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Abrupt state change of river water quality (turbidity): Effect of extreme rainfalls and typhoons

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HIGHLIGHTS

- Evaluation of impact of typhoons on river quality.
- First attempt using statistical methods for abrupt state changes of turbidity.
- Daily turbidity correlated with daily flow rate for all the eleven events studied.
- Typhoon Morakot and subsequent rainfall events leads to high river turbidity.

GRAPHICAL ABSTRACT

High turbidity water: (left) in a reservoir; (right) raw water in a water treatment plant.

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ABSTRACT

River turbidity is of dynamic nature, and its stable state is significantly changed during the period of heavy rainfall events. The frequent occurrence of typhoons in Taiwan has caused serious problems in drinking water treatment due to extremely high turbidity. The aim of the present study is to evaluate impact of typhoons on river turbidity. The statistical methods used included analyses of paired annual mean and standard deviation, frequency distribution, and moving standard deviation, skewness, and autocorrelation; all clearly indicating significant state changes of river turbidity. Typhoon Morakot of 2009 (recorded high rainfall over 2000 mm in three days, responsible for significant disaster in southern Taiwan) is assumed as a major initiated event leading to critical state change. In addition, increasing rate of turbidity in rainfall events is highly and positively correlated with rainfall intensity both for pre- and post-Morakot periods. Daily turbidity is also well correlated with daily flow rate for all the eleven events evaluated. That implies potential prediction of river turbidity by river flow rate during rainfall and typhoon events. Based on analysis of stable state changes, more effective regulations for better basin management including soil-water conservation in watershed are necessary. Furthermore, municipal and industrial water treatment plants need to prepare and ensure the adequate operation of water treatment with high raw water turbidity (e.g., >2000 NTU). Finally, methodology used in the present of this study can be applied to other environmental problems with abrupt state changes.

1. Introduction

Challenges of river basin management are shifting, from pollution sources and control (e.g., total maximum daily loads and assimilative capacity analysis (Lee and Chang, 2005), non-point sources

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management (Zushi et al., 2008)) to dealing with extreme rainfalls and their effects, such as runoff (Frans et al., 2013) and flood (Hirabayashi et al., 2013; Vaghefi et al., 2014). In particular, global warming may lead to extreme events of rainfall with changing local rainfall duration and intensity (IPCC, 2007; Wang et al., 2013). In Taiwan, the rainfall trend of shorter duration and higher intensity is clearly evident by the analysis of daily rainfall record from 1950s to 2000s (Jhong et al., 2009). Moreover, the probability of extreme rainfall events and crisis of water scarcity is increasing in southern Taiwan with uneven distribution of rainfall (Jhong et al., 2009). Since 2009, problems of high turbidity (>2000 NTU) have caused significant concern to the public and regulatory agencies in the Gaoping river. In Taiwan, rainfalls almost concentrate in two seasons, plum season from April to May and typhoon season from June to September. The high rainfall intensity with shorter duration (e.g., 15 mm during 1-h period) in rainy seasons certainly exceeds river capacity causing flood while significant amounts of water are flowing into ocean.

Therefore, in the past decades, the main problem facing river quality management associated with heavy rainfalls mostly causing by typhoons is its high turbidity in river, due to landslide and erosion. In fact, erosion rate in the Gaoping river basin has been reported as 10–30 mm/yr (Dadson et al., 2003). Extremely high turbidity (more than 6000 NTU) may lead to water treatment plant shutdown. Particularly, in summer of 2009, typhoon Morakot (extremely high rainfall over 2000 mm in three days (Aug 8–10)) caused serious disaster with complete shutdown of many water treatment plants. In general, turbidity is caused by colloids; however such high turbidity during high rainfall events in Taiwan is due to silt, clay and suspended solids by interaction of rainfall, upstream erosion and in-stream re-rolling sediment. In short, it is worthwhile investigating the impact of Morakot and subsequent typhoons on river water quality (turbidity) in southern Taiwan.

In particular, one needs to see how turbidity changes at the onset of, during and after the typhoon event. Identification of changes in turbidity pattern is of importance since it can reveal how previous stable states have been changed during an extreme rainfall event, and assist water treatment plants to plan strategies against sudden shutdown. This is analogous to perturbation caused by external elements and once external element is removed, it is slowly returned to the original state in ecosystem (Hirota et al., 2011; Veraart et al., 2012), lake eutrophication (Hargeby et al., 2007; van Nes et al., 2007) and pollutant in rive (Tsuzuki, 2015). For example, Hargeby et al. (2007) reported two lakes in southern Sweden shifting repeatedly between clear water state and turbid water state in 1970–2004. They reported accumulation of nutrients leading to change of stable states.

In view of frequent occurrence of typhoons in Taiwan and their impact on river water quality, this study was undertaken to address the following questions: (1) What is the effect of Morakot and subsequent typhoons on river turbidity? (2) Is the rate of increasing turbidity correlated with rainfall intensity? (3) How long will it take to reach the original pre-typhoon state? And (4) what is the impact of subsequent typhoons after Morakot on river turbidity. The results will be useful for more effective regulations for soil-water conservation in watershed and adequate operation of water treatment plants with high source water turbidity. To the best of knowledge, this is the first attempt to illustrate the cumulative effect of typhoons on river water quality (turbidity).

2. Materials and methods

2.1. Gaoping river weir and watershed information

The length of the Gaoping river is 171 km, the second longest one in Taiwan, covering watershed area of 3257 km^2. The upstream of Gaoping weir was used for obtaining turbidity data. The weir is used for withdrawing river water as source water for domestic and industrial water uses. Location of the Gaoping weir close by meteorological station is shown in Fig. 1.

Three relevant time-series datasets were collected: rainfall, river flow rate, and river turbidity. All were in the period of Jan 1, 2003 to Dec 31, 2013, a span of 11-yr daily data with each over 4000 daily records. Daily rainfall data (Fig. 2a) were collected from Shipu meteorological station of Central Weather Bureau, near the Gaoping river weir. In addition, for heavy rainfall events, hourly rainfall data were collected to determine rainfall intensity (total rainfall in an effective rainfall event divided by the rainfall duration). For example, an effective rainfall starts 20:10 and ends next day 6:00, then the duration in dominator of rainfall intensity is only 8 h. In the present study, effective rainfall refers to rainfall more than 0.5 mm/h. Daily flow rate and turbidity data monitored at the Gaoping river weir (Fig. 2b and 2c) were obtained from Southern Water Resources Bureau. River flow rate is continuously monitored while river turbidity monitored daily at 7–8 am with a laboratory turbidimeter (HACH 2100N used in 2003–2011 and 2100AN in 2012 with maximum detected limits: 4000 and 10,000 NTU, respectively). It is noted that the peak turbidity and peak daily flow rate does not occur at the same time. Basically, the cyclic data variations of higher rainfall/flow rate/turbidity are due to typhoon events and other extremey high ranfall events in rainy searsons. Since typhoon Morakot of 2009 was the major typhoon causing serious damages (Kao et al., 2012; Huang and Montgomery, 2013), therefore in this study, two periods are divided as pre-Morakot (2003–2008) and post-Morakot (2009–2013) periods including Morakot and subsequent typhoons.

2.2. Statistical analysis

For better illustration of typhoon impact on river quality, statistical approaches (e.g., paired annual mean and standard deviation (SD), frequency distribution, moving SD, skewness and autocorrelation) were used in this study. Annual mean and SD of river turbidity are a paired indicator which can easily be analyzed and understood regarding the change of state at a yearly scale. Frequency distribution is an effective approach that can find out the extreme data from its long-tail pattern for long-term data. Moving SD/skewness/autocorrelation are useful techniques that can identify the accumulated effects of rainfall events.

2.2.1. Skewness and autocorrelation

Skewness is a statistic indicator to measure shape of data distribution. For example, normal distribution exhibits a symmetric bell shape, indicating that skewness is exactly equal to zero. However, when skewness >0, meaning distribution of skewing right, it is defined as positive skewness. The larger positive skewness is, the more shape of skewing right becomes; and skewness <0 vice versa. Change of skewness will reveal the transition of stable states while comparing with its present state (Chatfield, 2004; Dakos et al., 2012). Correlation coefficient is another statistic indicator to identify the relationship of datasets x and y. Similarly, autocorrelation is a statistic coefficient to identify the correlation of dataset x itself with different time interval. The range of autocorrelation is in [−1, +1]. For example, autocorrelation approaching 1.0 means data sparse (i.e., distributed wide range of values indicating high variation) with positive correlation; autocorrelation approaching −1.0 indicating high variation with negative correlation; and autocorrelation approaching zero concentrating in a narrow range (Chatfield, 2004; Ren and Watts, 2015).

For all n observations of data, x_i, $i = 1, 2, \ldots, n$. The SD is the root of variance, given by

$$\mathrm{SD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - x)^2} \tag{1}$$

then, the skewness is defined as the ratio of the third momentum (m_3)