Continuous simulation or event-based modelling to estimate flood probabilities?

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Abstract

Risk analysis will become more important in formulating cost-effective solutions to flood problems. For this purpose, we need reliable estimates of flood frequencies in terms of inundation depths, as well as the possible damage that may result from the flooding. This article deals with the first aspect.

Hydrologists are using many different modelling techniques for estimating the flood frequency. These methods can be divided into two categories: event based design and continuous simulation approaches. In the first approach, the probability of extreme water levels is derived directly by simulating a large number of storm events, for which the probability has been determined in advance. Each event is characterized by a combination of stochastic variables that may contribute to flooding, such as rainfall volume, antecedent conditions, rainfall pattern, event duration, etc. An important feature of this approach is that it is assumed that the probability of the simulated storm event is equal to the probability of the calculated maximum water level. In the second approach, the water level probabilities are derived with standard flood frequency analyses of a (measured or calculated) time series of water levels.

In this paper, both approaches are discussed. Their results are compared for two catchments in the Netherlands. It is shown that the probability of floods is different when using continuous simulations and a stochastic event-based approach. It is concluded that for this type of problem a continuous simulation is to be preferred.
Keywords: probability of floods, continuous simulation, stochastic events.

1 Introduction

Many studies have been carried out to estimate the consequences of expected climate change on the behaviour of water systems (IPCC [1], Parker [2], Monirul

www.witpress.com, ISSN 1743-3541 (on-line)

et al. [3]). The general expectation of these studies is that many water systems around the world are not able to maintain the present level of protection against flooding without adaptive measures. In the Netherlands, the national government, provinces, water boards and municipalities have lounged a mutual action program to prepare the Dutch water systems for future changes. Part of this program is a nation wide check of all small regional water systems with respect to the probability of flooding by heavy precipitation (taking into account climatically changes), and to formulate the measures necessary to improve our water systems. For this purpose, some standards have been proposed for different types of land use (see Table 1). In a preliminary estimation the cost of the measures to comply with these standards are € 38 billion for the period till 2050.

Table 1: Proposed standard in the Netherlands, with respect to flooding (due to heavy rainfall).

land use	return period [1/yr]
grassland	1/10
agriculture	1/25
(greenhouse) horticulture	1/50
urban and industrial areas	1/100

The last year, all water boards started system analyses, to check whether these standards are presently being met, and to determine possible measures. A wide range of rainfall runoff model applications is used to estimate the frequency of flooding. A major problem that they are facing is that a great variety of methods exist to estimate flood probabilities, which lead to different answers.

In principle the available methods can be divided into two categories: stochastic event-based simulations and continuous simulations. This paper discusses the advantages and disadvantages of both methods. Besides the differences in applicability and reliability of the results, other aspects, as reproducibility and transparency, are addressed, as these are important factors in assessing the potentials of both methods. Applicability is an obvious criterion. Reproducibility is necessary, as the water systems behaviour has to be evaluated for different scenarios. And last but not least, transparency is required, both for decision makers and residents. For example, in case the water system needs more space, it has to be clear for provinces and municipalities (who are responsible for spatial planning) for what reason. Transparency is also needed for the residents, who want to know whether a flood (and the resulting damage) was "an act of God" or due to negligence of the water board. This makes that the water boards need to have a clear explanation on how they decide which flood frequency is beyond the offered level of protection.

2 Methods

2.1 Stochastic event-based simulations

The event-based approach calculates peak flows, and water levels that belong to combinations of stochastic variables, that affect the magnitude of floods. Main feature of this method is that a statistic analysis is applied on the input variables of the model, and that the probability of the input is expected to be valid to the output of the model.

In the simplest form the event-based approach consists out of a single design storm with a fixed duration. This design storm duration is a very significant determinant of the computed peak discharge, and often chosen equal to the concentration time of a water system. Next, the return period of the design storm is ascribed to the calculated water level. This is not correct; while more design storms exist, with other combinations of return period, event duration, and initial conditions, which may lead to the same water level.

So, instead of one variable a number of hydrologic model inputs, that contribute to the magnitude of flooding, are treated as random variables and combined to events in the stochastic event-based approach. Possible stochastic variables are intensities, volume, duration, pattern, initial ground water level, wind, and status of structures, on the condition that their distributions are known.

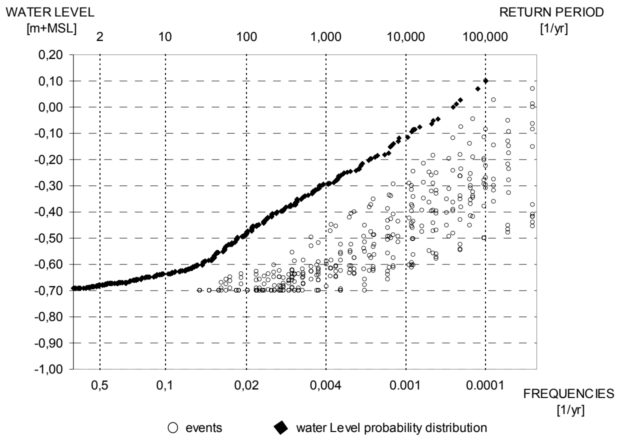

Figure 1: Results of a calculation with probabilistic events. The water level probability distribution function is determined by a cumulative summation of the probabilities of 360 events.

However many variants of the event based approach exist in practice, four steps can be distinguished in all applications of this approach. At first, All stochastic variables have to be identified that may contribute to an increased surface water level. Such as rainfall volume, antecedent conditions, rainfall pattern, event duration, et cetera. For each of these variables a probability density function, including dependencies among some climatic and hydrologic parameters, has to be determined. Secondly, all possible events are constructed by combining the stochastic variables from step 1, with e.g. Monte Carlo sampling procedures. The probability of occurrence of each event is determined by the probability of the stochastic variables. In the third step, the maximum discharge or water level from each event is calculated with a rainfall-runoff model. At last, a probability distribution function is found by a cumulative summation of the probabilities of all events that have a water level above a considered water level for all water levels (See Figure 1).

The validity of using single-event design storms to size flow controls (the traditional method) has been questioned for some time (Marsalek [4], McPherson [5]), but are still often applied in hydrologic engineering (Levy and McCuen [6], Watt et al. [7]). The results of each single event based flood frequency study can be criticized, as the normative event duration depends on the drainage area and the precipitation intensities of the event.

The stochastic event-based approach has been less often criticized compared to a single design event. Lamb [8] has shown that event-based rainfall-runoff modeling, which does not simulate antecedent conditions, yields flood frequencies distributions that differ more than the results of a continuous rainfall-runoff simulation. We would like to add the impossibility to incorporate operational water management strategies properly in these events. For example, the preference for pumping in weekends and at night (cheaper electricity), and the increased willingness to anticipate during periods of extreme precipitation.

2.2 Continuous rainfall-runoff simulation

This approach calculates flood frequencies from a long simulated time series of water levels, with a model of the surface water system of interest. Input for the simulation is a continuous series of either observed precipitation or constructed with a stochastic rainfall generator. The longest available series in the Netherlands is the since 1906 hourly measured precipitation series at the head office of the Royal Dutch Meteorological Institute at the Bilt. Daily series are available from far back in the 19th century, but are not useful as you loose many of the fluctuations in water levels with a simulation of daily precipitation. These kinds of long-term simulations were uncommon, but are in reach of the present calculation capabilities of modern computers (calculation time has become hours instead of weeks).

The output of the simulation with almost 100 years of hourly precipitation values is a series of water levels of equal length. The final processing consists of common flood frequency analyses techniques (a Generalized Extreme Value through the annual maxima, or a Generalized Pareto Distribution through peaks over threshold). So, statistics is applied on the output of the model. Advantage of a continuous simulation is that the number of subjective choices and number of operations is small. Disadvantage is that extrapolations beyond the length of the precipitation series become inaccurate.

Continuous simulations have been criticized for some time. Warnings that can be found in literature are the extensive data needed to calibrate, validate and run a continuous simulation. Secondly, the cost of computer time required. And, at last the specialized hydrologic expertise required to calibrate these models (Associate Committee on Hydrology [9]). At present, the ever-growing computing power of desktop units does not seriously limit the use of continuous simulation any more. Necessary hydrologic expertise is not limited to continuous simulations solely, but also counts for event based approaches. The main limitation follows from the lack of sufficiently long rainfall records. This however can be solved by the station year method (Buishand [10], Wallis [11]), or by generating long precipitation series with a stochastic rainfall generator. (Hingray [12]).

2.3 Case studies

Both the stochastic event-based approach and continuous simulation were applied in several case studies. All models were simulated with the hourly precipitation of the years 1906-2002. A typical result of a simulation is shown in Figure 2. As can be seen in figure 2A peaks are equally distributed over the last century. Notice that the management strategies differ throughout the year. In summertime a 30 cm higher target level is maintained than during the winter, to avoid low ground water levels, but that it is not clear in advance whether a annual maxima occurs in summer or wintertime.

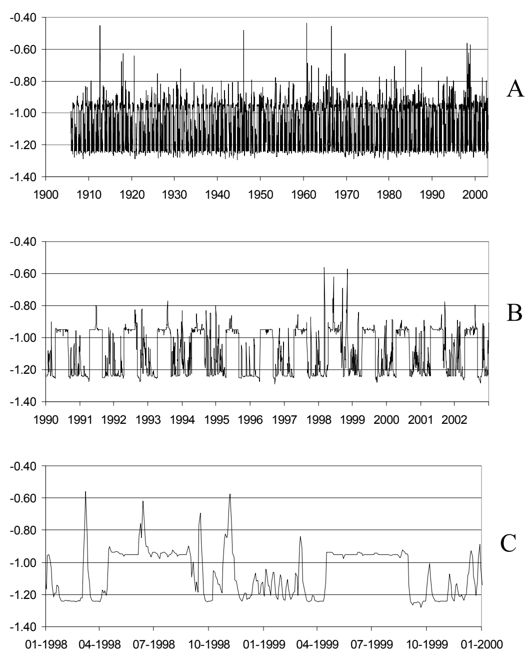

Figure 2: Results of a continuous simulation with the precipitation from 1906-2003 on three different time scales. The target level during April-September is a 30 cm higher than in October – March.

For the probabilistic approach, with statistic on the input of the model, the stochastic variables precipitation volume, precipitation pattern, duration and initial ground water level were taken into account (See Figure 3). The probabilistic approach delivered almost consequently higher results than the results of our continuous simulation.

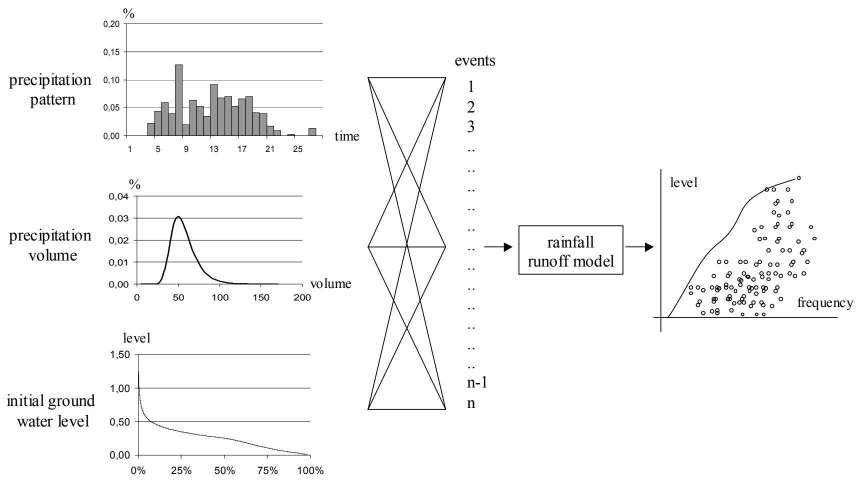

Figure 3: Stochastic event based approach.

The differences between both methods can be reduced by refining the probabilistic approach by adding more stochastic variables, like duration, or discretizing the pdf's of the stochastic variables in more classes, and by taking the dependency between stochastic variables into account. This however increases the number of operations and the calculation time.

3 Discussion

3.1 Applicability

An average water board in the Netherlands manages 1,500 km2, which is divided in hundreds of (sub) catchments. So, a concise practical method is preferred to analyze the present situation, impact of climate change, necessary measures or other 'what if…' scenarios of all these areas. A continuous simulation is simpler when many water systems have to be analyzed, because the model input exists of an observed rainfall and evaporation series only. This input is independent from the water system, so no special operations are necessary. The final processing of a simulation consists of common extreme values statistics. To apply an event-based approach the probability density from the various variables and their mutual dependence have to be determined or assessed before any calculations can be made. Some of the pdf's of these variables are unique to a certain water system. Or worse, are affected by the considered scenario, and should be determined before each calculation. This limits the practical applicability when numerous calculations have to be made.

3.2 Reproducibility

Reproducibility is necessary, as calculations may have to be repeated to assess the impact of spatial changes on the water systems behavior. The quality of results of rainfall runoff modeling – and the basis for reproducibility - depends strongly on the hydrologic input data. The formulation of the operating procedure of a continuous simulation can be concise: hourly precipitation values from 1906 to 2002 The Bilt, The Netherlands. A short description facilitates the harmonization of calculations, and limits the probability of failures, when calculations of several water systems or scenarios have to be done. This applies also for the future when simulations might need to be reproduced i.e. for determining the feasibility of a new alternative. The reproducibility is more difficult with a probabilistic modeling approach. So clarification of the procedure needs special attention. On the one hand, while from each water system and all events have to be recorded which stochastic variables are distinguished, and how the probability distribution of these events is determined. On the other hand, while many subjective choices are made to formulate these events, which may be decided otherwise by another modeler, with a simpler model or faster PC.

3.3 Transparency

Management of a water system has always been a process of weighing cost and benefit. From which the latter is equal to the expected damage that can be prevented with this cost. So, the water infrastructure needs to be enlarged when an area develops from rural to urban to reduce the probability of flooding. The consequence of a larger interval between events is an increased believe of residents in absolute safety. However, when a flood event happens the question raises, whether a certain event was an act of god or whether the water board was negligent. So, a transparent method is required to be able to explain to non-engineers what the present level of protection is, and how this level is determined. Our experience is that a simulation of water levels with 100 years of observed precipitation is sooner understood, and leads to discussion than a probabilistic modeling approach in which events are calculated that have not ever occurred, and from which is not sure whether they ever occur.

4 Conclusion and recommendation

In this paper we compared and discussed a continuous rainfall-runoff simulation with a stochastic event-based approach to determine probabilities of extreme floods. The fundamental difference is whether statistic is applied on the input or output of the model. In general the stochastic event based approach is associated with uncertainty of parameters, assumptions and simplifications. With a continuous rainfall-runoff simulation the uncertainty is still present, but many assumptions and simplifications from the event-based approach can be excluded, because they are a direct or indirect component of the precipitation input series. When using a continuous simulation, no assumptions have to be made related to the dependence between the different stochastic variables; the variables to be included and the effects of operational strategies, since these are part of the input series or the model. For this reason a continuous simulation provides more reliable results than an event based approach. Besides, the possibility of making mistakes is much smaller.

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