Journal of Hydrology 508 (2014) 328–342

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Formation of the density currents in the zone of confluence of two rivers

T. Lyubimova [a,*], A. Lepikhin [b], V. Konovalov [a], Ya. Parshakova [a], A. Tiunov [b]

[a] Computational Fluid Dynamics Laboratory, Institute of Continuous Media Mechanics UB RAS, Perm, Russia
[b] Surface Hydrology Laboratory, Mining Institute UB RAS, Perm, Russia

ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form 4 October 2013
Accepted 26 October 2013
Available online 14 November 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Ellen Wohl, Associate Editor

Keywords:
River confluence
Density currents
Vertical stratification
Mineralization
Numerical simulation
In situ measurements

SUMMARY

The peculiarities of the formation of density currents in the zone of confluence of two rivers with strongly different hydrochemical regimes are studied numerically and experimentally. The three-dimensional numerical simulation shows that the water of the river of higher mineralization and density flows under the water of the river of lower mineralization and density and vice versa. And besides, such overlapping of the water streams is observed both upstream and downstream of the confluence of two rivers. The results of numerical simulation are supported by the data of expedition observations and in situ measurements. A similar phenomenon, namely, a flow of two overlapped oppositely directed water streams was previously discovered in the mouth zone of the rivers flowing in the sea. Our study reveals the existence of a new type of the hydrological systems, in which such a phenomenon occurs.

1. Introduction

Numerical simulation of the substance transfer processes plays a decisive role in projecting and designing of water systems for public water supplies. The peculiar features of natural watercourses (rivers, channels) are their length, small radius of curvature and relative shallowness. These are the advantages that can essentially simplify the mathematical description of the examined processes through the use of two-dimensional models (Graf and Altinakar, 1996), (Petrescu and Sumbasacu, 2010), (Duan and Nanda, 2006). However, such an approach proves itself only in the case when impurities have no effect on the character of the fluid motion in a water basin. In the general case, the parameters of the hydrodynamic system depend on the impurity concentration. This dependence has a profound effect on the hydrodynamic characteristics of natural pools and requires the application of three-dimensional models (Lyubimova et al., 2010). Due to the presence of heavy impurities the process of water mixing at the point of river confluence is retarded. This effect is described in work (Weigold and Baborowski, 2009), which is concerned with studying the influence of the tributary streams of the Elba river on the quality of its water.

In the case when impurities have no effect on the hydrodynamic characteristics of the system, water mixing at the confluence of rivers occurs in a shear layer, which is characterized by high kinetic turbulent energy (Rhoads and Sukhodolov, 2008). As a rule, the boundary between confluent flows is close to the place of their confluence and can be determined based on the differences in the characteristics of these flows, for example, in temperature, conductivity (Gaudet and Roy, 1995; Rhoads and Kenworthy, 1995; Rhoads and Sukhodolov, 2001), also in concentration of impurities (Kenworthy and Rhoads, 1995). In some cases the interface can extend down stream for a considerable distance from the confluence (MacKay, 1970). In the present work, the specific features of the confluent stream mixing are investigated in relation to the flow velocity in the presence of heavy impurities. A three dimensional numerical simulation of the behavior of the hydrodynamic system in the region of meeting of two rivers has been carried out. In the literature, one can find a great number of papers dealing with three-dimensional modeling of the channel and river dynamics (see, for example, Khosronejad et al., 2007; Weiming et al., 2000; Baranya et al., 2010; Rhoads and Sukhodolov, 2001; Biron et al., 2004). In the region of river confluence the intensity of horizontal water mixing can increase in the case when the width of the tributary stream is less than that of the main channel (Biron et al., 2004), it can also be affected by the curvature and morphology of the channel bottom. In our study, a numerical simulation of a flow in the channels of invariable depth is performed in the presence of

* Corresponding author. Tel.: +7 3422396646; fax: +7 3422378487.
E-mail address: lubimova@psu.ru (T. Lyubimova).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.10.041

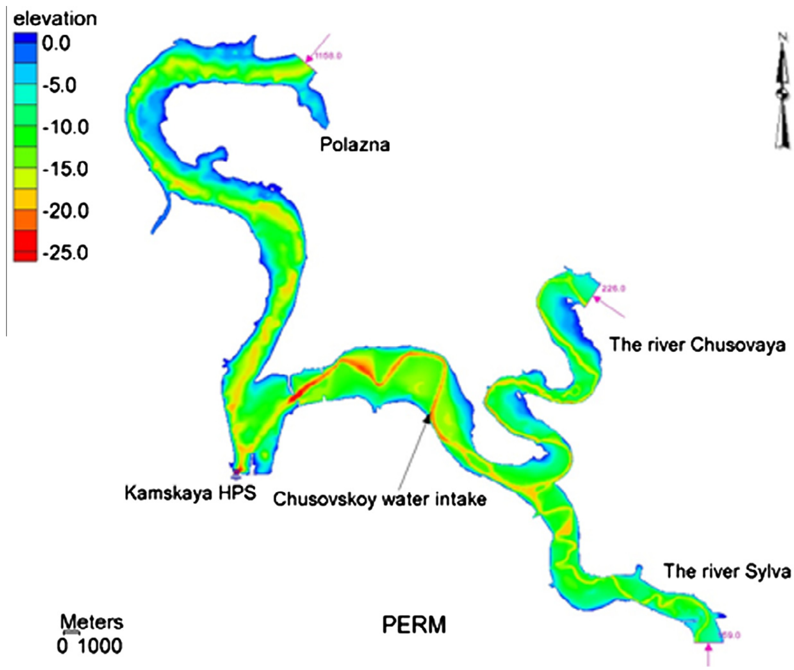

Fig. 1. Bottom morphometry of part of the Kama water reservoir.

heavy impurities whose density depends on the impurity concentration, which leads to the formation of vertical density stratification. The density stratification can also be caused by the temperature difference of waters in the confluent rivers (Cook and Richmond, 2004). In this case, the waters of one river "dive" under the waters of the other river. In the case of the river inflow in the ocean a more dense water may flow into the basin of less dense water, i.e., the sea water runs into the river mouth when the tidal current is in flood (Liu et al., 2007).

In the present paper, the peculiarities of the formation of density currents in the zone of confluence of two rivers with different hydrochemical regimes are studied on the example of confluence of Sylva and Chusovaya rivers (Perm region, Russia). The solution to this problem in the discussed case is complicated due to the fact that the water intake is located in the zone of hydraulic backwater of the Kama hydroelectric power station and the hydrodynamic regime in this zone depends not only on the cumulative effect of hydrological regimes of Chusovaya and Sylva rivers but also on the filling level of the Kama water reservoir and on the reset mode on the Kama hydroelectric power station. Additionally to the scientific importance, this study is of very high priority since in the vicinity of the confluence of Chusovaya and Sylva rivers there is Chusovaya water intake which is the main source of potable water for Perm city having more than one million inhabitants.

2. Peculiarities of hydrological and hydrochemical regimes of the system

The hydrological system under consideration is the lower, near-dam, part of the Kama reservoir located in the Western Ural in the immediate vicinity of the city of Perm (Fig. 1). The size of the area under consideration from the Kama hydroelectric power station to the Polazna village is about 40 km and the distance from the Kama hydroelectric power station to the confluence of the rivers Chusovaya and Sylva is about 23 km. Red arrows with numbers in Fig. 1 show the average water inflows. In situ measurements included the study of the hardness of water in the currents at distances up to 40 km upstream of the rivers from the point of their confluence.

The examined rivers have nearly equal catchment areas: the catchment area of Sylva river is about 19.7 thousand squared kilometers and that of the Chusovaya river – about 23 thousand square kilometers. The flow rates during spring floods and summer droughts of the Chusovaya river are much higher than of the Sylva river whereas the flow rates during winter droughts of the Chusovaya river is lower than that of the Sylva river due to peculiarities of its catchment area (Fig. 2A and B). The characteristic features of rivers with deep winter drought, the Sylva and Chusovaya rivers among them, is that the variability of flow rates during winter droughts is much smaller than the flow rates of the spring flood.

Due to topo-geochemical peculiarities of the catchment areas the examined rivers show essential difference in their chemical compositions, including the difference in the degree of total mineralization and in the ratio of separate ingredients. From Fig. 3 it follows that these differences are most pronounced at low flow rate typical for the limiting case of winter droughts.

At the same time, as is evident from Fig. 4, the relations between mineralization and total hardness of water for both rivers are quantitatively and qualitatively similar and are described by the linear correlation dependences (Table 1).

The correlation dependences for flow rate, hardness and mineralization of waters in the Sylva and Chusovaya rivers given in Table 1 will be used later to relate the values of flow rate to the values of mineralization chosen for numerical experiments (Table 2).

3. Computational experiment

The results of multi-year monitoring of the Sylva and Chusovaya rivers conducted month by month since 1957 till 1997 (Fig. 5), were used to obtain a linear correlation between flow rates of the two rivers.

$$y = 1.5\quad x - 26.0.$$

Here y is the flow rate in the Chusovaya river measured in meters per second and x is the flow rate in the Sylva river. In this case the correlation coefficient is $R = 0.91$.

The dependence allows us to consider a wide range of flow rates in both rivers including values close to a mid-annual flow rates and