Calculating the water dissipation of buildings in urban areas based on global nighttime light data

Han Gao

College of New Energy and Environment, Jilin University

Jiahong Liu (✉ liujh@iwhr.com)

China Institute of Water Resources and Hydropower Research

Chao Mei

China Institute of Water Resources and Hydropower Research

Wang Hao

China Institute of Water Resources and Hydropower Research

Weiwei Shao

China Institute of Water Resources and Hydropower Research

Chuang Liu

China Institute of Water Resources and Hydropower Research

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Abstract

Urban water dissipation is increasing gradually as urbanization progresses. Urban water dissipation mainly includes the dissipation of water in buildings and natural water evapotranspiration. Previous studies have mainly focused on calculating natural evapotranspiration in urban areas and have overlooked the dissipation of water in buildings under the influence of strong human-related water use activities. In this paper, the concept of building water dissipation (BWD) was proposed to describe the phenomenon that water dissipation occurs inside buildings. Moreover, a BWD calculation model was established and applied to calculate global building water dissipation. To reveal the specific water dissipation inside buildings, it is necessary to obtain the urban building floor area first. This paper proposed a new method to calculate the urban building floor area based on global nighttime light data obtained from NPP-VIIRS. Taking the floor area results into the BWD calculation model, the global building water dissipation in urban areas was found to be 127 billion m^3 in 2015. The vast building water dissipation that occurs in urban areas mostly results from rapidly developing economies and intense human activities. The results provide a basic understanding of the nexus between water resources and the energy-heat island effect in urban areas.

Introduction

The sustainable utilization of urban water resources is vital to the sustainable development of residents' lives and the urban social economy. Since the urban population has grown rapidly in recent years, many studies have focused on water resource consumption¹ and urban drainage systems² by analyzing urban water cycle systems³ and the impacts of urban expansion on water security⁴. The urban water cycle is one of the foremost contemporary research themes and provides the foundation for urban water resource management⁵. Cities are typical natural-social dualistic water cycle areas⁶ and consist of a natural water cycle with the principal process of "precipitation-infiltration-evapotranspiration-runoff" and the social water cycle with the process of "supply-consumption-dissipation-discharge"⁵⁻⁷⁻⁸. Water dissipation and its mechanism are the key components in the "intake-conveyance-use-dissipation-drainage-recycling-reuse" process of water in urban areas. However, water dissipation has been ignored in previous studies of urban evapotranspiration and the urban water cycle⁹. Urban water dissipation primarily means that water vapor conversions occur in the process of various indoor water use activities; this is a difficult and challenging component in the research of the urban water cycle¹⁰. According to the characteristics of water dissipation, urban surfaces can be divided into five types: building interiors, building roofs and hardened ground, soils, vegetation, and water surfaces. Among these types, the water dissipation that occurs inside buildings mostly reflects the social aspects of water dissipation. Water dissipation occurs on the urban surfaces of the other four types; this is classified as urban surface evapotranspiration and reflects to the natural water dissipation component in cities¹¹. "Evapotranspiration" (ET) and "dissipation" constitute the water vapor conversion process of the hydrological cycle and are the primary sources of water vapor in urban areas⁹. Moreover, several methods have been used to estimate ET, including the water balance method¹², the meteorological method¹³, and the energy balance remote sensing model¹⁴.

With a rapid increase in the urban population and economic development, building water dissipation has an increasing trend¹⁵. Previous studies have concentrated on the natural side of the urban hydrological cycle and have shown that most urban evapotranspiration comes from water surfaces or green land types, such as trees, grasslands, and other vegetation-coverage areas¹¹. However, previous studies have ignored the water dissipation that occurs on the social side, which accounts for a large proportion of the city's water consumption. In this paper, the concept of building water dissipation (BWD) was proposed to refer to the water dissipation caused by human activities in buildings.

Building water consumption accounts for a large share of the total water use in cities. Buildings are major underlying surfaces in cities because their roofs exist as impervious surfaces, while indoor areas are vital places for water dissipation in the social water cycle¹⁰. Significant water use activities occur inside buildings to support urban citizens' daily lives. The BWD is mainly influenced by the number of building floors^{16–17}, the level of economic development¹⁸, and human activities¹⁹. The indoor water vapor produced by human activities will travel outside through doors, windows, and other channels to participate in the atmospheric water cycle. Nevertheless, this component of water dissipation has been ignored in previous studies of urban evapotranspiration and the urban water cycle⁹.

Nighttime light (NTL) observations from remote sensing products provide us with temporal and spatial human activity measurements²⁰. Many studies have applied nighttime light data to analyses of urban construction^{21–23}, social and economic situations²⁴, environmental circumstances²⁵, climate change²⁶, etc. The nighttime light intensity can also reflect the level of urbanization. The higher the light intensity in a region is, the more intense the human activities in the region are. Different artificial light source types, such as streetlights and residential and vehicle lights, have specific time signatures. This feature makes it possible to estimate the amount of brightness contributed by each light source²⁷. The artificial lights of buildings play a significant role in urban nighttime light.

At present, the two most widely used nighttime light data sources are the Defense Meteorological Satellite Program/the Operational Linescan System (DMSP/OLS) and National Polar-orbiting Partnership/Visible Infrared Imaging Radiometer Suite (NPP/VIIRS)²⁸; these products are provided by the National Oceanic and Atmospheric Administration (NOAA) and the National Geophysical Data Center (NGDC)²⁹, respectively. The DMSP-OLS data can be used to map urban areas in global regions^{28–30} to study the urbanization process^{31–32}. Urban areas are clearly expanding globally by looking at the area of nighttime light. According to changes in the nighttime light intensity value, the urban-rural boundary can be identified³³, and the temporal and spatial changes in the urbanization pattern can be analyzed. Nighttime light data can also be used to extract urban commercial areas²¹ and to analyze urban economic development. These data are often applied to assess spatial distribution information such as population density³⁴. More recently, the day/night band (DNB) data of the Visible Infrared Imager Radiometer Suite (VIIRS) of the Suomi National Polar-Orbiting Partnership have improved the quality of nighttime light data over that of the DMSP/OLS data with a higher spatial resolution, broader radiometric measurement range, more accurate radiometric calibration, and better geometric quality³⁵. Moreover, the DNB dataset has a

longer time series, which makes up for the defect in that DMSP data are only updated until 2013. Compared with the DMSP-OLS nighttime light data, the VIIRS data can reflect human habitation and socioeconomic activities more clearly³⁶ and can be used to extract urban land areas and urban build-up areas²⁸, estimate urban building densities and simulate population densities³⁴.

This study proposes the concept of building water dissipation, which is closely related to human daily life and industrial production. The mechanism and calculation of urban water dissipation have great significance in analyzing the fluxes involved in the urban water cycle. This paper mainly calculated the building water dissipation in the global region based on NPP-VIIRS nighttime light (NTL) data. The dataset from the year 2015 was selected in this study. The calculation method of the urban water dissipation was proposed based on the floor areas of urban buildings, as identified using global nighttime light data. Methods such as statistics and bionics were used to study the process of BWD and to measure the relevant calculation parameters.

Methods

Building water dissipation.

Building water dissipation is a process that accompanies water consumption. Based on the principle of bionics, this paper compares building areas to concrete forests composed of urban building trees⁹⁻¹⁰. Figure 1 shows the main type of water dissipation that occurs inside a building: the conversion of the phase of water from liquid to gaseous. Then, with air circulation, the water vapor inside a building is released into the air through the doors, windows, vents, and other pathways, such as through the leaf pores of trees, participating in the hydrological cycles in urban areas⁹⁻¹⁰.

The internal water dissipation links of urban buildings mainly include water used for drinking, showering, cooking, flushing, etc. For instance, water vapor evaporation occurs in the process of showering, steam is released in the process of cooking, water vapor evaporation occurs in the process of drying wet clothes, and evaporation occurs from the scrubbing of surfaces such as floors, glass surfaces, walls, desktops, etc.

Correction and Treatment of NTL.

To correct oversaturation in nighttime light (NTL) data, it is necessary to find a suitable lighting threshold value with which to identify and remove oversaturated areas. The more developed a city is, the higher its nighttime light brightness is. In this study, four developed cities, Beijing, Shanghai, Guangzhou and Shenzhen, were chosen to ascertain the maximum lighting values of urban areas in China. The data showed that the maximum lighting values of Beijing, Shanghai, Guangzhou and Shenzhen were 256, 202, 264 and 195, respectively. The nighttime light value of 264 was selected as the maximum lighting value in China. This selected value can almost cover the range of the nighttime lighting in urban areas throughout the whole country. Pixels representing oversaturated light values in other areas of China were removed. The nighttime light image of China was resampled to a pixel size of 500 m × 500 m and then reprojected

to the Albers projection coordinate system. As shown in Figure 2, a lighting value of 15 was chosen as a threshold value to distinguish urban and rural areas; thus, the nighttime lighting range of 15-264 represents urban building areas in China.

The geographic coordinate system of the NPP-VIIRS nighttime light data is GCS_WGS_1984, and the image grid deforms with a change in latitude. First, the global image data were projected to the Albers projection coordinate system and then resampled to a pixel size of 500 m × 500 m²⁸. Since the NPP-VIIRS sensor has a higher sensitivity than the DMSP-OLS sensor, weak nighttime light appears in some areas in the high-noise images. It is thus necessary to denoise the global nighttime light image. The brightness value of nighttime light data is closely related to the level of urban economic development. In this paper, several developed cities were selected, such as New York, Los Angeles, London, and Beijing; their maximum lighting values were 260, 317, 428 and 256, respectively. As shown in Figure 3, 428 was selected as the global maximum brightness value, and this threshold was used to eliminate the excessive brightness values present in some regions of the world.

Calculation of the building floor area.

To calculate the urban building floor area, the nighttime light comprehensive coefficient α is introduced. It is assumed that the higher the light brightness is, the higher the building density is, i.e., the larger the building floor area is. Moreover, the cumulative value of the building floor area is proportional to the cumulative brightness value. The calculation formula can be expressed as follows:

$$A = \sum_{i=1}^n \alpha \times P \times V_i \times C_i \quad (1)$$

where A is the total building floor area of the city in km²; P is the pixel size, and the value used in this paper is 0.25 km²; V is the nighttime light value; C is the number of pixels; and n is the nighttime light data value category. The maximum nighttime light values represents the brightest parts of a city and are usually located in the centers of downtown areas. The minimum nighttime light values represent areas with fewer buildings. The comprehensive light coefficient α is 0.015. To verify the accuracy of the urban building distribution represented by the nighttime light data, Xiamen was introduced as the sample city in this study, and the vector boundary of the Xiamen administrative region was used to extract the lighting image data of Xiamen city, as shown in Figure 4. According to the extracted light data, the lighting data values 15 to 196 were selected to represent lights within the urban buildings of Xiamen city, and a coverage comparison was made between this area and the urban area extracted from the Google satellite mixed map of Xiamen city. The coverage results are shown in Figure 5. It can be seen that the coverage precision between the two areas is high; thus, it can be concluded that the coverage represented by nighttime light values above 15 is equal to the distribution scope of urban buildings in the study area. According to the notice "Review of Xiamen urban construction in the 70th anniversary of reform and opening up" published on the official website of the Xiamen Municipal Bureau of Statistics in 2017³⁷, the building floor area of Xiamen in 2017 was 190 million m². Since there were no floor space data available

for Xiamen in 2015, the building floor area data reported for Xiamen in 2017 replaced the 2015 value in the calculation. The proportions of the nighttime light values in Xiamen are shown in Figure 6. The average daily water dissipation per unit building area differs regionally because the level of economic development varies among different regions of the world. According to the lighting value of Xiamen city, the global lighting data were analyzed. Lighting areas with values of 15-428 were selected for the analysis and calculation of the building areas, as shown in Figure 7.

Calculation of the global BWD.

Artificial water dissipation, also known as enhanced evaporation, mainly refers to the internal water dissipation processes that occur in urban buildings and to artificial water sprinkling on hardened roads. With the acceleration of urbanization, the proportion of building water dissipation is gradually increasing. The higher the degree of economic development is, the greater the building water dissipation is. In this paper, the following formula was used to calculate the building water dissipation:

$$B_D = A \times D_f \times 365 / 10000 \quad (2)$$

where B_D is the water dissipation that occurs in buildings in one year in m^3 ; D_f is the average daily water dissipation per unit building area in cm/d , considering the economic aggregate, and the reference index is the per-capita GDP of each continent. The meanings of the other symbols are the same as those previously described.

It is supposed that D_f is related to the per-capita GDP level. The higher the per-capita GDP is, the greater the D_f value is. Since the economic development level varies greatly among the continents in the world, this paper used a sigmoid function to address each continent's per-capita GDP value to moderate the influences of the maximum and minimum per-capita GDP values on the D_f calculation. The function is as follows:

$$S(x) = \frac{1}{1 + e^{-x}}$$

where x represents the per-capita GDP of each continent, in units of 10^4 dollars.

Model Calibration

In this paper, Beijing, Xiamen, and Lanzhou were selected as sample cities to deduce and calibrate the rationality of the calculation parameters. The three sample cities selected in the process of calculating the urban building water dissipation are representative of northern, southern, and western China. There are apparent differences in the degree of economic development among these regions. By looking up the Statistical Bulletin of National Economic and Social Development published for Beijing in 2015³⁸, the urban building floor area was 595.04 km^2 in this year. According to formula (1), Beijing's urban building floor area was calculated to be 661 km^2 . The relative error (RE) was 90.0%. By consulting the Lanzhou Statistical Yearbook published in 2016³⁹, the urban building floor area was 103.65 km^2 at this time.

According to formula (1), Lanzhou's urban building floor area was calculated to be 104 km², and the RE was 99.5%. The proportions of the nighttime light values in Beijing and Lanzhou are shown in Fig. 8. Therefore, the comprehensive light coefficient α value of 0.015 was reasonable. The reason why the building floor area calculated by the light data was larger is that the statistical data may overlook the building floor areas in urban-rural fringe regions, while the calculation conducted using lighting data avoided this problem.

The water dissipation is equal to the water consumption minus the water drainage. By consulting the Beijing Water Resources Bulletin⁴⁰ and the Water Statistics Yearbook published in 2015⁴¹, Beijing's urban building water consumption was 1.37 billion m³, the water drainage was 1.07 billion m³, and the building water dissipation was 296 million m³. According to the Water Resources Bulletin of Gansu Province⁴² published in 2015, Lanzhou's building water dissipation was 31.5 million m³ at this time. Consequently, in accordance with formula (2), the D_f value of Beijing were 0.12 cm/d and that of Lanzhou was 0.08 cm/d.

Table 1 shows that the per-capita GDP of Beijing was 17064 dollars³⁸ in 2015, as Beijing is one of China's developed cities and can be compared with the developed regions in the world. Xiamen's per-capita GDP was 14514 dollars⁴³; Xiamen is a fast-growing city in China and can be compared with developing regions elsewhere in the world. The per-capita GDP of Lanzhou City was 9060 dollars³⁹, and Lanzhou is a less developed city compared to the other two studied cities; Lanzhou can be compared with less developed regions globally. The per-capita GDP conversion results obtained according to the sigmoid function are shown in Table 2.

Table 1
Information of sample cities

City	Location	Climate type	Average temperature	per capita GDP(dollars)
Beijing	115°15'-117°39'E 39°21'-41°9'N	Temperate continental mon-soon	12.5°C	17064
Xiamen	117°53'-118°26'E 24°23'-24°54'N	Southeast Asian tropical mon-soon	21.1°C	14514
Lanzhou	102°36'-104°35'E 35°34'-37°00'N	Temperate continental mon-soon	10.3°C	9060

Table 2. Conversion results of study areas according to Sigmoid function

Study area	x(per capita GDP 10^4 dolloars)	S(x)	D _f (cm/d)
Beijing	1.7064	0.846	0.120
Lanzhou	0.906	0.712	0.080

The three sample cities selected in the process of calculating urban building water dissipation are representative of northern, southern, and western China. There are apparent differences in the degree of economic development among these regions, so the BWD intensity also differs. The intensity values were obtained by dividing the building water dissipation by the area of nighttime light. In 2015, the BWD intensity in Beijing was 188 mm and that in Lanzhou was 148 mm.

Results And Discussion

Table 3 shows that the global building floor areas in 2015 followed the trend of Asia > North America > Europe > South America > Africa > Oceania. Asia has the largest territory and population in the world. The total GDP of Asia ranked first in the world in 2015, and its building floor area was also largest. As most of North America's area consists of large nations, and the economic rankings of the United States and Canada are at the forefront of the world, a similar condition to North America, there are several developed countries in Europe, whose total GDP and per-capita GDP were close to those of North America in 2015. People's living standards are relatively high in North America and Europe. Oceania's building floor area was smaller than that of developing Africa, mainly because of its small territorial area and small population.

Table 3. Global building floor area

Continent	North America	South America	Europe	Asia	Oceania	Africa
Floor area (10^4km^2)	6.94	3.44	5.55	10.1	0.209	1.82

The building water dissipation in a region is related to the economic situation and human water consumption habits of that region. The per-capita GDP was regarded as the reference parameter and was used to calculate the D_f value. To ensure the rationality of the calculation results, this paper selected the per-capita GDP of countries with vigorous light intensities on each continent, as shown in Fig. 9. In the figure, the mean value is taken to represent the urban per-capita GDP of each continent, and the per-capita GDP data were obtained from World Bank⁴⁴, as shown in Table 4. According to the statistical data of the per-capita GDP of each continent in 2015 released by the World Bank and calculation results, Oceania >

North America > Europe > Asia > South America > Africa. To calculate the D_f values of the six continents reasonably, this paper used the $S(x)$ values of the six continents to subtract the $S(x)$ values of Beijing and Lanzhou; the smaller the absolute value of the difference was, the more similar the degree of economic development was. Then, based on the D_f values of Beijing and Lanzhou, the D_f values of each continent were calculated according to the proportional relationship. The results are shown in Table 5.

Table 4
Per capita GDP (Constant dollar in 2010) of continents in 2015

Continents	Countries	Per capita GDP	Mean value
Oceania	Australia	55079.892	55079.892
North America	Canada	50262.03	51215.1
	America	52168.13	
South America	Brazil	11431.15	10999.66
	Argentina	10586.16	
Europe	France	41793.55	40745.04
	Germany	45208.06	
	the United Kingdom	42017.14	
	Italy	33961.4	
Africa	South Africa	7556.789	6269.001
	Gabon	9521.289	
	Morocco	3222.054	
	Algeria	4775.873	
Asia	Japan	47102.58	21427.2
	Korea	26063.71	
	Saudi Arabia	21399.11	
	China	6500.418	
	Iran	6070.187	

Table 5
D_f values of six continents

Study area	x(per capita GDP 10 ⁴ dolloars)	S(x)	D _f (cm/d)
North America	5.1215	0.994	0.141
South America	1.0999	0.750	0.0843
Europe	4.0745	0.983	0.139
Oceania	5.5079	0.996	0.141
Asia	2.1427	0.895	0.127
Africa	0.6269	0.652	0.0732

After the calculations, Fig. 10 shows the resulting total water dissipation of buildings on all continents in 2015: Asia > North America > Europe > South America > Africa > Oceania. In 2015, the global building water dissipation was 127 billion m³. Asia has the largest share (36.8%) of the building water dissipation due to its largest population and fast-growing economy. The building water dissipation of North America accounted for 28.0% of the global total, and approximately 88% of North American areas belong to developed countries, such as the United States and Canada. In particular, the U.S. economy ranks first in the world, with a very high human development index (HDI) and economic development level. Canada is the second-largest country globally, with a vast territory and a high level of economic development. Europe is similar to North America in an economic sense, and the building floor area of Europe is next to that of North America, so the building water dissipation of Europe ranked third, accounting for 22.2% of the total BWD in the world. Oceania has the lowest building floor area proportion and the smallest population, so its building water dissipation was the lowest.

The BWD intensity is also relevant to economic development. Figure 11 shows the BWD intensities in 2015 in cities of the six continents globally: the BWD intensity in North America was 285 mm, that in South America was 177 mm, that in Europe was 263 mm, that in Oceania was 217 mm, that in Asia was 253 mm, and that in Africa was 140 mm. Due to the intense lighting at night and the large building floor areas of North American cities, the water dissipation per unit urban area was high on this continent.

The above values represent the average building water dissipation in cities on each continent. For buildings in cities, the population number is relatively steady^{45–47}, so the indoor water dissipation fluctuates minimally and is almost unchanged¹⁰.

Conclusion

The study identified the building areas and distributions in urban areas using NPP-VIIRS nighttime light data collected in 2015. In the calculation process, Xiamen was selected as a sample city with which to calculate the comprehensive nighttime lighting coefficient α . Beijing and Lanzhou were selected as

sample cities to verify the rationality of the D_f values for urban buildings with different degrees of economic development, and several main conclusions were obtained, as follows.

According to the nighttime light data of Xiamen city obtained in 2015, this paper deduced that the light comprehensive coefficient value α was 0.015, and the global urban building area was 0.281 million km². The building floor areas of cities on each continent were mainly proportional to the cumulative light brightness value in the corresponding region. Therefore, the higher the per-capita GDP was and the greater the population was, the higher the light brightness value and the larger the building floor area of the region was.

This paper identified the social duality attributes of UWD and proposed the concept of building water dissipation (BWD) and the water dissipation mechanism in buildings. The artificial water supply is the main source of water dissipation for human activities and the primary leading source for social water dissipation in urban areas. Building water dissipation and the use of artificial sprinklers on roads were regarded as the social side of the UWD. This study estimated the water dissipation of urban buildings globally. The results showed that the total water dissipation amount was 127 billion m³ in 2015, and the building water dissipation in Asia accounted for 36.8% of this total and ranked 1st in the world. It could be concluded that human-related water activities play an increasingly significant role during the social-natural dualistic water cycle process⁴⁸. North America and Europe have highly developed economies, and their building water dissipation accounts for 28.0% and 22.2% of the global total, respectively. The higher the degree of economic development is, the greater the water dissipation inside buildings is. The results provide a quantified assessment of urban water dissipation caused by human activities in urban areas of the world; these results are meaningful for analyzing the nexus between water and energy use in urban areas. These results also link the heat island effect with water use in urban areas based on the hydrothermal equilibrium theory.

Declarations

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Author contributions

All authors contributed to the study conception and methodology. Material preparation, data collection and analysis were performed by H.G. and J.L. The manuscript was mainly written by H.G. and all authors commented on previous versions of the manuscript text. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to J.L.

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Figures

Figure 1

Building water dissipation comparing to concrete “tree”

Figure 2

Correction of night light (a) and urban building area of China in 2015(b). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Correction of global night light in 2015. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Night light data in Xiamen urban areas in 2015. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Urban building distribution and night light data coverage results in Xiamen in 2015. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

Proportions of nighttime light values in Xiamen

Figure 7

Global night light data representing urban building distribution. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 8

Proportions of nighttime light values in Beijing (a) and Lanzhou (b)

Figure 9

The countries selected to calculate Df for each continent. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 10

Global floor area and building water dissipation in 2015

Figure 11

The intensity of global building water dissipation