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Operational regulation of a hydropower cascade based on the mitigation of the total dissolved gas supersaturation

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ABSTRACT

Spillway discharge leads to total dissolved gas (TDG) supersaturation in the plunge pool, and these gases cannot dissipate to restore equilibrium after traveling tens or even hundreds of kilometers downstream of the spillway. Supersaturated TDG is detrimental to fish and may cause gas bubble disease. The negative impact is enhanced when cascade reservoirs are in operation. Field observations of the TDG concentrations were performed in the lower reaches of the Dadu River in the summers of 2009 and 2012. The relationships between the TDG concentration and various impact factors were analyzed. Increasing the unit discharge rate and downstream water depth can accelerate the production of TDG supersaturation, a ski-jump was a better pattern for dissipating energy than an underflow, and the power generation system did not contribute to the TDG production. The TDG dissipation showed that the dissipation coefficient increased with an increasing flow rate. An investigation was conducted to explore the cumulative effect of a hydropower cascade. A controlled cascade reduced the TDG production by reducing the occurrence of a discharge at the downstream cascade is beneficial. Based on the field observations, which were focused on operational regulation, mitigation measures for TDG supersaturation for the watershed management of a hydropower cascade were suggested and discussed.

1. Introduction

A flood always brings flow, sediment and nutrients downstream, accompanied by an eco-environmental impact on an ecosystem, especially on fish (Cai et al., 2010). A hydropower cascade is constructed for flood control and to generate electricity (Hu et al., 2014), but negative impacts gradually emerge after a dam has been in operation for several years (Wang, 2015). One such impact is the supersaturation of the total dissolved gas (TDG) levels downstream of a high-dam spillway, and such TDG supersaturation may be evident tens or even hundreds of kilometers downstream of the dam (Feng et al., 2014a). TDG supersaturation may cause bubble disease in fish and increase fish mortality (Weitkamp and Katz, 1980; Liang et al., 2013; Geist et al., 2013). In the summer of 2014, a spillway at the Xiluodu Dam in China caused high TDG supersaturation in the next cascade reservoir, i.e., the Xiangjiaba Reservoir. This event resulted in more than 100,000 kg of dead fish (Yangtze River Fisheries Research Insitute Chinese Academy of Fishery Sciences, 2014) and became a new and urgent concern for both the government and society.

The TDG level downstream of a dam indicates the total amount of gas present in the water, which depends on the pressure, turbulence and water temperature (Shen et al., 2014). Elevated TDG levels result from the dissolution of air bubbles captured during spillway events. When bubbles are carried to great depths and high-pressure regions develop in the plunge pools, the dissolution of the bubbles increases, and the air is transferred from the bubbles into the water. The dissipation of the TDG in the downstream reaches of the dam is mainly dependent on the turbulence, pressure and mass transfer across the free water surface. As the pressure decreases or the turbulence and mass transfer increase, the TDG dissipation accelerates, and the dissolved gas is transformed into micro bubbles. After the micro bubbles coalesce into form bubbles in the deep water, the bubbles rise due to their buoyancy and are released at the free water surface. When cascade power stations are constructed, reservoirs typically occur between power stations. When the reach of a natural river is transformed into a reservoir, the depth of the water increases, and the velocity, turbulence and mass transfer across the free water surface decreases. As a result, the TDG dissipation decelerates, and the negative impacts of elevated TDG levels on fish are enhanced. Furthermore, the TDG concentration is consistently supersaturated in the forebay of the next cascade power station and is transported and dissipated throughout the reservoir. Thus, the negative impact of the TDG accumulates with each power station in the cascade.

A large quantity of fish was found dead due to bubble disease in the lower reaches of the Columbia River in the 1960s (Weitkamp et al.,

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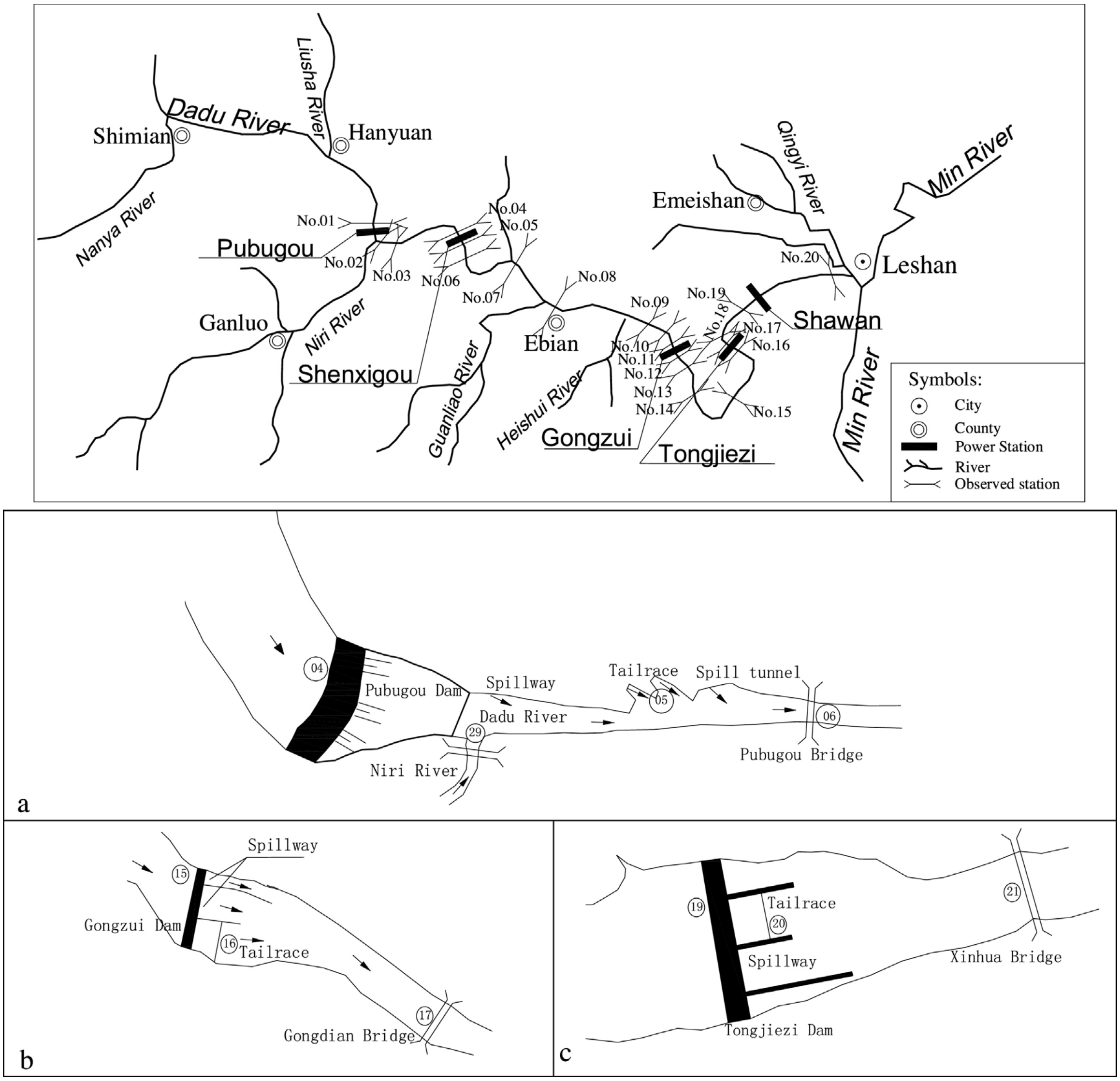

Fig. 1. Sketch of the observation stations on the lower reaches of the Dadu River. (a. Damsite region of Pubugou; b. Damsite region of Gongzui; c. Damsite region of Tongjiezi).

2003) during a period of spillway discharge. To explore the production of TDG supersaturation as a result of the spillway, field observations were performed by the United States Army Corps of Engineers (USACE), mainly within plunge pools downstream of the spillway (US Army Corps of Engineers, 2005). Kamal (Kamal et al., 2016) performed an observation on the dissipation of supersaturated TDG in a cascade reservoir system in Canada to analyze the impact factors. An empirical model was developed to predict the TDG production by a spillway that dissipated energy through a hydraulic jump. Mannheim (Mannheim and Weber, 1998) employed a physical model to explore the process of air dissolution, but this physical model performed poorly with respect to the re-emergence of entrapped air, air dissolution and turbulence in the plunge pools. The volume of air caused by the spillway jets was low, and fewer bubbles were in the water, but they were larger in size than in the prototype. Hibbs (Hibbs and Gulliver, 1997), Geldert (Geldert et al., 1998) and Orlins (Orlins and Gulliver, 2000) attempted to explore the TDG production downstream of a spillway via a numerical approach. The air entrapment and gas transfer at the spillway surface and the transfer within the plunge pools were considered in the model. The model included four fitting coefficients in the bubble and surface transfer terms, which were determined using only field data. Turan (Turan et al., 2007), Uban (Urban et al., 2008) and Politano (Politano et al., 2009; Politano et al., 2012; Politano et al., 2014) developed mathematical models using multi-dimensional multi-phase flow calculations. A bubble-number density-transport equation was implemented to predict the bubble size, which could change due to bubble-liquid mass transfer and the pressure. The bubble size and gas volume fraction at the inlet boundary conditions were selected during the calibration process following a trial-and-error process to match the TDG field data. Based on observations of several large rivers in China, Qu (Qu et al., 2011) determined the variables that affected the TDG production and dissipation and analyzed their specific relationships. Working from a large set of field data, Li (Li et al., 2009) proposed an empirical model to evaluate the TDG production by a spillway that dissipated energy via a ski-jump. Prior published reports have mainly focused on the process of TDG generation in the plunge pools, and few reports exist on the TDG dissipation processes in the rivers downstream of the dams. Pickett (Pickett et al., 2004) first proposed a longitudinal dissipation model that assumed that the TDG followed first-order kinetics. Feng (Li et al., 2015) improved the model by validating the dissipation coefficient using field data. Johnson (Johnson et al., 2010) used a two-dimensional model to evaluate the effect of the TDG on the fish in a section of a river that was tens of kilometers long. The mass transfer process in the model was simulated using a simple empirical formula related to the wind speed alone. Feng (Feng et al., 2013; Feng et al., 2014b) proposed a laterally averaged two-dimensional model to predict TDG transport and