Advances in Water Resources 52 (2013) 207–220

Contents lists available at SciVerse ScienceDirect

Advances in Water Resources

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

Study on nutrient distribution and interaction with sediments in a macro-tidal estuary

Dongfang Liang [a,*], Xiaolin Wang [b,1], Bettina N. Bockelmann-Evans [b], Roger A. Falconer [b,2]

[a] Department of Engineering Mechanics, MOE Key Laboratory of Hydrodynamics, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Cardiff School of Engineering, Cardiff University, The Parade, Cardiff CF24 3AA, UK

ARTICLE INFO

Article history:
Received 23 July 2012
Received in revised form 17 November 2012
Accepted 20 November 2012
Available online 29 November 2012

Keywords:
Nutrients
Water quality
Shallow water flows
Sediment transport
Adsorption/desorption
Estuaries

ABSTRACT

An integrated hydro-environmental model has been developed for predicting the distribution of nutrients in estuarine and coastal waters. This paper also reports on an application of the model to the Loughor Estuary in the UK, which has a high tidal range. The horizontal two-dimensional model considers the hydrodynamic, sediment transport, dissolved oxygen and nutrient cycling processes. In particular, the effect of sediment suspension and deposition on the nutrient distribution in the water column has been included in the model. A TVD-MacCormack scheme has been adopted to numerically solve the coupled partial differential equations. Field surveys and laboratory experiments in connection with the Loughor Estuary were conducted to obtain measured data for model calibration and verification. It was found that the linear isotherm model gave a good approximation of the adsorption/desorption processes over the range of nitrogen and phosphorus concentrations measured in the natural estuary. Through experiments on the collected soil samples, the salinity-dependent partition ratios between the adsorbed and dissolved nutrients were determined. The results of the established model showed good agreement with the measured data. Finally, the model was used to examine the implications of changing the sewage effluent discharge scheme on the nutrient distributions in the estuary.

1. Introduction

With increasing attention being paid to the protection of coastal and estuarine environments, fully understanding and accurately predicting the fate of pollutants in such waters have become more of a high priority to water utilities and other stakeholders. Among the different types of water pollution, eutrophication has been identified as one of the greatest contemporary threats to the well-being of coastal ecosystems [30]. It is widely accepted that the increased availability of nutrients is a major factor that drives eutrophication in lakes, estuaries and slow-moving streams. Excessive nutrients stimulate plant's growth, and algal blooms occur if such growth is not restricted. When algae die and accumulate at the bottom of a water body, where bacteria consume them, oxygen in the water column is depleted, which causes an ecosystem imbalance and even detrimental effect to human health. Therefore, the ability to predict the nutrient levels in the water column is important in hydro-environmental impact assessments.

Nutrients can come from many sources, such as fertilizers applied to agricultural land, industrial/municipal effluents from sewage treatment works, organism and plant decomposition within the water body, and nutrient re-suspension from the bed. Inorganic nutrients are the building blocks for aquatic plants. Among the four macronutrients, *i.e.*, phosphorous, nitrogen, carbon and silica, the first two are often the primary limiting and controllable nutrients. The transport processes of nutrients are very complex, involving: advection, dispersion/diffusion, adsorption/desorption, and chemical/biological conversions. Advection and dispersion are governed by the flow conditions. The sediment–nutrient interaction via adsorption/desorption is affected by the flow, grain size and mineralogy, salinity, *etc.* [1]. The chemical reaction and biological transformation rates are influenced by many environmental factors, such as light intensity, pH, temperature, salinity, *etc.*

With the rapid progress in computing technology, numerical simulations play an increasingly important role in addressing the hydro-environmental challenges [19,35]. Although numerous water quality models have been developed and applied for such studies in recent decades, most of these studies have only considered the dissolved nutrients. In reality, many pollutants, such as heavy metals, bacteria, pesticides, and nutrients also adsorb onto the surface of sediments, preferentially very fine sediments. Hence, sediments can also serve as a carrier and reservoir of pollutants, whether they be in suspension in the water column or temporarily

* Corresponding author. Tel.: +86 21 34204472.
E-mail addresses: d.liang@sjtu.edu.cn (D. Liang), wangxiaolin00@gmail.com (X. Wang), Bockelmann-Evans@cf.ac.uk (B.N. Bockelmann-Evans), FalconerRA@cf.ac.uk (R.A. Falconer).
[1] Present address: Peterborough Office, Halcrow Group Limited, UK.
[2] Tel.: +44 29 2087 4280.

0309-1708/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.advwatres.2012.11.015

dormant on the bed. The attached state and the dissolved state are exchangeable via the adsorption/desorption processes. So, sediment transport may contribute significantly to the nutrient distribution, *e.g.* sediment deposition acts to remove nutrients from the water column and re-suspension mobilises bed nutrients to re-enter the water column. More and more attempts have been made to better understand the interactions between nutrients and sediments. Fitzsimons et al. [10] found that the desorption of the NH_4^+ from the re-suspended sediments accounted for approximately 50% of the increase in the dissolved NH_4^+ concentration in the Thames Estuary. Chao et al. [6] concluded that the sediment–phosphorus interactions might control the phosphorus levels in water bodies with high sediment concentrations. Hou et al. [14] revealed that bed sediment was a significant internal source of phosphorous in the intertidal area of the Yangtze Estuary. This study therefore aims to establish a sophisticated hydro-environmental model, capable of accounting for the sediment effects on nutrient processes, and demonstrate a model application to the Loughor Estuary, sited along the northwest coast of the Bristol Channel, UK.

As seen in Fig. 1, the Loughor Estuary is located to the west of the Loughor Road Bridge and Rail Bridge, where the waterway turns abruptly from a southerly direction to a westerly direction, towards Carmarthen Bay. It is a shallow and muddy estuary, with tidal streams of up to 1.5 m/s and frequently shifting sandbanks. The estuary has a tidal range of up to 8 m, and the tidal influence extends upstream to Pontardulais. At high water on an average spring tide, the estuary covers an area of approximately 45 km^2, with a width of 6.6 km at the widest section. At low water, the main channel of the River Loughor winds across the estuary bed through an expanse of sandflats. The southern shore has the largest continuous area (22 km^2) of saltmarsh in Wales, which supports one of the largest cockle fisheries in Britain. Large numbers of over-wintering wildfowl and waders feed in the intertidal and saltmarsh areas, so these areas have been designated as both a Special Protection Area for the wildlife and a Sensitive Area under the Urban Waste Water Treatment Directive in 2001. As seen in Fig. 2, the Loughor Estuary occasionally suffers from eutrophication, which threatens the biological diversity and stability, causing negative economical impacts on tourism and aquaculture [3]. A better understanding of the nutrient cycle in the estuary is urgently needed, in order to explore ways of nutrient removal.

This study has included the refinement of a numerical model for simulating the hydrodynamic, sediment transport and water quality processes in macro-tidal estuaries, but with particular emphasis being focused on modelling the sediment–nutrient interactions. The parameters for describing the sediment–nutrient interactions were determined by adsorption isotherm experiments. The model was first verified against field-surveyed data, and then used for a scenario analysis to examine the effects of changing the operation scheme of sewage treatment works (STWs).

Fig. 2. Slick of algal foam floating in the Loughor Bridge area in 1999.

2. Integrated hydro-environmental model

2.1. Overview

Estuarine and coastal waters can generally be classified to be shallow, since their depth is much smaller than the horizontal scale of the flow. For an estuary with a small freshwater inflow and a large tidal range, the vertical stratification is not significant. It can be seen later that the Loughor Estuary is indeed a very shallow macro-tidal water basin with a tiny amount of freshwater input. Therefore, a depth-integrated modelling framework has been adopted in the present study, which assumes a hydrostatic pressure distribution in analysing the flow and the complete vertical mixing over the depth in analysing the solute distribution. The evolution of the flow field is governed by the fully-dynamic shallow water equations, which are based on the principles of mass conservation and momentum conservation [19,16,17]. Correspondingly for solute transport, the following two-dimensional

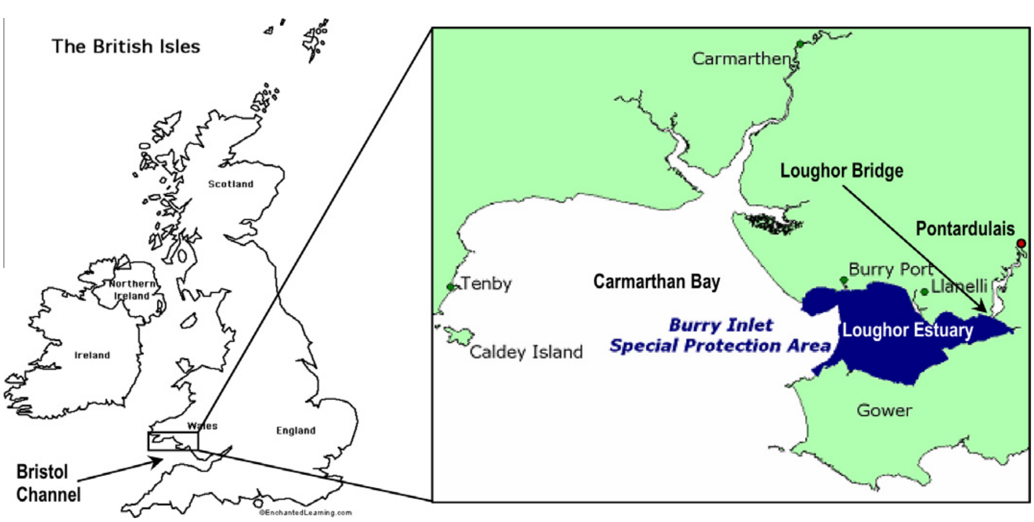

Fig. 1. Location of the Loughor Estuary and Carmarthen Bay.