European Journal of Operational Research 000 (2018) 1–8

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Decision Support

Safe dike heights at minimal costs: An integer programming approach

P. Zwaneveld[a,*], G. Verweij[a], S. van Hoesel[b]

[a] CPB Netherlands Bureau for Economic Policy Analysis, P.O. Box 80510, The Hague NL-2508 GM, The Netherlands
[b] Department of Quantitative Economics, Maastricht University, P.O. Box 616, Maastricht, MD 6200, The Netherlands

ARTICLE INFO

Article history:
Received 21 March 2017
Accepted 7 March 2018
Available online xxx

Keywords:
OR in environment and climate change
Cost-benefit analysis
Decision support systems
Integer programming
Flood prevention

ABSTRACT

Optimal dike heights are of crucial importance to the Netherlands as almost 60% of its surface is under threat of flooding from sea, lakes, or rivers. This area is protected by more than 3500 kilometres of dunes and dikes. These dunes and dikes require substantial annual investments of over 1 billion euro. In this paper we propose an integer programming model for a cost-benefit analysis to determine optimal dike heights. We improve upon the model proposed by Brekelmans, den Hertog, Roos and Eijgenraam (2012). Our model provides an alternative approach with almost complete flexibility towards input-parameters for flood probabilities, damage costs and investment costs for dike heightening. We present an easy-to-implement algorithm that provides an optimal solution to the problem. The method has been implemented and tested for the most recent data on flood probabilities, damage and investment costs, which were recently used by the government to determine the new safety standards in the Dutch Water Act.

© 2018 Elsevier B.V. All rights reserved.

1. Introduction

The 1953 flood in the South-western part of the Netherlands is, after more than 60 years, still in the Dutch collective memory. It resulted into the death of 1835 people. Almost 200,000 hectares of land were flooded, 67 dike breaches arose and immense economic damage resulted (10% of the Dutch GDP). The government rapidly appointed the so-called Delta Committee in order to design measures for preventing similar disasters in the future. The Delta Committee asked Van Dantzig (1956) to develop a mathematical approach to formulate and solve the economic cost-benefit decision model concerning the optimal dike height problem.

The work of the Delta Committee, including the work by Van Dantzig (1956), resulted in statutory minimal safety standards which were in place until the year 2016. These safety standards against flooding were defined on the basis of a dike ring area. A dike ring is an uninterrupted ring of water defences. In total, there are 53 dike ring areas, each having a certain minimum safety standard (i.e. maximum flood probability). The tightest (i.e. lowest) flood probability was 1/10,000 per year for the most populated part of the Netherlands. This number is derived from Van Dantzig (1956).

At present, protection against flooding is an important issue worldwide (Adikari & Yoshitania, 2009; Syvitski, Kettner, & Overeem, 2009). Devastating floods occur more and more frequently, e.g. in Bangladesh (2004, 2007, 2012), Pakistan (2010), and the well-known serious flooding in and around New Orleans in 2005, which killed about 1500 people and created enormous damage.

Renewed interest in determining optimal dike heights in the Netherlands arose – again – after a critical situation in 1995. The rising water levels of the major rivers Rhine and Meuse forced 200,000 people to evacuate. Fortunately, no serious flooding occurred. This event triggered the Dutch government to ask CPB Netherlands Bureau for Economic Policy Analysis to develop an economic cost-benefit analysis to determine optimal safety levels for dike rings along the river Rhine. The results of this analysis are presented in Eijgenraam (2005, 2006) and Eijgenraam, Brekelmans, den Hertog, and Roos (2017). The government initiated an investment project of several billion euros to bring the dikes adjacent to the major Dutch rivers up to standards (Ministry of Infrastructure & the Environment, 2009).

Gradually, awareness grew in the Netherlands that the safety levels against flooding were from the 1950s and were therefore in need of a thorough reconsideration. Since then, both the population size and the economic value of the protected land have increased significantly. Moreover, the knowledge about the causes of flooding has increased, as well as the technical measures to prevent flooding or reduce its consequences. Finally, the sea level and the discharge levels of the rivers during winter have risen in this period. Therefore, the Dutch Central Government initiated a safety programme as part of an overall new Delta Programme (Delta Pro-

---

[*] Corresponding author.
E-mail addresses: p.j.zwaneveld@cpb.nl (P. Zwaneveld), g.verweij@cpb.nl (G. Verweij), s.vanhoesel@maastrichtuniversity.nl (S. van Hoesel).

https://doi.org/10.1016/j.ejor.2018.03.012
0377-2217/© 2018 Elsevier B.V. All rights reserved.

Please cite this article as: P. Zwaneveld et al., Safe dike heights at minimal costs: An integer programming approach, European Journal of Operational Research (2018), https://doi.org/10.1016/j.ejor.2018.03.012

gramme Commissioner, 2012), with the aim of developing and setting down new water safety standards and implementing the EU Flood Risks Directive (EU, 2007).

Several research projects have been initiated to prepare these new standards. A new economic cost-benefit analysis (CBA) was carried out by the hydraulic research and consultancy company Deltares (Kind, 2011). This CBA is based upon a mathematical model developed by Brekelmans, den Hertog, Roos, and Eijgenraam (2012), an extension of the previous models by Van Dantzig (1956) and Eijgenraam (2006). The Minister of Infrastructure and the Environment (Schultz van Haegen-Maas Geesteranus, 2013) approved the result of the cost-benefit analysis to increase safety in specific regions (Eijgenraam et al., 2013, see also the video presentation by the Minister at the Franz Edelman Award 2013). In the past few years, a decision process of central and local governments (municipalities, counties and district waterboards) has resulted in the new legally binding safety standards for flood risks (Delta Programme Commissioner, 2016).

We present a new modelling approach to determine the optimal timing and extent of dike heightening or strengthening. We will use the terms heightening and strengthening interchangeably throughout this paper. Our new modelling approach entails three major advantages in comparison with Brekelmans et al. (2012).

The first advantage is that the model provides substantially more flexibility with respect to the input data. Some crucial assumptions of the underlying model by Brekelmans et al. (2012) are rather restrictive. Hence, the State Secretary on Water Infrastructure (Atsma, 2011) asked for a more made-to-measure approach, which is able to include more local-details for safety measures, especially low-cost solutions, to increase safety. The model is well equipped to include this type of measures in coming research projects. Situations in which this flexibility is crucial:

- For the major rivers a maximum exists to the discharge that can enter the Netherlands. Hence, the overflow probability of dikes will become zero in cases where these dikes are above a certain height.
- Damage that occurs when a dike (ring) fails differs up to a factor 20–100, depending on the exact location of the breach (CPB, 2011; VNK2, 2011).
- For some dikes (e.g. the Afsluitdijk, Grevers & Zwaneveld, 2011), it is possible to renovate certain constructions, like vessel locks and drainage sluices, up to a certain safety level at relatively low costs.
- After a ‘standard’ strengthening of a dike (by increasing its height and width), additional safety can be obtained by means of tailor-made, low cost measures (like ‘strengthened’ grass for a more robust dike covering), which yield a safety equivalent of 50 centimetres dike heightening.
- A time-varying discount rate may be appropriate and is already prescribed in France and the UK (UK DfT, 2011; Hepburn, 2007).

The second advantage is that our solution procedure guarantees optimality as it is based on solving an integer linear programming (ILP) formulation. This ILP formulation is solved very quickly by standard ILP solvers such as CPLEX. The approach by Brekelmans et al. (2012) can only guarantee optimality for quadratic cost functions since these allow a reformulation to a convex problem. For most instances, Brekelmans et al. (2012) use a heuristic and case-specific approach with no optimality guarantee.

The third and final advantage is that the procedure is easy to implement. Ease of implementation is not only very important for the use of our results in Dutch practice, but also to disseminate our results to less wealthy countries.

The ILP formulation is obtained by two ideas that are implemented consecutively. First, the data are discretized: the time horizon is divided in fixed length periods, and the heights are discretized in fixed length steps. Of course, the finer the discretization the more accurate the approximation of the continuous model. However, theoretically finer discretizations do not substantially influence the quality of the optimal solution. In practice, finer discretizations do not really make much sense: height increases more accurate than 20 centimeters are not really realizable. Moreover, with respect to time, intervals of less than three months (on a time horizon of 50 years or longer) never influenced the optimal costs with more than 1%. In fact, since every height increase takes five to ten years it is not realistic to consider periods smaller than one year. These two discretizations allow us to compute costs for all time-height combinations directly from the formulas as developed by Brekelmans et al. (2012), and any other cost functions that arise from practice (see above). The discretizations of time and height also allow us to introduce binary variables for every time-height combination (and change from one pair to another). The ILP formulation contains shortest path constraints for each dike segment, which are coupled by type 1 special ordered set constraints (SOS1), see Beale and Tomlin (1970). Thus, we can use discrete dynamic programming and branch-and-cut as methods to solve the problem. Unfortunately, dynamic programming still takes a lot of time for solving, specifically when finer discretizations are used. Therefore, we use branch-and-cut (B & C) to solve the ILP which uses very little time to solve the problem to optimality. In fact, all considered problem instances were solved with the standard package CPLEX.

This manuscript is structured as follows. We start in Section 2 with the introduction of the integer linear program for the nonhomogeneous case, the most general problem. In Section 3, we discuss some implementation issues, such as the discretizations used, and variable elimination rules (preprocessing). Then the computational results are presented. We conclude in Section 4 with some remarks and future research. In the appendices we present three more integer linear programs. In appendix A we present a model, model A, for the homogeneous case, where there is essentially exactly one segment. This model is considerably simpler than the non-homogeneous model, namely a min-cost flow problem. In appendix B we present model B, a simplification of our main model C. Model B introduces cost variables which replace the binary connecting variables. This makes the constraints simpler, but introduces non-integrality and therefore this model is not really performing better than model C. Finally, in appendix C, we present model D, which generalizes model C by allowing for height dependent damage costs.

2. Cost-benefit model as an integer programming model

In this section, we define the problem of determining optimal dike heights, and we present an integer programming (IP) formulation for the problem.

The optimal timing and heightening of a dike ring is based on a cost-benefit analysis, where we attempt to minimize the total (discounted) social costs, consisting of investment costs for heightening the dikes and the expected loss by flooding. In this section we will first describe the problem of optimally heightening the dikes in more detail, and then we will develop the IP-formulation.

2.1. The cost-benefit problem

The basic question is on when and to which safety level to heighten the dikes. The basic dilemma is the trade-off between paying up the investment costs of heightening a dike ring or accepting a (higher) probability of dike failure with all associated costs of flooding.

The costs of flooding include damage costs, cost of evacuation, rescue costs and immaterial costs (e.g. victims, sufferings). These

Please cite this article as: P. Zwaneveld et al., Safe dike heights at minimal costs: An integer programming approach, European Journal of Operational Research (2018), https://doi.org/10.1016/j.ejor.2018.03.012

Download English Version:

https://daneshyari.com/en/article/6894645

Download Persian Version:

https://daneshyari.com/article/6894645

Daneshyari.com