Mapping the impacts of dammed reservoirs on downstream hydrologic system and regional climate in the continental U.S. – a GIS-based approach

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Abstract:

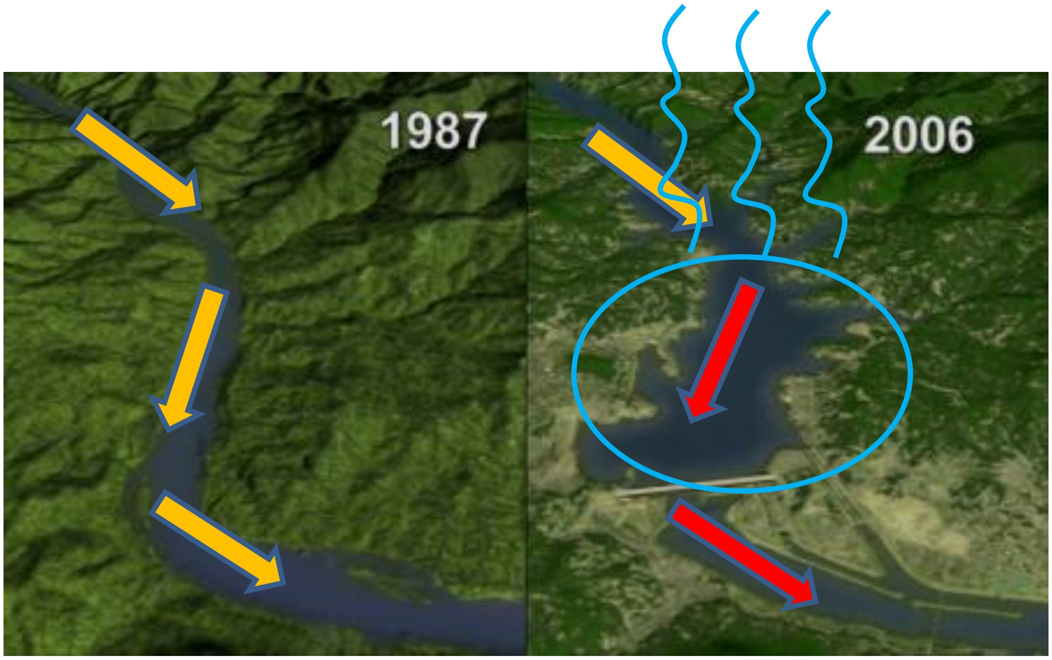
Man-made reservoirs in the U.S. are mainly formed by intensive dam constructions since 1950s, and they become very important landscape features. On one hand, dams regulate the horizontal river transport from the land surface to the ocean, which throws an anthropogenic interference to the natural hydrologic system; On the other hand, dammed lakes render the evaporative fluxes on land increase due to the increased retention time of water on land, thus affecting regional climate such as precipitation formation on downwind areas. Nevertheless, a systematic investigation on the total impacts of the above two is hard to get due to the generally unpublished dam operation records, as well as lack of meteorological measurements for all dams. In this study, two global GIS-based datasets of dams (point shapefile), lakes and reservoirs (polygon shapefile), and NLDAS-2 evapotranspiration (NetCDF time series file) are integrated and analyzed to quantify the two impacts. Degree of regulation (DOR) is introduced and calculated as indicator of interference to downstream areas. ET from Noah land surface model is extracted and associated with each dammed reservoir in CONUS to indicate water vapor contribution to the atmosphere. Spatial distributions in the newly created thematic maps are analyzed, and it is seen that the water bodies over southeast region of the U.S. contribute more ET to the atmosphere, which would have shifted the circulation pattern to some degree. That might potentially be linked with changing rainfall patterns and regional climate in southeast regions of CONUS, though this effect might not be very significant.

Keywords:

Man-made reservoirs; interference; downstream hydrologic system; regional climate; GIS

1. Introduction

Human has built dams and water impoundments for thousands of years for flood-control, hydropower, water supply, irrigation, navigation, recreation [e.g. *Lehner et al.*, 2011], and various human needs. Intensive dam constructions world-wide since 1950s [*Chao B.F.*, 1995] have thrown large human interferences to both the natural hydrologic system which locates downstream of a man-made dam, and the upper-lying atmosphere through increased evaporative fluxes, which would bring more water vapor to form rainfall, and potentially may change the regional circulation pattern to some degree.



Above figure shows the Three-Gorges Dam in China (the world largest hydropower station), and it illustrates the two aspects of dam impacts that are examined in this. On one hand, the construction of the dam certainly regulates greatly the horizontal transport of river flows which feeds into the ocean eventually, and downstream rivers narrowed due to the controlled amount of water; besides, the big water impoundments increased the residence time of water on land, which increased the ET fluxes over the region and its downwind areas.

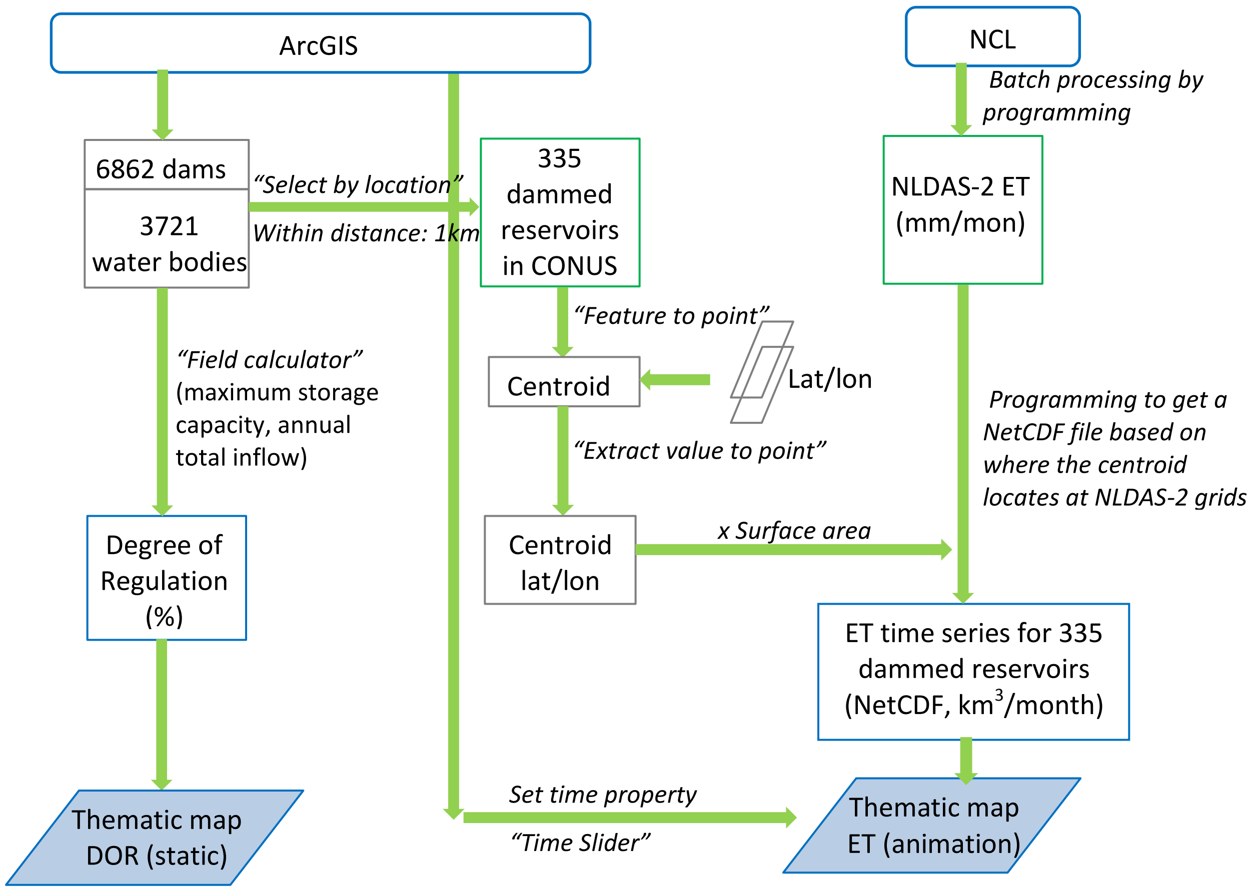
However, due to the unpublished dam releases (or reservoir operation records) and scarce stations where eddy-covariance measurements of ET are continuously taken, it is hard to map the two impacts especially in a scale like continental United States (hereafter, CONUS). In this study, a systematic investigation on U.S. dammed reservoirs are made through creating two thematic maps (one static and one dynamic) based on best available data (GRanD dams, and NLDAS ET for CONUS) using a GIS-based approach. The aim is to understand systematically about the impacts of dams on downstream hydrologic system and upper-lying regional climate through analyzing spatial patterns.

Finally, some problems related to the dataset uncertainties and issues to be addressed for future work are discussed.

2. Dataset, Tools, and Pre-Processing

2.1 Tools and Methodology

In this project, ArcGIS 10.2 and NCAR Common Language (NCL) 6.1.2 are jointly used for data processing, analysis, display and animation. Below is a schematic diagram showing the use of the two tools and functionalities. Detailed dataset information and processing procedures are provided afterwards.



2.1.1 *Vector file for dams*

Global Reservoir and Dam (GRanD) dataset V1.01 maintained at Columbia University is downloaded from http://sedac.ciesin.columbia.edu/data/set/grand-v1-dams-rev01/data-download. This dataset consists of 6862 dams global-wide, and available reservoir and dam information is compiled in database. GRanD is an updated database after the *World Register of Dams*, where georeferencing, error-checking, and cross-validation are done to ensure data quality [*Lehner et al.*, GRanD Technical Documentation, 2011]. CONUS dams are selected using "select by location" and the criteria is "within a distance of 1km from source layer", and lakes/reservoir polygon is set as source layer because several attributes in this layer must be retained and corresponding well with dams. A set of 335 dams with all attributes from GRanD and DLWD is used in this study.

2.1.2 *Vector file for lakes/reservoirs*

Global Lakes and Wetlands Database (GLWD, Level-1 data) is downloaded from http://worldwildlife.org/pages/global-lakes-and-wetlands-database, and is by-far the mostly reviewed dataset for studying water bodies taking advantage of GIS capabilities. Large lakes and reservoirs, smaller water bodies, and wetlands are all included. Level-1 data comprises the 3067 largest lakes (area ≥ 50 km^2) and 654 largest reservoirs (storage capacity ≥ 0.5 km^3) worldwide, and includes extensive attribute data.

2.1.3 Raster file for ET estimation

NLDAS-2 (National Land Data Assimilation System – Phase 2) datasets are available from the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC), link: disc.sci.gsfc.nasa.gov/hydrology/data-holdings. The original format is GRIB-1, but it can be easiliy converted to NetCDF file using an inbuilt function in NCAR Common Language (NCL). NLDAS-2 currently runs four different physical models as its land components, namely Noah, Mosaic, SAC, and VIC, where the first two were originally designed by meteorologists and the last two were from hydrologic community. More detailed information about these four models' similarities and differences can be found in Table 2 of *Lohmann et al.* (2004).

In this study, monthly average data from Noah Land Surface Model (LSM) are chosen to provide evapotranspiration (ET) estimates. In all, there are 464 columns and 224 rows for CONUS region, with the raster size (spatial resolution) being 0.125º (12.5km).

2.2 Degree of Regulation (DOR)

Besides the various methods used to pre-process the collected dataset, and methods to extract ET flux values to quantify impacts of dams on upper-lying climate, Degree of Regulation (DOR) is used to quantify dams' impacts on downstream hydrologic system, it follows the equation in *Lehner et al.* (2011):

$$DOR = \frac{Storage\ capacity}{Total\ annual\ inflow}$$

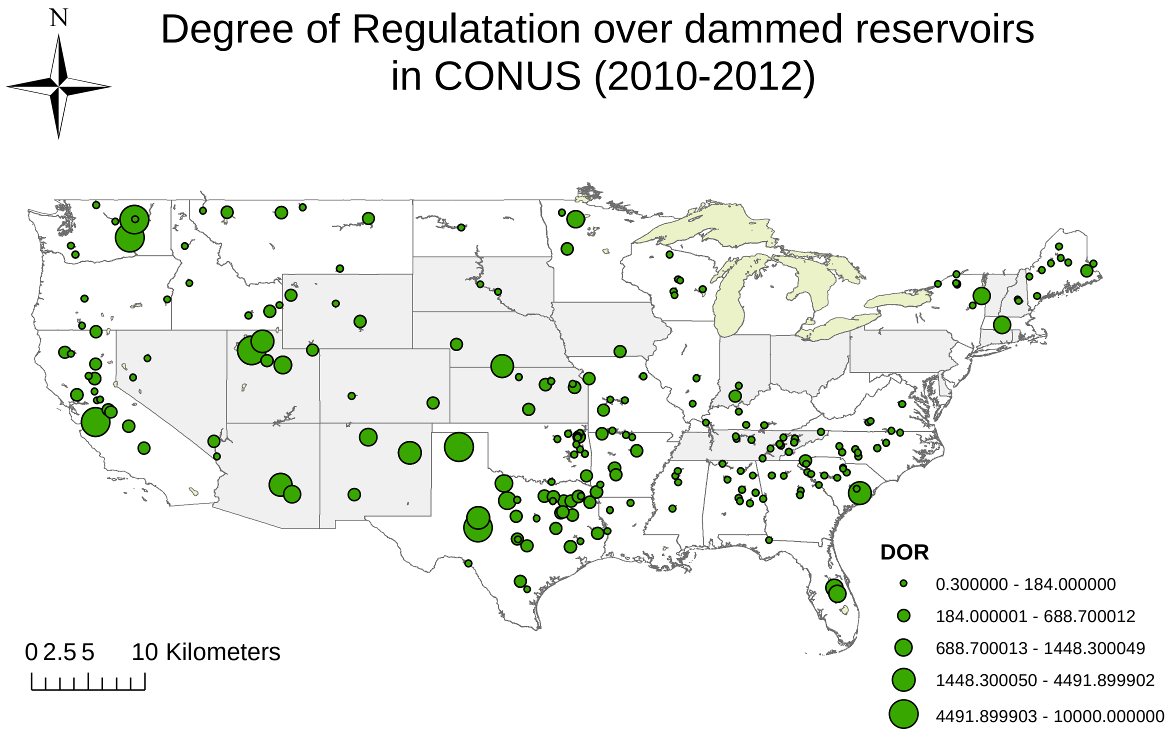
where storage capacity has a unit of million cubic meter (Camp_mcm), and total annual inflow has a unit of liters per second (Dis_avg_ls). The final calculation is converted into days, and divided by 365 days to get DOR percentage:

$$DOR\_percentage = \frac{DOR}{365\ days\ in\ a\ year}$$

A threshold of 10,000 is applied to cap the DOR_percentage, indicating that the maximum DOR_percentage can be as much as 10,000%, which is highly regulating.

3. Quantification of Impacts on Downstream Hydrologic System

Below shows the thematic map on DOR_percentage for 335 dams over CONUS.

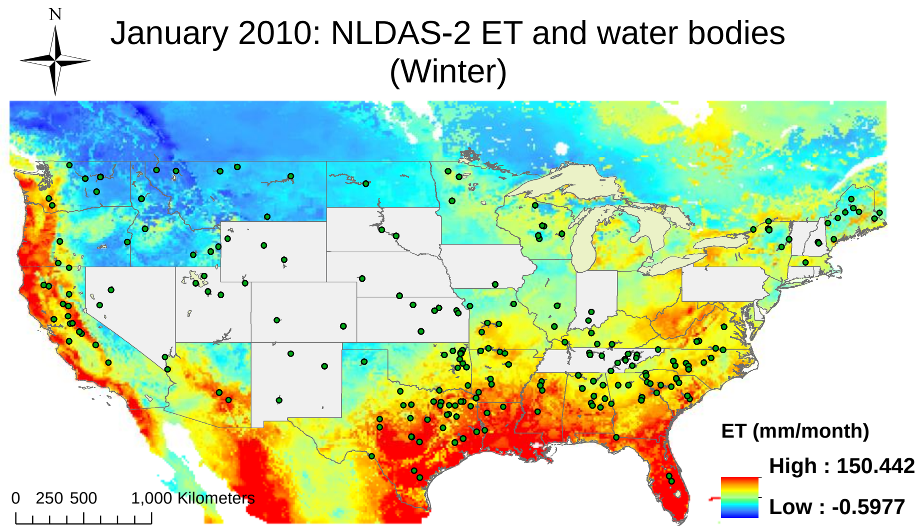


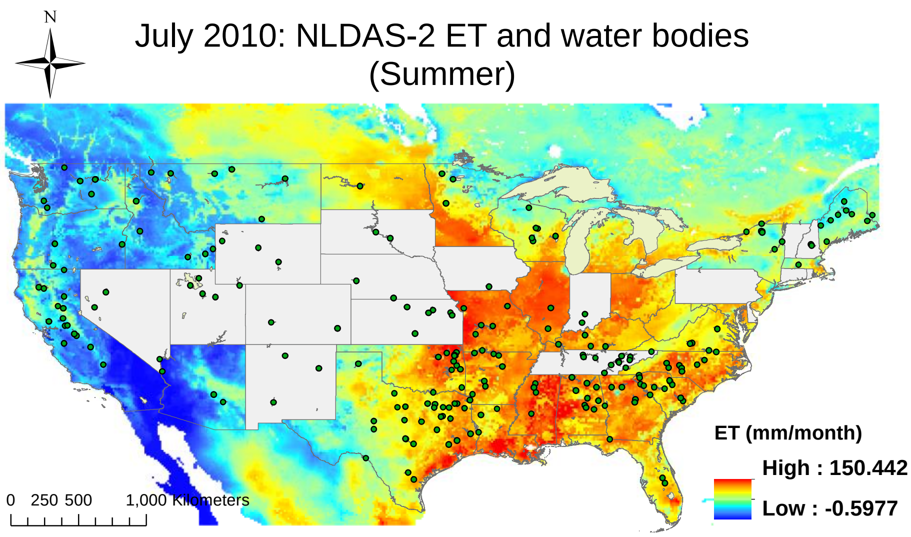
Highly regulated dams are mainly located at central and west U.S., which is related to the fact that the total annual inflows are generally less due to drier climate. In both Texas and Utah, there are more than two dams that show a DOR percentage much larger than 100%. That being said, in relatively dry regions, the construction of dams tend to play a more important role in regulating horizontal water transport, especially those ones with large storage capacity. Lake Buchanan and Lake Travis, the biggest two freshwater supplies for the city of Austin, has a DOR percentage of 224% and 329% respectively. Lake Buchanan has a much larger surface area, but its regulation on downstream hydrology is smaller than that of Lake Travis due to its shallower depth and smaller storage capacity, but since the surface area is bigger, it may contribute a bigger ET flux back to the atmosphere.

For most of the eastern part of the U.S., the DOR percentage is less than 100%, which means the dam regulation on downstream is relatively small. However, there are still some dams in Massachusetts, New York, Florida, and South Carolina that are highly regulating. For example, the Quabbin Winsor Dam in Massachusetts has a DOR percentage of 915%. This is a dam which provides flood control, and it locates most nearing the coast. The big storage capacity and relatively smaller annual inflow (already regulated by upstream dams) causes it to have a very large DOR percentage.

4. Quantification of Impacts on Upper-Lying Atmosphere

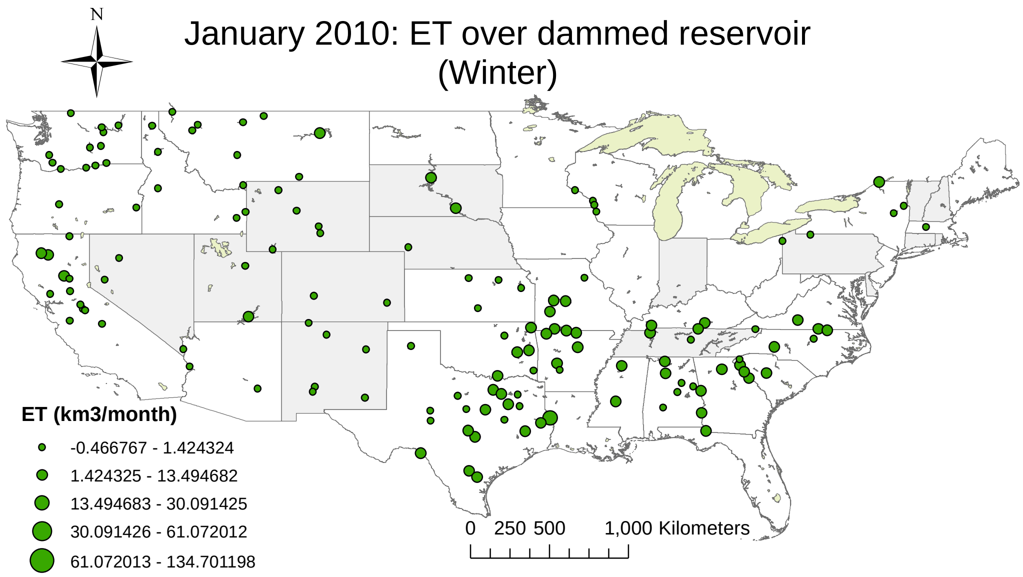
The use of NLDAS-2 ET products is proposed to quantify reservoir evaporation and their water vapor contribution to the atmosphere. In this study, the monthly NLDAS-2 data covers the period from 2000 to 2012, and a total of 156 NetCDF file is processed and integrated into one file using NCL. Then it is imported into ArcGIS for further processing and display. An animation is shown in the PPT presentation, here a static map for Winter and Summer month in 2010 is shown.

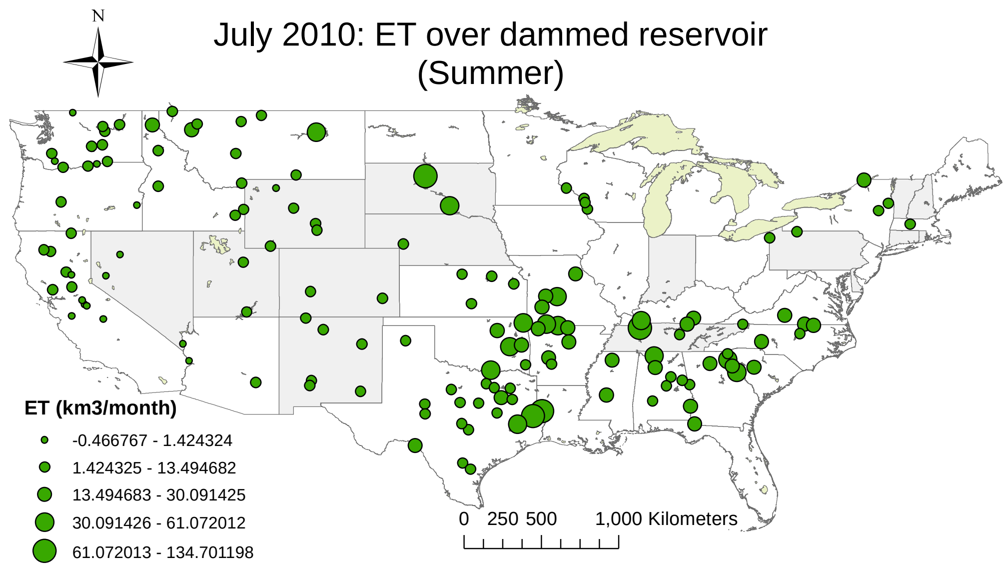




During winter season, the ET fluxes are mostly high over the coastal regions in the U.S., because when temperature is low, the ET is mainly controlled by water availability, and coastal regions are more humid than inland areas; During summer times, the high ET region extends into the High Plains of the U.S. (including large parts of Kansas, Oklahoma, Nebraska, etc.), mainly because of the North American monsoon which brings water toward inland areas.

Following steps described in Part 2, a NetCDF file which associates each dammed reservoir with a time series of ET fluxes (mm/month) is created and put into ArcGIS to compute final volumetric ET by multiplying reservoir surface area. An animation for ET fluxes is shown in PowerPoint presentation, here a map for Winter and Summer month in 2010 is shown for interpretation.





It is seen on that generally the reservoirs over southeastern part of the U.S. contribute more water vapor to the atmosphere due to the two factors – the higher ET rates and the larger humidity over those areas. This pattern is completely opposite from the dams' impacts on downstream areas, where northwester parts are more impactful. We see during summer this amount of water going back to the atmosphere can be up to 100km^3 for an individual reservoir, so we can get the addition of this amount can be several thousand cubic kilometers. Reservoir constructions in Missouri, west Texas, Kentucky, and Georgia are among the biggest to contribute more vapor back to the atmosphere rather than routes this amount of water to the ocean. Two dammed reservoirs in South Dakota are also highly contributing, where they locate at the Missouri river and impound large areas of water.

5. Conclusions and discussions

5.1 Conclusions

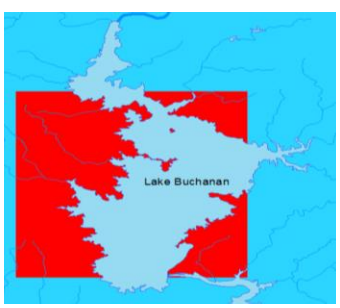
Through collecting the newly developed GIS datasets of dams and lakes/reservoirs, NASA NLDAS-2 data products, and appropriate pre-processing procedures, two thematic maps (one static and one dynamic) on impacts of dams on downstream hydrologic system and upper-lying atmosphere are created. Degree of Regulation (DOR) percentage are introduced and computed, and shown spatially for CONUS dams; NLDAS-2 ET values are extracted to the centroid of each dam over CONUS, to quantify the contribution of water vapor from the big water impoundments after dam constructions.

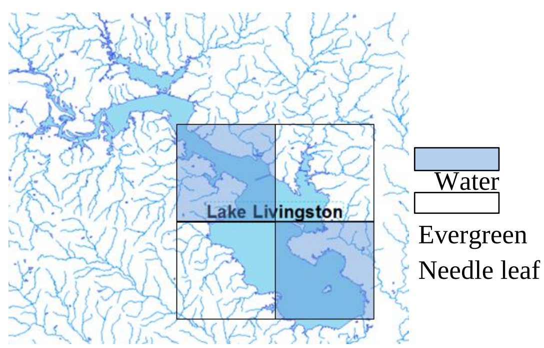
We can see that highly regulated dams are generally located at drier regions (central north, central and west CONUS), where total annual inflows are generally smaller such that the building of dams would throw a bigger regulation on horizontal river transport, thus impacting the downstream flows more. Southeast and east U.S. have larger total annual inflow, so flow rate impediments by dams are relatively smaller. But there are still dams close to the coast which are highly regulating.

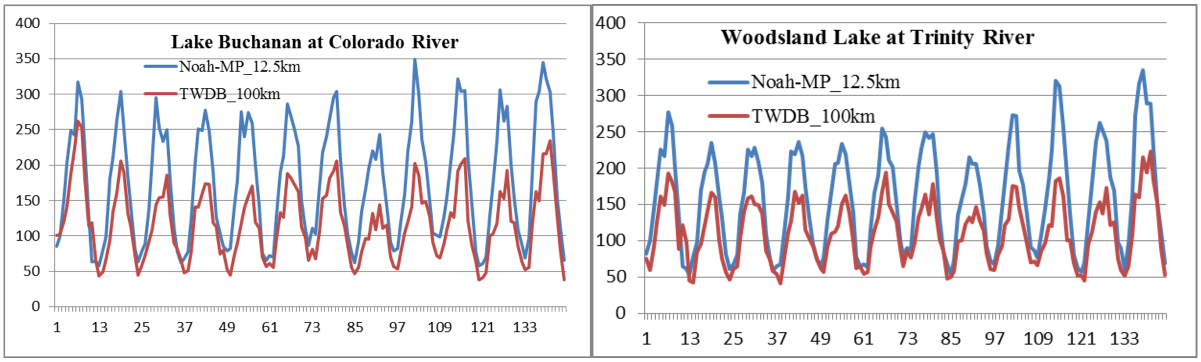
5.2 Discussions

It is found in this study that large portions of the DOR values are much greater than 100%, which may indicate the further improvements on the DOR index definition, such that it can be better scaled to 0-100%. Currently the scales are not shown clearly for differences between DORs lower than 100%, due to the existence of large DORs. A better interpretation can be gained with further information on DOR thresholds.

We note that NLDAS-2 ET data are model outputs from Noah LSM, so the insufficient model physics/parameterizations would cause uncertainties and errors in ET estimation for open water body. A more detailed look at comparison of Noah-MP ET fluxes with Texas Water Development Board (TWDB) quadrangle-based ET products are compared for two lakes in Texas – Lake Buchanan and Lake Livingston, below is the figure showing the comparison:







We found from above figure that Noah LSM with Multiple Physics (thus Noah-MP) model, which uses Panman-Monteith equation to parameterize actual ET fluxes over bare soil and open water body, gives reasonable seasonal variability in ET, but the overall estimation in summer each year is largely exaggerated. That might make the dot size in the thematic map for dammed reservoir ET be exaggerated as well. One possible reason is that currently neither Noah model, nor the updated Noah-MP model, incorporates the physics to model lake depth and the heat capacity of the water body. It treats lakes/reservoir as surface-watered grids with unlimited water supply. So during summer time the relatively cool water body cools down the region due to large depth and heat capacity, but it is not modeled or parameterized by Noah or Noah-MP, thus resulting in such discrepancy. But we also note that TWDB ET data is a 100-km quadrangle-based product, thus its accuracy in representing the lake/reservoir actual ET might have been underestimated as regional mean value. Future work should incorporate acquiring eddy-covariance data at sites, and compare it with modeled ET, thus ensuring accurate ET maps for dammed reservoirs over CONUS.

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