiversity and a host of bird, insect, mammal and other aquatic species associated with agricultural ecosystems. Additionally, dam construction promoted the urbanization of areas surrounding the reservoirs, further catalysing changes in land use that result in decreased NPP_T. Changes of land use within the Wujiang catchment have been described by a number of previous studies (Wen and Pu 2010, Gao et al. 2008 etc.). The Wujiang catchment experienced rapid urbanization during the years investigated (Zhang et al. 2008), and the process was possibly promoted by the construction of the cascade dams. Dam-induced disturbance, such as road construction and urban development generally increases in the reservoir surroundings at the expense of the vegetation communities (Pauleit et al. 2005). Changes in land cover ultimately alters the composition of surface vegetation, soil physico-chemical properties, and thus inevitably influences NPP_T (Yan et al. 2009). In reference to this study, the coverage of each land cover category within the 1 km reservoir buffer was found to be altered after dam construction, particularly through flooding and the expansion urban areas and a loss of vegetative habitats (e.g. forest) (Table 4). For example, forest area within the 1 km buffer of GPT decreased from 302 km^2 to 294 km^2 after dam construction. Although the changes are small, the loss of productive riparian land can have a significant effect on NPP_T within the 1 km buffer zones. The further study should be on the changes in NPP_T within the water fluctuation zones of the reservoir. Rapid changes in land use are relevant to vegetation carbon storage globally (Fearnside 2000, Houghton et al. 2004). And in this study, we showed how dam construction contribute to this change. Within the region, NPP_T contributed by cropland, forest and grassland decreased by 0.31%, 0.38% and 1.45% respectively (the mean value of change in contribution (%) for the reservoirs GPT, HJD, SL, YZD, Table 4) after dam construction. The results are consistent with the NPP study in China's Three Gorges Dam project, which also showing a NPP_T reduction in forest, grassland and cropland respectively (Xu et al. 2011).

The accuracy of NPP_T calculation

The CASA model has previously been used successfully previously for the long-term monitoring of vegetation biomass at the regional scale (Bian et al. 2010). Due to the coarse resolution of the MODIS data, some areas of urban land cover and open water might have been erroneously included in the computation of NPP_T. But NPP_T analyses at a broad scale means the effect of such error on the results was likely to be minor because of a low coverage of urban and water bodies. However, when the CASA model is applied at a moderate or fine scale, the accuracy of the modelled NPP_T needs to be taken into consideration when interpreting results (Zhu et al. 2007). This discrepancy was caused by the presence of mixed land use pixels within water and terrestrial defined areas. 250 m resolution mixed pixels are defined by the dominant land cover classes in the pixel. In this work, mean NPP_T for water (including lake and rivers) and urban cover were assumed zero in the 1km buffer analyses. A comparison of simulated NPP_T in this work and that of other models (Supplemental Table S2) indicated that a certain difference between vegetation types, for example NPP_T of cropland are consistent across models while grassland and forest vary more. We attribute this to the low-resolution MODIS 250 m data, might not have sufficient resolution to distinguish the reservoir and terrestrial boundary. In future studies, it would be worth beneficial to use high spatial resolution remote sensing data (e.g. Sentinel-2 MSI, Landsat-8) to clearly identify the boundary between each land use class and vegetation category to accurately estimate NPP_T with eco-physiological models. This is particularly important in reservoir water fluctuation zones where bordering land types have such stark difference in NPP_T.

Conclusions

This study explored the long-term effect of the construction of 10 dams in the Wujiang catchment on the distribution patterns of annual NPP_T, at both catchment and landscape scales by integrating remote sensing images and the CASA terrestrial carbon model. The hypothesis that the construction of a single dam impacts NPP_T at a catchment scale has been overestimated. Results showed that the impact on NPP_T, of a single dam is scale-dependent, mainly affecting only a 1 km riparian buffer strip. The study also found that dam construction reduced NPP_T mainly by changing land cover, through facilitating the development of urbanization and the direct increase of inundation zones at the expense of vegetated habitats in the riparian zone. From 2000 to 2014, the total NPP_T in the Wujiang catchment fluctuated over time, reaching the maximum of 55648 GgC in 2002 and a minimum of 41946 GgC in 2011. A sharp reduction of NPP_T in 2011 might reflect a dam-induced cumulative impact on NPP_T at a catchment scale, although it was difficult to separate the cumulative impact associated with dam construction from the wider influences such as climate factors. Overall, the key environmental impacts of dam construction on primary productivity consist of the loss of riparian vegetation through the reservoir impoundment and dam facilitated development of urbanization. Further study should be focussed on the water fluctuation zones of the reservoir.

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References:

Alexandrov GA, Oikawa T, Yamagata Y. 2002. The scheme for globalization of a process-based model explaining gradations in terrestrial NPP and its application. Ecol. Modell. 148: 293–306.

Apps MJ, Peng C. 1998. Simulating carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in central Canada: Part II. Sensitivity to climate change. Global Biogeochem. Cycles 12: 393–402.

Azami K, Suzuki H, Toki S. 2004. Changes in riparian vegetation communities below a large dam in a monsoonal region: Futase Dam, Japan. River Res. Appl. 20: 549–563.

Bastviken D, Tranvik LJ, Downing JA, Crill PM, Enrich-Prast A, Luyssaert S, Battin TJ, Cole JJ, Tranvik LJ, Bastviken D, Cole JJ, Pace ML, Tranvik LJ, Benoy G, Cash K, McCauley E, Wrona F, Guérin F, Kemenes A, Forsberg BR, Melack JM, Melack JM. 2011. Freshwater methane emissions offset the continental carbon sink. Science 331: 50-50.

Bian JH, Li AN, Deng W. 2010. Estimation and analysis of net primary productivity of Ruoergai wetland in China for the recent 10 years based on remote sensing. Procedia Environ. Sci. 2: 288–301.

Bian JH, Li AN, Song MQ, Ma LQ, Jiang JG. 2010. Reconstruction of NDVI time-series datasets of MODIS based on Savitzky-Golay filter. Int. J. Remote Sens. 14: 1-9.

Bornette G, Amoros C, Lamouroux N. 1998. Aquatic plant diversity in riverine wetlands: The role of connectivity. Freshw. Biol. 39: 267–283.

Bracken LJ, Croke J. 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. Hydrol. Process. 21: 1749–1763.

Brown S, Sathaye J, Cannell M, Kauppi P. 1996. Mitigation of carbon emission to the atmosphere by forest management. Commonwealth Forestry Review 75: 80-91.

Cao M, Woodward FI. 1998. Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. Nature 393: 249–252.

Colonnello G, Medina E. 1998. Vegetation changes induced by dam construction in a tropical estuary: The case of the Manamo river, Orinoco Delta (Venezuela). Plant Ecol. 139: 145–154.

Cramer W, Kicklighter DW, Bondeau A, Moore B, Churkina G, Nemry B, Ruimy A, Schloss AL. 1999. Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Glob. Chang. Biol. 5: 1–15.

Degu AM, Hossain F, Niyogi D, Pielke R, Shepherd JM, Voisin N, Chronis T. 2011. The influence of large dams on surrounding climate and precipitation patterns. Geophys. Res. Lett. 38: L04405.

Dixon RK, Solomon AM, Brown SA, Houghton RA, Trexier MC, Wisniewski J. 1994. Carbon Pools and Flux of Global Forest Ecosystems. Science 263:185-190.

Dugan PJ, Barlow C, Agostinho AA, Baran E, Cada GF, Chen D, Cowx IG, Ferguson JW, Jutagate T, Mallen-Cooper M, Marmulla G, Nestler J, Petrere M, Welcomme RL, Winemiller KO. 2010. Fish migration, dams, and loss of ecosystem services in the mekong basin. Ambio 39: 344–348.

Emer C, Venticinque EM, Fonseca CR. 2013. Effects of dam-induced landscape fragmentation on Amazonian ant-plant mutualistic networks. Conserv. Biol. 27: 763–773.

Fang JY, Chen AP, Peng CH, Zhao SQ, Ci L. 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. Science 292: 2320–2322.

Fearnside PM. 2000. Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary. Vegetation. Clim. Change 46: 115–158.

Feng X, Liu G, Chen JM, Chen M, Liu J, Ju WM, Sun R, Zhou W. 2007. Net primary productivity of China's terrestrial ecosystems from a process model driven by remote sensing. J. Environ. Manage. 85: 563–573.

Freden F. 2011. Impacts of dams on lowland agriculture in the Mekong River Catchment. Probrane z: www.lup.lub.lu.se.

Gao, J., Pan, G., Jiang, X., Pan, J., Zhuang, D., 2008. Land-use induced changes in topsoil organic carbon stock of paddy fields using MODIS and TM/ETM analysis: A case study of Wujiang County, China. J. Environ. Sci. 20: 852–858.

Gehrke PC, Gilligan DM, Barwick M. 2002. Changes in fish communities of the Shoalhaven River 20 years after construction of Tallowa Dam, Australia. River Res. Appl. 18: 265–286.

Goetz SJ, Prince SD, Goward SN, Thawley MM, Small J. 1999. Satellite remote sensing of primary production: An improved production efficiency modeling approach. Ecol. Modell. 122: 239–255.

Gordon E, Meentemeyer RK. 2006. Effects of dam operation and land use on stream channel morphology and riparian vegetation. Geomorphology 82: 412–429.

Graf WL. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79: 336–360.

Grumbine RE, Xu J. 2011. Mekong hydropower development. Science 332: 178-179.

Harms TK, Grimm NB. 2008. Hot spots and hot moments of carbon and nitrogen dynamics in a semiarid riparian zone. J. Geophys. Res. Biogeosciences 113: G01020.

Houghton RA. 2004. The annual net flux of carbon to the atmosphere from changes in land use 1850-1990. Tellus 51B: 378–390.

Jenkins JC, Chojnacky DC, Heath LS, Birdsey RA. 2003. National-scale biomass estimators for United States tree species. For. Sci. 49: 12–35.

Jenkinson DS, Adams DE, Wild A. 1991. Model estimates of CO_2 emissions from soil in response to global warming. Nature 351: 304–306.

Julien Y, Sobrino JA. 2012. Correcting AVHRR Long Term Data Record V3 estimated LST from orbital drift effects. Remote Sens. Environ. 123: 207–219.

Kellogg CH, Zhou XB. 2014. Impact of the construction of a large dam on riparian vegetation cover at different elevation zones as observed from remotely sensed data. Int. J. Appl. Earth Obs. Geoinf. 32: 19–34.

Law BE, Turner D, Campbell J, Lefsky M, Guzy M, Sun OJ, Van TS, Cohen WB, Wu J, Jones KB, Li H. 2006. Carbon fluxes across regions: Observational constraits at multiple scales. Scaling and Uncertainty Analysis in Ecology. pp. 167–190.

Li SX, Zhou LF, Wang HJ, Xiong MH, Yang Z, Hu JX, Liang YG, Chang JB. 2013. Short-term impact of reservoir impoundment on the patterns of mercury distribution in a subtropical aquatic ecosystem, Wujiang River, Southwest China. Environ. Sci. Pollut. Res. 20: 4396-4404.

Lieth H. 1975. Some prospects beyond production measurement. Prim. Product. Biosph. Springer-Verlag, New York. pp. 285–304.

Likens GE. 1975. Primary production of inland aquatic ecosystems. Prim. Product. Biosph. Springer-Verlag, New York. pp. 185–202.

Ling TY, Soo CL, Heng TLE, Nyanti L, Sim SF, Grinang J. 2016. Physicochemical characteristics of river water downstream of a large tropical hydroelectric dam. J. Chem. 2016: 1-7.

Liu J, Chen JM, Cihlar J, Chen W. 1999. Net primary productivity distribution in the BOREAS region from a process model using satellite and surface data. J. Geophys. Res. 104: 27735–27754.

Luo T, Li W, Zhu H. 2002. Estimated biomass and productivity of natural vegetation on the Tibetan Plateau. Ecol. Appl. 12: 980–997.

Maavara T, Lauerwald R, Regnier P, Cappellen PV. 2017. Global perturbation of organic carbon cycling by river damming. Nat. Commun. 8. DOI: 10.1038/ncomms15347.

Maraseni TN, Mitchell C. 2016. An assessment of carbon sequestration potential of riparian zone of Condamine Catchment, Queensland, Australia. Land use Policy 54: 139-146.

McCrady RL, Jokela EJ. 1998. Canopy dynamics, light interception, and radiation use efficiency of selected loblolly pine families. For. Sci. 44: 64–72.

Melillo JM, McGuire AD, Kicklighter DW, Moore B, Vorosmarty CJ, Schloss AL. 1993. Global climate change and terrestrial net primary production. Nature 363: 234-240.

New T, Xie Z. 2008. Impacts of large dams on riparian vegetation: Applying global experience to the case of China’s Three Gorges Dam. Biodivers. Conserv.17:3149-3163.

Oťaheľova HH, Ot’ahel J, Pazur R, Hrivnak R, Valachovic M. 2011. Spatio-temporal changes in land cover and aquatic macrophytes of the Danube floodplain lake. Limnologica 41: 316-324.

Parton WJ, Scurlock JMO, Ojima DS, Gilmanov TG, Scholes RJ, Schimel DS, Kirchner T, Menaut JC, Seastedt T, Garcia Moya, E, Kamnalrut A, Kinyamario JI. 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem. Cycles 7: 785–809.

Paruelo JM, Epstein HE, Lauenroth WK, Burke IC. 1997. ANPP estimates from NDVI for the central grassland region of the United States. Ecology 78: 953–958.

Pauleit S, Ennos R, Golding Y. 2005. Modeling the environmental impacts of urban land use and land cover change - a study in Merseyside, UK. Landsc. Urban Plan. 71: 295–310.

Peng CH, Apps MJ. 1998. Simulating carbon dynamics along the boreal forest transect case study (BFTCS) in the Central Canada. Part II. Sensitivity to climate change. Global Biogeochem. Cycles 12: 393–402.

Peng CH, Apps MJ, 1999. Modelling the response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes. Ecol. Modell. 122: 175–193.

Peng SL, Guo ZH, Wang BS. 2000. Use of GIS and RS to estimate the light utilization efficiency of the vegetation in Guangdong, China. Acta Ecol. Sin. 20: 903–909 (in Chinese).

Pimm SL, Raven P. 2000. Biodiversity. Extinction by numbers. Nature 403: 843–845.

Potter CS, Randerson JT, Field CB, Matson PA, Vitousek PM, Mooney HA, Klooster SA. 1993. Terrestrial ecosystem production: A process model based on global satellite and surface data. Global Biogeochem. Cycles 7: 811–841.

Prince SD. 1991. A model of regional primary production for use with coarse resolution satellite data. Int. J. Remote Sens. 12: 1313–1330.

Qiu JN. 2011. China faces up to “terrible” state of its ecosystems. Nat. News 471: 19–19.

R Development Core Team. 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, http://www.R-project.org (accessed March 6, 2017)

Rathgeber C, Nicault A, Guiot J, Keller T, Guibal F, Roche P. 2000. Simulated responses of Pinus halepensis forest productivity to climate change and CO_2 increase using a statistical model.Glob. Planet. Change 26: 405-421.

Raymond PA, Hartmann J, Lauerwald R, Sobek S, McDonald C, Hoover M, Butman D, Striegl R, Mayorga E, Humborg C, Kortelainen P, Durr H, Meybeck M, Ciais P, Guth P. Global carbon dioxide emissions from inland waters. Nature 503: 355-359.

Reich PB, Turner DP, Bolstad P. 1999. An approach to spatially distributed modeling of net primary production (NPP) at the landscape scale and its application in validation of EOS NPP products. Remote Sens. Environ. 70: 69–81.

Ruimy A, Saugier B, Dedieu G. 1994. Methodology for the estimation of terrestrial net primary production from remotely sensed data. J. Geophys. Res. 99: 5263–5283.

Running SW, Hunt ER. 1993. Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. Scaling Physiol. Process. Leaf to globe. San Diego, CA: Academic Press. pp 141–158.

Running SW, Thornton PE, Nemani RR, Glassy JM. 2000. Global Terrestrial gross and net primary productivity from the earth observing system, in: Methods in Ecosystem Science. New York: Springer Verlag. pp 44–57.

Schulze ED, Wirth C, Heimann M. 2000. Managing Forests After Kyoto. Science 22: 2058–2059.

Silva DD, De Marco P, Resende DC. 2010. Adult odonate abundance and community assemblage measures as indicators of stream ecological integrity: A case study. Ecol. Indic. 10: 744–752.

Smith P, Davies CA, Ogle S, Zanchi G, Bellarby J, Bird N, Boddey RM, McNamara NP, Powlson D, Cowie A, Van Noordwijk M, Davis SC, Richter DDB, Kryzanowski L, Van Wijk MT, Stuart J, Kirton A, Eggar D, Newton-Cross G, Adhya TK, Braimoh

AK. 2012. Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: Current capability and future vision. Glob. Chang. Biol. 18: 2089–2101.

Wen J, Pu L. 2010. Impacts of Land Use Change on the vegetation carbon storage in rapid development area: a case study of Wujiang City, China. Multimed. Technol. (ICMT), 2010 Int. Conf.

Wildi W. 2010. Environmental hazards of dams and reservoirs. Near Curric. Nat. Environ. Sci. 88: 187–197.

Xiao J, Zhuang Q, Law BE, Baldocchi DD, Chen J, Richardson AD, Melillo JM, Davis KJ, Hollinger DY, Wharton S, Oren R, Noormets A, Fischer ML, Verma SB, Cook DR, Sun G, McNulty S, Wofsy SC, Bolstad PV, Burns SP, Curtis PS, Drake BG, Falk M, Foster DR, Gu L, Hadley JL, Katul GG, Litvak M, Ma S, Martin TA, Matamala R, Meyers TP, Monson RK, Munger JW, Oechel WC, Paw UKT, Schmid HP, Scott RL, Starr G, Suyker AE, Torn MS. 2011. Assessing net ecosystem carbon exchange of U.S. terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations. Agric. For. Meteorol. 151: 60–69.

Xu X, Tan Y, Yang G, Li H, Su W. 2011. Impacts of China's Three Gorges Dam Project on net primary productivity in the reservoir area. Sci. Total Environ. 409: 4656–4662.

Yan HM, Liu JY, Huang HQ, Tao B, Cao MK. 2009. Assessing the consequence of land use change on agricultural productivity in China. Glob. Planet. Change 67: 13–19.

Yin YP, Huang BL, Wang WP, Wei YJ, Ma XH, Ma F, Zhao CJ. 2016. Reservoir-induced landslides and risk control in Three Gorges Project on Yangtze River, China. J. Rock Mech. Geotech. Eng. 8: 577–595.

Zhang H, Ma WC, Wang XR. 2007. Rapid urbanization and implications for flooding risk management in Hinterland of the Pearl River Delta, China: The Foshan Study. Sensor 8: 2223-2239.

Zhang JX, Liu ZJ, Sun XX. 2009. Changing landscape in the Three Gorges Reservoir Area of Yangtze River from 1977 to 2005: Land use/land cover, vegetation cover changes estimated using multi-source satellite data. Int. J. Appl. Earth Obs. Geoinf. 11: 403–412.

Zhang X, Zhu Y, Yao H. 2008. Measurement and pattern analysis of urban sprawl using remote sensing and GIS A case study of Wujiang, China(1978 -2004), in: 2008 International Workshop on Earth Observationand Remote Sensing Applications. pp. 1–6.

Zhu W, Pan Y, He H, Yu D, Hu H. 2006. Simulation of maximum light use efficiency for some typical vegetation types in China. Chinese Sci. Bull. 51: 457–463.

Zhu W, Pan Y, Zhang J. 2007. Estimation of net primary productivity of Chinese terrestrial vegetation based on remote sensing. J. Plant Eco. 31: 413-424 (In Chinese).

Tables

Table 1. The characteristics of cascade dams in Wujiang Catchment

Table 2. Comparison of annual NPP_T pre- and post-dam construction in the Wujiang catchment. N is the number of years in each period, pre/post. Mean-difference is the change in mean NPP_T between pre-dam and post-dam period. P-value gives the significance of the mean difference, tested using a T-test. (DHS-Dahuashui, GLQ-Geliqiao, GPT-Goupitan, HJD-Hongjiadu, PS-Pengshui, ST-Shatuo, SL-Silin, SFY-Suofengying, YP-Yinpan, YZD-Yinzidu)

Table 3. ANOVA results indicating significance of the change of NPP_T across different buffer strips (0-1, 1-3, 3-5, 5-7, 7-10 km) before and after dam construction. (DHS-Dahuashui, GLQ-Geliqiao, GPT-Goupitan, HJD-Hongjiadu, PS-Pengshui, ST-Shatuo, SL-Silin, SFY-Suofengying, YP-Yinpan, YZD-Yinzidu)

Table 4. The change of area and NPP_T across different land use classes within 1 km reservoir buffers of four investigated reservoirs (GPT-Goupitan, HJD-Hongjiadu, SL-Silin, YZD-Yinzidu).

Table 5. The change in the coverage of different land categories and relevant NPP_T for the whole Wujiang catchment in the years 2000, 2005, 2010 and 2014

Figures

Figure 1. Geographical positions of the cascade dams in the Wujiang catchment (reservoir boundaries are shown and labelled). Sub-catchments for each reservoir are shown in distinct colours. The investigated catchments represented a containment relationship, in that downstream sub-catchments contain all upstream sub-catchments) (DHS-Dahuashui, GLQ-Geliqiao, GPT-Goupitan, HJD-Hongjiadu, PS-Pengshui, ST-Shatuo, SL-Silin, SFY-Suofengying, YP-Yinpan, YZD-Yinzidu)

Figure 2. Total NPP_T in the Wujiang catchment from 2000 to 2014 and year of dam construction. Annual precipitation (mm) and air temperature (℃) during the investigated years were also presented in the figure.

Figure 3. (a) 30 m Topography of the Wujiang Catchment. (b) Spatial distribution of mean NPP_T for the period 2000 to 2014. (c) Standard deviation of mean NPP_T between 2000 and 2014.

Figure 4. Boxplot comparing median NPP_T pre-and post-dam construction). The number under the dam label refers to the normal water level of each reservoir (m). (DHS-Dahuashui, GLQ-Geliqiao, GPT-Goupitan, HJD-Hongjiadu, PS-Pengshui, ST-Shatuo, SL-Silin, SFY-Suofengying, YP-Yinpan, YZD-Yinzidu)

Figure 5. Comparison of the normalized mean NPP_T before and after dam construction over increasing spatial buffer strips sizes (0-1, 1-3, 3-5, 5-7, 7-10 km) for each reservoir. (* $P<0.01$, ** $p<0.05$, t-test)

Figure 6. Land use patterns in the Wujiang catchment during the years 2000, 2005, 2010 and 2014