Study of impacts of floods on the water quality in an arid zone: the case of the Tarim River in Northwest China

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ABSTRACT

This paper presents the results of the study undertaken at the Tarim River Basin in Northwest China to analyze impacts of flooding on water quality. It was shown that irregular rainfall was the cause of flash floods that affected many ecosystems and eroded soils. Simulation results and the existence of relationships between flood volume and flood peak allowed potential model application that included flood peak estimation. The analysis of water pollution through sample sediment was helped by spectroscopy techniques and it was found that the flood was the main cause of many chemical elements in water. The floods affected the quality of water in the Tarim River where it was slightly basic with $pH = 8.1$ before flooding and acidic with $pH = 6.9$ after flooding.

Key words | arid zone, flood, Tarim River, water pollution, water quality

INTRODUCTION

Floods are among the most frequent and costly natural disasters. There are several conditions that cause floods and some of them include heavy rain for several hours or days that saturate the ground. Although loss of life to some of them include heavy rain for several hours or days disaster and affects coastal development (Thompson 1999). Flooding is the nation’s most common natural disaster and affects coastal development (Thompson 1994). Flooding can happen in every part of the world. However, it has been shown through several studies that all floods are not the same since some can develop slowly during an extended period of rain, or in a warming trend following a heavy snow, while others, such as flash floods can occur quickly, even without any visible signs of rain (Pilgrim et al. 1988). It is important to be prepared for flooding no matter where you live, but particularly if you are in a low-lying area, near water or downstream from a dam. Even a very small stream or dry creek bed can overflow and create flooding (Ramaswamy 1975; Jordan 1997). Floods can also occur in rivers, when the flow exceeds the capacity of the river channel, particularly at bends or meanders. Floods often cause damage to homes and businesses if they are situated in the natural flood plains of rivers. When humans continue to inhabit areas threatened by floods, damage is inevitable and also the perceived value of living near the water exceeds the cost of repeated periodic flooding. Deforestation or other anthropogenic activities will reduce a forest’s water absorption capacity (O’Connor et al. 2004), thus increasing runoff. Large dams affect the river channel both upstream and downstream: the reservoir acts as a sediment trap, and the sediment-free stream below the dam scours the channel (FAO 1988; Powell & Gabe 2009). Flooding may result from the volume of water within a body of water, such as a river or lake, which overflows or breaks levees, with the result that some of the water escapes its usual boundaries (O’Connor et al. 2004). The hydrology of arid and semi-arid regions is considerably different from that of humid regions, but historical data from arid regions is very limited. It has been widely stated that the major limitation of the development of arid zone hydrology is the lack of high quality expressions (McMahon 1979; Pilgrim et al. 1988). In the past, some studies have tried to investigate the influence of flooding on the environment, which has led to improved understanding of the characteristics and importance of spatial rainfall in some parts of the world and the controls on groundwater recharge of alluvial aquifers from ephemeral surface flows (Parissopoulos & Wheater 1990, 1991, 1992a, b; Walters 1990; Wheater et al. 1991; Sorman & Abdulrazzak 1993). Other studies have
described the hydrological processes in arid areas and have shown that depending on the hydrogeological characteristics of the area, the transmission loss can provide a major source of recharge to the underlying aquifer. Also, flood hydrographs commonly have an extremely short rise time (15–30 min) (FAO 1981); and the construction of flood detention structures can slow the transmission of the flood and lead to the focusing of recharge on particular locations (Michaud & Sorooshian 1994). This being the first study in the region, we tried to assess the long-term impacts of flooding on water quality in the Tarim River Basin with specific methods for strong analysis. We investigated the impact of flooding on water quality in this region, in which we proceeded by measurement of possible chemical compositions that were contained in river water before and after flooding. A mechanism for sustainable environmental protection in the arid zone was suggested.

MATERIALS AND METHODOLOGY

Description of study area location

The Tarim Basin (Figure 1) is about 1 million km² in area bounded to the north, south and west by major mountain ranges with peaks greater than 6,000 m and mountain ranges which are perennially covered by snow. The floor of the Basin is about 480,000 km². About 60% of this is the Taklamakan desert which is the second largest desert in the world and is of low relief with windblown sand ridges (Crerar et al. 1988). The Tarim River which is over 1,300 km long is fed by five major river systems (Aksu, Yarkant, Hotan, Kaidu-Konqi and Weigan rivers). Geographical properties are characterized by a longitude at river outlet of 88.31° E, latitude at river outlet: 39.48° N; area of river basin: 1.02 × 10⁶ km², length of river: 2,437 km (Tarim mainstream: 1,321 km) and the altitude range: 780–8,600 m. The summers in the Tarim Basin are warmer and the winters are very cold with some particular seasonality to the scarcity of rainfall around 50 mm, which is due to the high mountains and its distance from great sources of moisture (Crerar et al. 1988). For its part, the natural vegetation is most developed beside the river that flows into this basin. Two types of flooding were identified:

(i) Coastal flooding in which the storm surges cause an abnormal rise in groundwater level associated with hurricanes and other storms at the lake. Surges result from strong on-shore winds and/or intense low pressure cells and ocean storms (Powell & Gabe 2009). Water level is controlled by wind, atmospheric pressure, existing...
astronomical tide, waves and swell, local coastal topography and bathymetry, and the storm’s proximity to the coast (Walters 1990; Sorman & Abdulrazzak 1993).

(ii) River flooding in which land-borne floods occur when the capacity of stream channels to conduct water is exceeded and water overflows banks. Settlement of floodplain areas is a major cause of flood damage (Parissopoulos & Wheater 1990). Note that all these floods appear to be flash floods. The demography of the Tarim River Basin is estimated to be about 8.26 million people. The land is used in the following ways: the natural vegetation and artificial system which is composed of trees, shrubs and grasses; natural lands and wetlands, cropland estimated to be 13,630 km², and these are the major wheat and cotton production areas in the plain. There are several land use maps and remote sensing data that are available for the Tarim River Basin (Görgens & Boroto 2003; Hughes 2004). The studies also indicate that the average annual surface water is estimated at 39.83 km³, its average annual groundwater is 3.07 km³ and the water is produced mainly in the mountain area where rare runoff is produced in the plain area (Hughes 2004). The climate in the Basin is classified as ‘Middle Latitude Desert’ (Hulsewé & Loewe 1979). During January, the average monthly temperature is about −7 °C and in July it rises to about 26 °C in the Aksu oasis. Extremes in temperature are great and may range from −27 °C in winter to 39 °C in summer. Average annual rainfall is 48 mm and average annual pan evaporation is 1,900 mm.

**Geographical and geological process of flood in the Tarim River Basin**

In this region it was identified that water flows to the lowest point very rapidly because of the gravity. A rainfall of 2–3 mm doesn’t sound like much until it spreads out over the field. The 2–3 mm of rain produce a tremendous amount of water that has to go somewhere and hence the geographical process identified underground seepage depending on the saturation of the soil. Geologically, the water of the Tarim River eventually spills over the river’s banks and floods into the low lying land. The water has nowhere to go and can remain there for several days until it is absorbed into the ground or evaporates. Like other parts of the world, the highly localized nature of convective floods producing rainfall in many arid areas has long been recognized as a key factor for determining catchment-scale response (Osborn et al. 1979; FAO 1981). In this part of China, flood hydrographs commonly have an extremely short rise time (12–25 min), and the flood waters move downstream as a discrete wave front, the so-called ‘wall of water’, or as a series of waves, over a dry alluvial channel.

In February 2006, thousands of people were affected by floods caused by the snow that melted in the Xinjiang Uyugur Autonomous Region. More than 11,000 people were trapped and 6,427 houses damaged the week of February 11–18, 2006. This region had heavy snowfall for two days from February 11, but sudden changes in temperatures caused the frozen snow to thaw very quickly. Temperatures went up to above freezing point, almost 12 °C higher than the average monthly temperature for this time of year. Direct economic losses from the floods reached 6.46 million yuan (US$800,000). The influence of flash floods on the main channel of the Tarim River, can be associated with greatest flood of the main channel that comes from the GLOF of the upper reaches of the Kunmalik River, especially augmented by great ablation flood.

**Flood control measures**

**Rainfall–runoff modeling**

The study from the regions (Pilgrim et al. 1988) showed that there exists a different mix of hydrological processes in the arid regions and in the headwater region a direct relationship exists between rainfall on the basin surface and runoff, whereas transmission losses play an important role in the channel phase. A software program (HYSIM = Hydrological Simulation Model developed by Oxford Scientific Software working with Water Resource Associates) of simulation models has been developed for rainfall–runoff modeling in the arid headwater region (Sharma & Murthy 1996). This study, used long-term rainfall and PET data to produce long-term flow records, flood studies, effects of improved drainage and groundwater recharge. Moreover, graphical relationships among the software system discharge-effective rainfall-basin area and time to peak-effective rainfall-basin area were developed for the prediction of the rising limb of the ephemeral flow hydrographs in the headwater area (Holder 1985; Sharma & Murthy 1996), where the following formula is commonly used for this simulation model:

\[
\frac{dQ}{dx} = na^{2/n}WQ^{2(1–1/n)} – (n2^{2/n}/Wa)Q^{1(1−1/n)}
\]
In this case, $Q \, (m^3 \, s^{-1})$ is discharge; $x \, (s)$ is time; $\alpha$ and $n$ are numerical constants in the discharge-stage relation. The calculation of $Q$ is as follows: $Q = a h^n$, $c \, (n^3 \, s^{-1} \, m^{-2})$; this means the infiltration rate per unit area, $W \, (m)$ is width of flow gauging section and $a'$ is a shape factor. The calculations take into consideration an error of 10% between hourly discharges.

### The Integrated Modeling strategy

The method of the Integrated Modeling strategy is illustrated in Figure 2 based at present on a simple multivariate model of rain gauge rainfall, it has been developed and used in many studies (Anderson 1968; Dawdy 1979; McCuen 1982; Wheater et al. 1991). It was also used to provide random input successions of daily rainfall to the rainfall–runoff model. The rainfall–runoff model conceptualizes the catchment as a network of planes and channels, with discrimination between Jebel and Alluvial planes.

It includes a number of options to represent runoff from the plane elements, including the US Soil Conservation Service (SCS) method. The following formula was used for this model:

$$\frac{dV_v}{dx} = -KV_X$$

(2)

where $x$, distance downstream; $V_X$, flow volume at location $X$; and $K$, constant of proportionality, which can be expressed as $V_X = V_A(l - \alpha) x$ where $V_A$ is the flow volume at $A(x = 0)$ and $\alpha$ represents the proportion of flow lost per unit distance.

### Hydrologic-flow-routing

The hydrologic-flow-routing equations for the movement of floods are used in many studies for testing the impact of flooding in groundwater; the objectives are estimation of volume of runoff from a watershed facing development pressures and the prediction of changes in runoff volume resulting from several hypothetical land-use scenarios. Two formulas are used in this study to determine the impact of flow in the Tarim River Basin:

1. Calculating Runoff: SCS Curve Number Method

$$Q = \left( \frac{P - 0.2[(1000/CN) - 10]}{P - 0.2[(1000/CN) - 10]} \right)^2$$

(3)

where $Q$, runoff; $P$, precipitation; CN, SCS curve number. (Based on soil and land cover).

2. The modified hydrologic-flow-routing equation used by Sharma & Murthy (1996) is:

$$\left( \frac{2S(j + 1)Dt}{Dt} \right) + (Q(j + 1)Dt)$$

$$= \left[ \left( \frac{2S(j + 1)Dt}{Dt} - QjDt \right) + l(j + 1)Dt \right] + l(j + 1)Dt$$

(4)

In this case $1(t)$ is input, $Q(t)$ is output, $Q_L(t)$ is transmission loss, and $S$ is storage.

The time horizon is broken into intervals of duration $Dt(s)$, indexed by $j$; i.e. $t = 0, Dt, 2At, ..., jDt, (j + 1)Dt, ...$ and the value of $Dt$ is taken as the time interval of the inflow hydrograph, $1(t)$.

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**Figure 2** | Illustration of the integrated modeling procedure.
Water pollution analysis

To assess the reality of water quality in the Tarim River, under permission of the Ministry of Water Resources, People's Republic of China, two water samples at each location were collected in May and December 2009 from the Tarim River; sampling was done two times (8 water samples before floods and 8 after floods = 16 water samples in total) and taken in a 1 L polyethylene bottle rinsed three times with distilled water before analysis. The field measurements were also taken at the location, including water temperature, pH, conductivity, air temperature, and $E_{h}$ electrode. Conductivity and temperature were determined using YSI85D (with resolution of 0.1 $\mu$S/cm (0–499.9 $\mu$S/cm); 1 $\mu$S/cm (0–4,999 $\mu$S/cm), which also measure conductivity, salinity, DO, temperature) equipment (Das et al. 2007), and the pH level was measured by using a pH meter. After collection, water samples were acidified by using concentrated HNO$_3$ and stored at 4 °C in a refrigerator until analysis. Analysis of water samples was done through atomic mass spectroscopy (Mupenzi et al. 2009) following all procedures of typical MS (4000 Q TRAP LC/ MS/MS Instrument Applied Biosystems, Illinois USA, 2006).

RESULTS AND DISCUSSIONS

Distributed modeling of rainfall–runoff process in the Tarim River

The calibration for each sub-basin (upon and under) for a set of effects (the significant increase and decrease of flood peak and flood volume) was done using a single value of curve number, CN, for each sub-basin as indicated in Table 1. The dependence of $a$ and $CN$ was observed. The model was applied with constant $a$, and the SCS option for runoff generation. The model was modified to incorporate the observed relationship between transmission loss and upstream discharge. The subject to the constraint was $a > 1$; and thus no spatial variability in $a$ was considered at this stage. Definition of antecedent precipitation index was: 0, 1, 2, 3 and 4 as indicated in Table 2. The event taken into consideration was irregular rainfall for the period of 7 years between 2001–2008, which was the cause of flash floods in the region, which affected many ecosystems by eroding the surrounding soil and uprooting the vegetation especially, and trees that hold the soil in place and many damaged materials were identified in this region.

<table>
<thead>
<tr>
<th>Event</th>
<th>Grassland sub-basins</th>
<th>0</th>
<th>1</th>
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<th>3</th>
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<td>75</td>
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</tbody>
</table>

Table 1 | Analysis of calibration and validation performance, the original and improved models in the Tarim River

Table 2 | CN as a function of land use and antecedent conditions for grassland sub-basins and shrubland sub-basins

This study sets up a five-class antecedent precipitation index based on the number of dry days prior to an event, with an enhancement for prior heavy rainfall (Singh et al. 1993). Two land types for calibration of the events were used which are: grassland sub-basins as illustrated in Table 2 and shrubland, the model produces daily hydrograph volumes that show a highly consistent relationship for individual basins between hydrograph peak and volume.

Analysis of water pollution in the Tarim River

According to water chemical investigations of the Tarim River, the quality of the water signed values characteristic to flood seasons. The results of analysis of chemical compositions in the Tarim River using spectroscopy are summarized in Table 3. Through sediment analyses made after the contamination has passed away, arsenic, carbon, sodium, magnesium, potassium, silicate, copper and barium content of the water salinization by floating material of high heavy metal content deposited from the contamination wave, their average concentrations were 42; 31; 13...
8.3; 4; 3; 1 and 0.94 in mg/L before flooding and 42.6; 31.5; 14; 9; 5; 3.5; 1 and 1 in mg/L after flooding respectively. This confirms the results of the study taken in Qiala station of the Tarim River about water pollution, which revealed the following elements in this part of the Tarim River Basin: 8.09 of dissolved oxygen, 0.25 of NH₄-N (ammonium = a nitrogen compound which is usually colorless and readily soluble in water) and 1.61 of fluoride (Wang & Cheng 1999). The conclusion is that heavy metal pollutions have arrived with floods in two ways, namely, increase of water speed decreased the grade of sedimentation and the contaminated water got into the forebank, and together with this into one part of the forebank dead-beds too. It seems that after the withdrawal of the flood the sediment was conspicuous in these places. Note that the sources of water pollution are categorized as being a point source or a non-source point of pollution. In the Tarim River, two types of pollution are identified, toxic and inorganic substances. The conclusion is that the water in the Tarim River was slightly basic with pH = 8.1 before flooding and acidic with pH = 6.9 after flooding, implying that the drinking water gets contaminated with occurrence of heavy metals.

**CONCLUSIONS AND RECOMMENDATIONS**

The calibrated daily flow model was supported and these defined the relationships that were observed between flow volumes and hydrograph peaks, implying that the simulated flood volumes can help to estimate flood peak response of two types of flooding existing in the Tarim River Basin: toxic substance caused by excessive run-off brought about by heavy rains, and organic subsistence caused by storm surges. The floods affected the quality of water in the Tarim River. In this study, we suggest establishment of a method for sustainable environment, such as the safeguarding of vegetation cover on the mountains around the Tarim River Basin in order to avoid the high speed of water flow which is a source of flooding.

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