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Improving optimization efficiency for the total pollutant load allocation in large two-dimensional water areas: Bohai Sea (China) case study

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ABSTRACT

The total pollutant load allocation (TPLA) can be transformed into an optimization problem with regards to water quality constraints. The optimization calculation may become very time consuming when the number of water quality constraint equations is great. A Trial and Error Method (TEM) to remove the redundant points was first introduced through iterative calculations under structure and non-structure model grids. The TEM was applied for the TPLA in the Bohai Sea in China. The calculation time was reduced to about 2 min under the condition that 103,433 model grids met the water quality standards. In the best case, the optimization efficiency was improved by 98.9%. The allocation results showed that approximately 90% of total nitrogen (TN) load should be reduced in the 56 pollution sources around the Bohai Sea; of these values, roughly 85% of the reduction could come from 10 pollution sources.

1. Introduction

Within the context of both economic and population growth, more and more anthropogenic pollutants – particularly nutrients such as nitrogen and phosphorous – are being discharged into bodies of water and causing deterioration of the water quality and of the ecosystems. It becomes essential, then, that the total pollutants load entering into a water body be controlled. This control is exercised on the international level through a variety of means, some of which include the Total Maximum Daily Load (TMDL) in the United States (USEPA, 2014), the Maximum Allowable Loads Control in the Chesapeake Bay and Baltic Sea (Antti Iho et al., 2015), and the Total Pollutant Load Control System in Japan (Ministry of the Environment, Japan, 2011).

To control the total discharged pollutant loads, the maximum allowable load for each pollution source must be specified using the total pollutant load allocation (TPLA) approach (USEPA, 1991; Deng et al., 2010; Liao et al., 2013). Generally, there are two methods used to perform TPLA: scenario analysis and optimization with mathematical modelling. Optimization results, alone, can be used by the stakeholders to create allocation scenarios (USEPA, 1991), thus providing a powerful tool for use in decision-making processes. However, due to the complex nature of the calculation process, the optimization procedure is often very time consuming (Rauch et al., 1998; Pang and Lu, 2010; Karen et al., 2013). From previous experiences (Klepper, 1997; Chen and Wheater, 1999), the nonlinear optimization method is very difficult to handle when the number of optimization variables is greater than ten.

Accordingly, the linear programming method (LPM) could prove an effective tool to solve these multi-variable optimization problems. Generally, to reduce the complexity of a calculation, the response relationship between the pollutant loads and water quality can be approximated to be linear. Essentially, the pollutant concentration in water is the sum of the independent concentrations induced by each pollution source; if the objective function is linear, too, then it could be considered a linear optimization problem (Juan and Ge, 2012; Wu et al., 2006). While the optimization complexity is greatly reduced by LPM, it is still very difficult, however, when a large amount of water quality constraint equations have to be considered.

The TPLA within the context of two-dimensional water areas is an atypical optimization problem. The optimization efficiency, however, holds the potential to be improved greatly if the specific environmental characteristics are analyzed and used to reduce the number of constraint equations. This paper proposes and discusses a new method for the removal of most (but not all) of the redundant constraint equations. The model is then applied to solve the TPLA problem within the context of the Bohai Sea, making the values of the allocated loads much easier to calculate.

2. Study site

Surrounded by Liaoning Province, Hebei Province, Tianjin City and Shandong Province from the north to the south, the Bohai Sea is partially enclosed by the north-eastern region of China. The sea measures a

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total water area of approximately 77,000 km^2, about seven times that of the Chesapeake Bay (Antti Iho et al., 2015). The Bohai Sea is both flat and shallow, with an average depth of 18 m and maximum of 85 m.

As a result of China's rapid economic development over the last thirty years, the Bohai Sea has been, and continues to be, heavily polluted. According to the *China Coastal Marine Water Status Report*, approximately 14.3% of the coastal marine area does not meet any of the thresholds set by the *Sea Water Quality Standard* (State Ocean Administration, China, 2013) report. The algae bloom frequency and area both increased markedly following the 1990s (Zang et al., 2012), ultimately reaching an accumulated algae bloom area of 1880 km^2 by 2013 (State Ocean Administration, China, 2013). Although the Bohai Sea only shares approximately 2.5% of China's total marine area, its algae bloom area represents approximately 46% of the total. While there have been some improvements over the last fifty years, such as the fact that the average concentration of PO_4-P measured lower in 2005 than in the 1960s, many pollution-related metrics have, in fact, worsened. For example, the concentration of dissolved inorganic nitrogen (DIN) had been increasing continuously over that same time period (Sun, 2007), labeling total nitrogen (TN) as the priority nutrient pollutant to be controlled.

Along the Bohai Sea there are hundreds, even thousands, of pollution sources, some of which include rivers and direct discharge pollution sources such as domestic sewage and industrial effluents. The annual TN loads of all the pollution sources were estimated to equal 163.6 thousand tons, according to the monitoring data from 2010. These pollution sources were categorized into 56 distinct sources according to their spatial locations (Fig. 1). Of these locations, Daliaohe,

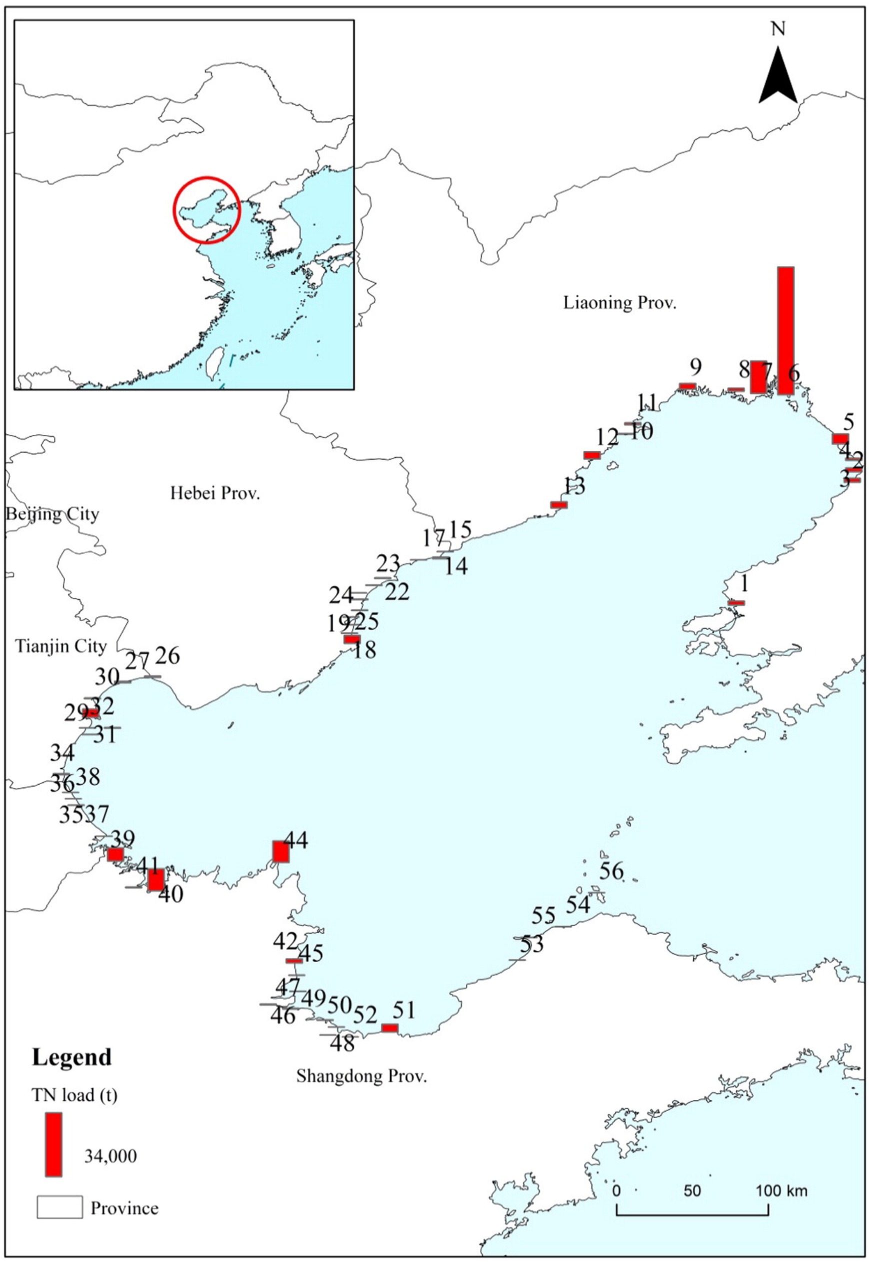

Fig. 1. Locations and TN loads of the integrated pollution sources around the Bohai Sea. 1. Fuzhouhe, 2. Shahe (Yingkou), 3. Xiongyuehe, 4. Daqinghe, 5. Dahanhe, 6. Daliaohe, 7. Liaohe, 8. Dalinghe, 9. Xiaolinghe, 10. Lianshanhe, 11. Wulihe, 12. Xingchenghe, 13. Liuguhe, 14. Shihe, 15. Shanhaiguan WWTP, 16. Xinkaihe, 17. Qingdao WWTP1, 18. Qingdao WWTP2, 19. Qingdao WWTP3, 20. Qingdao WWTP4, 21. Tanghe, 22. Daihe, 23. Yanghe, 24. Yinmahe, 25. Luanhe, 26. Douhe, 27. Jiyunhe, 28. Dashentang, 29. Dadongbengzhan, 30. Qingjinghuang, 31. Haihe, 32. Dagupaiwuhe, 33. Duliujianhe, 34. Ziyaxinhe, 35. Shibeihe, 36. Nanpaihe, 37. Xuanhuihe, 38. Liaojiawahe, 39. Majiahe, 40. Tuhaihe, 41. Chaohe (Binzhou), 42. Dehuixinhe, 43. Tiaohe, 44. Yellow River, 45. Guanglihe, 46. Xiaoqinghe, 47. Zhangsenghe, 48. Bailanghe, 49. Yuhe, 50. Bofa WWTP, 51. Weihe, 52. Shahe (Yantai), 53. Jiehe, 54. Huangshuihe, 55. Longkou WWTP, 56. Changdao WWTP.