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Shelter construction for fish at the confluence of a river to avoid the effects of total dissolved gas supersaturation

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ABSTRACT

Total dissolved gas (TDG) supersaturation downstream has a negative environmental effect on fishes. It is caused by discharge from high dams and increases the incidence of gas bubble disease and fish mortality. Downstream of a high dam, there is an area with low TDG saturation due to the gradual mass exchange of gases between the separation zone and the mainstream and the long retention time in the confluence, which contributes to the dissipation of saturated TDG at the confluence of the mainstream and its tributaries. This area can provide a temporary shelter for fish to avoid the effects of TDG supersaturation during dam discharge. A depth-averaged, two-dimensional model of TDG dissipation at a river confluence was established. The concentration field was verified by a flume experiment. A numerical simulation of the TDG at the confluence of the Zumuzu River and its tributary, the Mozigou River, was conducted. The simulation showed that the convergence of the tributary, which had a low TDG saturation level, could reduce the TDG saturation level of the mainstream. However, the low-saturation area was not large enough for fish to avoid the negative effects of TDG saturation due to a sharp river slope and a large flow ratio between the mainstream and its tributary. To expand the suitable shelter area with low TDG supersaturation levels in order to provide a suitable shelter for fish, some engineering measures were explored, including the excavation of the riverbed and the construction of resistance obstacles. After the engineering measures were introduced, we observed a 30-fold increase in the size of the area with low TDG saturation, which was as high as 10005 m^2 at 110% of the TDG saturation. Combined with the comprehensive analyses of the flow velocity and the water depth, the confluence region was thought to be suitable to protect the fish from the effects of TDG supersaturation. This study provides an important reference for protecting fish during high dam discharge.

1. Introduction

Total dissolved gas (TDG) supersaturation is known to increase the incidence of gas bubble disease and fish mortality (Weitkamp and Katz, 1980; Weitkamp et al., 2003; Tan, 2006). Persistent TDG supersaturation has been observed in river reaches up to 500 km downstream during discharges from a high dam (Chen et al., 2009). Such discharges are typically periodic and operationally unavoidable, so developing methods for enhancing fish survival during TDG supersaturation events is critical to maintaining a balanced ecosystem. There are two likely approaches for improving fish survival: (i) developing methods to increase the dissipation rate of TDG supersaturation, and (ii) providing or enhancing refuge areas with lower TDG saturation. The latter idea is the focus of the present study. Previous studies have shown fish have some ability to detect and avoid areas of high TDG supersaturation (Chen et al., 2012; Wang et al., 2015), which makes establishment or enhancement of refuges a promising approach.

The mixing behavior at the confluence of two rivers is a well-studied phenomenon (Best and Reid, 1984) that has typically been focused on sediment, scour, turbulent mixing, and pollutant dilution. A key feature of a confluence is a region, sometimes extending far downstream, where the tributary water retains its identity and is not fully mixed across the main stem river. From the perspective of providing a refuge, we are interested in quantifying the area where the tributary water intrudes into the mainstream.

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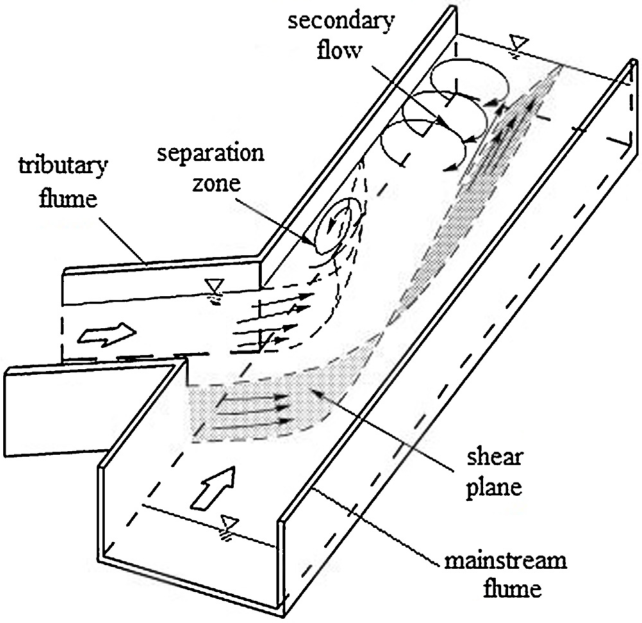

Fig. 1. The sketch of the unique flow characteristics at the confluence flume (Biron and Lane, 2008).

However, prior research on confluences is mainly concentrated on issues of sediment and mixing, whereas there are few studies of TDG. Therefore, research into hydrodynamics, transport and dissipation of TDG at confluences is needed to improve predictions of downstream areas with supersaturated TDG. Furthermore, this research provides a scientific basis for using a low TDG saturation region to improve the river ecosystem and provide mitigation measures for TDG supersaturation.

Confluences are inherently three-dimensional (3D) and contain non-hydrostatic eddy features (Bradbrook et al., 1998; Weber et al., 2001; Constantinescu et al., 2011), as shown in Fig. 1. However, they have been adequately modeled for engineering purposes with the 2D shallow-water equations (Zhao et al., 2005). It can be expected that the complex 3D mixing processes at a confluence will enhance dissipation of TDG supersaturation (i.e. by increasing the rate at which supersaturated water encounters the free surface), but the subject has not been studied in either the laboratory or the field. As a starting point, herein the TDG supersaturation is treated as a transported passive scalar that is dissipated (i.e. transformed into air bubbles or released across the free surface) at a known rate based on prior field observations for the main stem river. The neglect of additional TDG dissipation at the confluence is conservative in that it causes an underprediction in the expected refuge area of lower TDG.

Taylor (1944) was the first to develop an analytical model for a river confluence. This model predicted the tributary channel depth upstream of the junction. Best and Reid (1984) performed an experimental investigation on the characteristics of the separation zone with varying junction angles and flow ratios. They defined the separation zone shape index as the ratio of the width to the horizontal length of the separation zone, with a typical value of 0.19. Using a numerical simulation Wang et al. (2015) found that the shape of the separation zone at the confluence of the Yangtze River and the Jialing River was significantly affected by the topography. Trevethan et al. (2015) recently reported a field study for the confluence of the Negro and Solimoes Rivers including a series of velocity profiles, water quality, and seismic measurements to evaluate hydrodynamic and morphodynamic features of this confluence. Kang (2011) examined mixing at an idealized confluence, and is used herein as a validation case for our model.

There have been few studies of the TDG distribution and the gas-liquid interfacial mass transfer process near a river confluence. Observations of the Columbia River (United States Waterways Experiment Station, 1996, 1997) indicate, the mixing process between TDG supersaturated water from discharge with tail water in which the TDG is not supersaturated happened when the powerhouse is closed to dam. Most of the investigations on the dissipation process of supersaturated TDG focus on the natural rivers downstream of dams. The United States Army Corps of Engineers concluded that the TDG dissipation process can be modeled using first-order kinetic theory with field observations and theoretical analysis (United States Army Corps. of Engineers, 2005). The dissipation rate of TDG is modeled with dissipation coefficient, as a function of velocity, water depth and molecular diffusivity. Perkins and Richmond (2004) and Johnson et al. (2007, 2010) employed a depth-averaged, two-dimensional mathematical model to simulate the distribution of TDG within a few kilometers downstream of the Bonneville Dam and Ice Harbor Dam. Their dissipation coefficients were associated with wind speed. The dissipation coefficient has also been estimated from several experiments and field observations. Feng et al. (2010) developed a formula for a comprehensive dissipation coefficient from field observations of several rivers to replace the molecular diffusion coefficient proposed by Pickett et al. (2004). Although it has been convenient to use reaeration and dissolved oxygen studies as proxies for TDG in determining dissipation coefficients, the laboratory studies of Li et al. (2013) showed that TDG dissipation process is quantitatively different from reaeration, and the DO is not a good poxy for TDG. In field and laboratory studies, Feng et al. (2014) showed that dissipation rate of TDG increase with higher turbulence and a longer retention time.

Laboratory research has demonstrated that some fish have the ability to detect and avoid supersaturated TDG. Although it has not been directly observed in the field, it seems likely that fish could seek shelter in an area with low TDG supersaturation levels at a confluence to avoid the effects of the supersaturated TDG during a limited dam spill period. The present work examines the distribution of supersaturated TDG near a confluence in a numerical simulation. Potential intervention measures for enlarging the shelter area of low TDG were studied the model.

2. Mathematical model

2.1. Numerical model

A depth-averaged, 2D model applying the Reynolds-Averaged, hydrostatic (shallow-water) Navier-Stokes equations was used to simulate a river confluence and the transport of TDG:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (h+\zeta)u}{\partial x}+\frac{\partial (h+\zeta)v}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \zeta}{\partial x}+\nu_t\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{1}{\rho(h+\zeta)}(\tau_{sx}-\tau_{bx}) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \zeta}{\partial y}+\nu_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{1}{\rho(h+\zeta)}(\tau_{sy}-\tau_{by}) \tag{3}$$

$$\frac{\partial hG}{\partial t}+u\frac{\partial hG}{\partial x}+v\frac{\partial hG}{\partial y}=\frac{\partial}{\partial x}\left(\nu_t\frac{\partial hG}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_t\frac{\partial hG}{\partial x}\right)+hS_c \tag{4}$$