Integrated drought risk assessment to support adaptive policy making in the Netherlands

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Abstract. Adaptive policy-making to prepare for current and future drought risks requires an integrated assessment of policy actions and combinations of those under changing conditions. This entails quantification of drought risks, integrating drought

10 probability and socio-economic consequences for all relevant sectors that are potentially impacted by drought. The investment costs of proposed policy actions and strategies (various actions combined) can then be compared with the expected risk reduction to determine the cost-effectiveness. This paper presents a method to quantify drought risk in the Netherlands under changing future conditions and in response to policy actions. It illustrates how to use this information as part of a societal cost-benefit analysis and in building an adaptive long-term strategy. The method has been successfully applied to support decision

15 making on the Netherlands' national drought risk management strategy as part of the National Delta Program for climate change adaptation.

1 Introduction

Drought is a natural hazard that increases the water demand and at the same time reduces water availability for people, ecosystems and economic sectors. Climate change, population growth and upstream land use changes are often projected to

20 increase the risk of water shortage due to droughts. Long-term strategies are needed to adapt to changing drought conditions. Such a planning process requires drought risk assessment tools (Wilhite et al., 2000), which aid to understand drought frequency and its propagation through the hydrological system to impacted water users.

Drought risk assessments are carried out to inform decision makers on the possible consequences of drought hazards and the

25 potential benefits of risk reduction options. Drought risk is defined as the combination of drought probability and socio-economic and ecological consequences, where consequences are determined by the exposure and vulnerability of water users to water shortage. Consequences include direct effects, such as crop losses and shipping delays, indirect effects on the economy as a whole, such as unemployment and price changes, and intangible effects such as deteriorated water quality and biodiversity loss (see Logar and van den Bergh, 2012).

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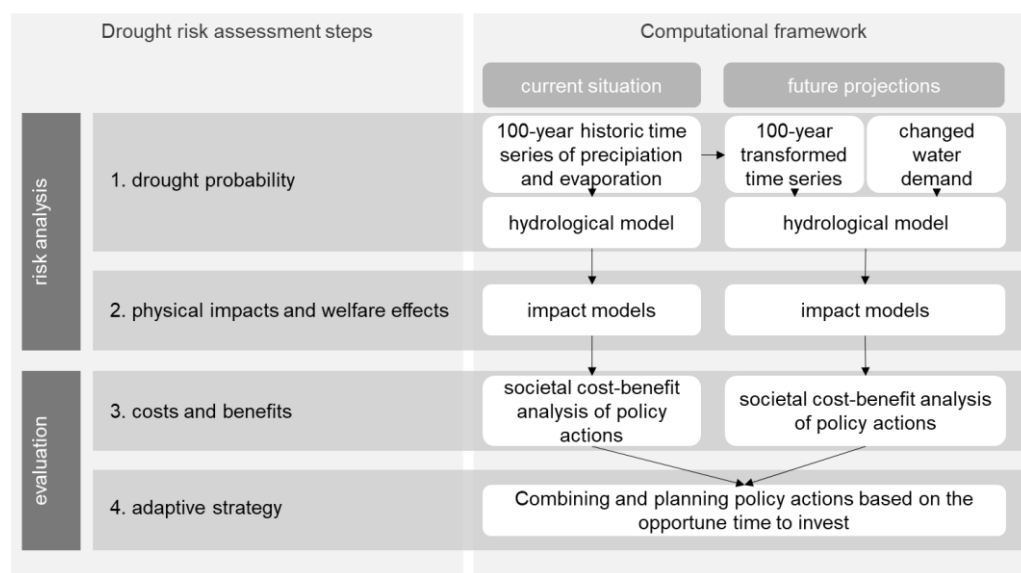
A risk-based approach to support drought risk management is rather new (Hagenlocher et al., 2019; Hall and Borgomeo, 2013). Much of the drought literature focuses on the quantification of meteorological or hydrological drought indicators on different temporal and spatial scales (e.g. Van Loon et al., 2016; Mishra and Singh, 2010; Veldkamp et al., 2015), and/or on the impact of drought on specific user groups like agriculture (e.g. Meza et al., 2021; Zhang et al., 2021), public water supply (e.g. Ajami
35   et al., 2008; Connell-Buck et al., 2011; Wendt et al., 2021) or electricity production (Byers et al., 2020).

Modelling drought impacts is a complex task because of the indirect and diffuse impacts of droughts, the lack of historic drought impact data, the variety of mechanisms that cause damage for different water users, and the multicausality of impacts such as heat waves and price effects (Bachmair et al., 2016; Blauhut et al., 2015; Musolino et al., 2018; Naumann et al., 2019;
40   Vogt et al., 2018; Wilhite et al., 2014). The majority of drought risk assessments over the past 50 years used an index-based approach (62%) to tackle the complexity of drought risk, while only 12% of the assessments used dynamic simulation methods (Hagenlocher et al., 2019). An index-based approach maps drought risk by combining drought indicators with weighted vulnerability factors (e.g. Blauhut et al., 2015; Carrão et al., 2016; Naumann et al., 2014). Dynamic simulation approaches on the other hand are able to capture the complex relationship between drought propagation and socio-economic impact and are
45   considered more useful for policy support when adaptation decisions have to be made (Hagenlocher et al., 2019). However, they require integrating hydrological system knowledge with social, economic and environmental impact mechanisms in a coupled system model. Only a few examples exist in which quantified drought risk is employed as part of a cost-benefit analysis to support decision-making on drought mitigation and adaptation policies (Hagenlocher et al., 2019; Logar and van den Bergh, 2012; Rossi et al., 2005). In many cases, water shortage has been assumed as proxy for drought impact because of
50   a lack of data and the complexity of the economic assessment (Rossi and Cancelliere, 2013).

This paper presents an integrated drought risk assessment carried out for the Dutch Delta program, which is a long-term government program to ensure that the Netherlands is climate-proof by 2050, including resilience to drought-induced water shortage. The presented drought risk assessment is based on dynamic simulation of the hydrological system and coupled impact
55   models that propagate water shortage to societal and economic impact. The framework is partly based on earlier research carried out by a consortium of Dutch research institutes, consultants, waterboards for the Ministry of Infrastructure and Water Management (Van der Vat et al., 2016) as well as for the European Horizon 2020 project IMPREX (IMproving PRedictions and management of hydrological Extremes) (Groot et al., 2020). The assessment framework consists of four steps (Figure 1). To analyse drought probability (step 1), a long (100-year) daily time series of hydrological and meteorological variables,
60   including precipitation, evapotranspiration, and river discharge, were used to represent a variety of droughts, both for historical situations and for future projections. In step 2, the time series were first simulated with a national hydrological model to obtain relevant hydrological and human responses such as river discharge, groundwater flow, irrigation, river water levels, salt concentration, groundwater extractions, and water temperature. Next, the welfare effects of water shortage were estimated by coupling economic impact models for agriculture, shipping, industry and drinking water with the national hydrological model.

65 The impact models first simulate the 'physical' impacts on the various drought prone sectors (e.g. agricultural yield losses in kg/ha, reduced draught and waiting times for shipping, and water quality for drinking water and industry) and subsequently estimate the national welfare effect, considering price elasticity and other market mechanisms. In step 3, the costs of proposed policy actions were compared with the calculated change in drought risks (i.e. annual average impacts summed over the different sectors) for different future scenarios of climate change and socio-economic developments. In step 4, this information

70 was used to determine the opportune time to invest. By comparing the costs of policy actions with the change in drought risk together with the determined opportune investment time, an adaptive strategy was built. Finally, the evaluation based on societal costs and benefits supported the decision by the Minister to allocate funds for drought risk mitigation.

75 Figure 1 Framework for drought risk assessment

2 Data and methods

2.1 Study area

The Netherlands is a low-lying delta with peat and clay soils as well as relative higher grounds with sandy soils. Fresh-water supply largely relies on two large transboundary rivers: the Rhine and the Meuse, a large fresh-water reservoir in the North

80 (IJssel Lake), and groundwater reserves in the higher grounds, including the coastal dunes. The estuary in the West is susceptible to salt water intrusion when river flows are low, limiting the fresh water intakes for industry, drinking water and regional water management including agricultural water supply. Ancient deep salt groundwater along the coastal area causes saline seepage into the drainage system of low-lying polders, which has to be flushed away. During dry summers, river water intakes are important for irrigation, flushing the regional surface water system, and maintaining surface water levels (to prevent

85   peat oxidation and land subsidence, and to ensure stability of embankments). Drought-related problems in the higher sandy areas arise from precipitation deficits in conjunction with the competition over groundwater between agriculture, nature and drinking water and industry.

One of the aims of the Dutch Delta Program is to ensure that the Netherlands remains resilient to drought-induced water

90   shortage. Every six years the long-term adaptation strategy and short-term policy actions are reassessed in view of the latest insights into climate change and socio-economic developments. New funds for policy actions are released based on an evaluation of their costs and societal benefits.

The focus of this paper is on two regions that depend on water supply from the main river system: region Southwest and region

95   North (Figure 2). Region North depends on water supplied from the IJssel Lake, which is in turn fed by the Rhine river and has a limited buffer capacity. One of the major inlets for region Southwest is vulnerable to salt water intrusion from the North Sea. An emergency supply route further upstream is available but with limited supply capacity. To illustrate the application of our framework, we present the assessment of a selection of five policy actions in these two regions. In reality, an extensive list of policy actions has been assessed for the Delta Program (Mens et al., 2020; Stratelligence, 2021).

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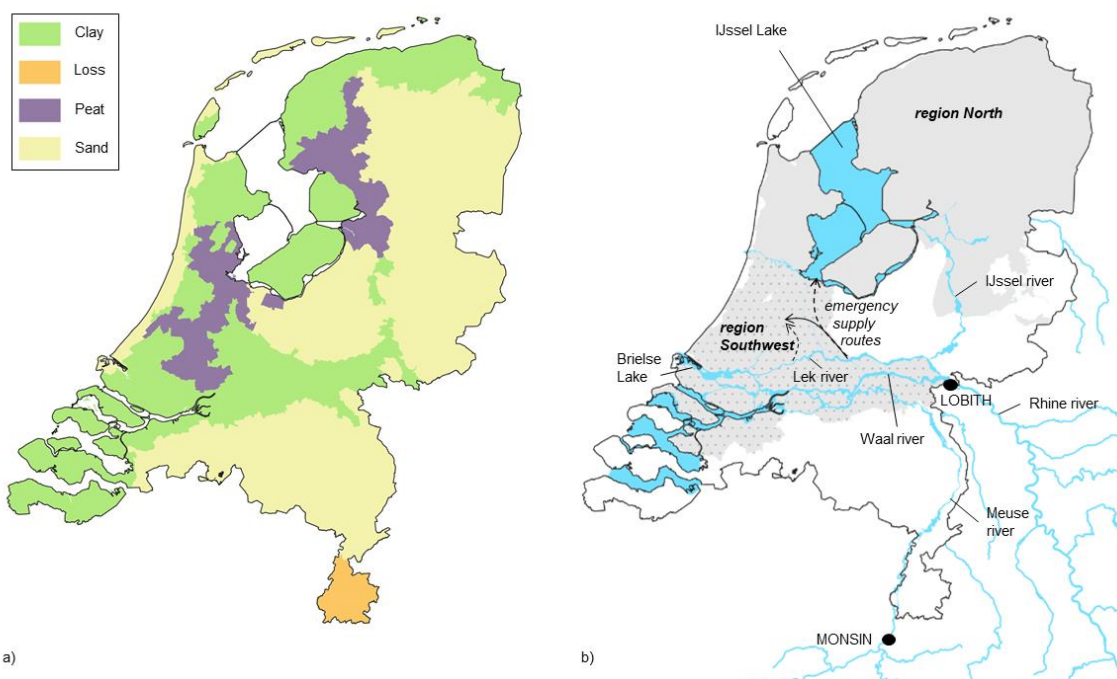


Figure 2 Study area: a) Major soil types of the Netherlands, b) major rivers, lakes, and water supply routes of the Netherlands and the location of the two focus regions in grey

2.2 Drought probability, water shortage and impacts

105 *Drought probability*

Drought hazard in the Netherlands is often measured as the cumulative precipitation deficit, which is the cumulative difference between potential evapotranspiration and precipitation in the growing season (April to September), set to zero if smaller than zero (Beersma and Buishand, 2004; Philip et al., 2020). This metric is used as a first indication of the projected change in meteorological drought. Drought impacts in the Netherlands are also determined by coinciding periods of low river flows in

110 the Rhine and/or the Meuse, which can be measured as the annual cumulative difference between daily river discharge and a user-defined threshold for the days those flows are below this threshold. This threshold was set at 1000 m^3/s for the Rhine and 50 m^3/s for the Meuse. Deficits are only counted when the duration of the low flow period is 7 days or longer.

Water shortage

115 The National Water Model (NWM; Mens et al., 2021) was used to simulate the propagation of droughts through the hydrological system, the National Water Model was used. This physically-based model simulates time series of actual and potential evapotranspiration, soil moisture and groundwater for phreatic groundwater and deeper aquifers, on a spatial resolution of 250x250 m. Also, daily time series of discharge, water levels, temperature and chloride concentration are available at several locations in the main river system. Water demand and water shortage are spatially aggregated over 17

120 regions and divided into three main use categories (i.e., irrigation, flushing and water level management).

Impacts

Water shortage can be combined with a physical dose-effect relationship to determine the physical impact on a sector (e.g. yield loss), which can then be combined with economic data to estimate the welfare effect. When welfare effects are combined

125 with the probability of water shortage, a drought risk curve is obtained which shows the probability distribution of the welfare effects. The impact of droughts was quantified in monetary terms for shipping, drinking water, industry, and agriculture. This selection was made from a list of sectors impacted by droughts in the Netherlands, based on reported impacts of historic droughts and in consultation with several drought experts. Drought impacts on soil subsidence, instability of peat embankments, water quality and biodiversity loss were considered relevant, but information was lacking to develop an impact

130 model. Instead, these effects were monetized with a shadow price (under the category 'other effects'). Other drought impacts, such as on recreation and urban green spaces, were not monetized because the impact was considered relatively small or these were not expected to be affected by policy actions. Since the focus is on national welfare effects, the additional costs of consumers or producers outside the Netherlands were not included.

135 *Agriculture*

We used the Dutch agricultural cost model (AGRICOM) to propagate the soil moisture deficits and irrigation amounts calculated by NWM to an annual crop yield reduction and irrigation costs. AGRICOM is based on empirical studies and mathematical models, developed for the first policy analysis for water management in the Netherlands in the eighties (Abrahamse et al., 1982), and updated in 2009 (Mulder and Veldhuizen, 2014) for use in the Dutch Delta Program. The
140 AGRICOM damage functions, relating crop-specific yield reduction with transpiration reduction, are comparable to those developed and applied by the Food and Agriculture Organization of the United Nations (Smith and Steduto, 2012). It additionally includes the cumulative effect of crop yield reduction throughout the growing season as well as yield reduction due to salinization stress. An economic tool (Polman et al., 2017, 2019) was used to assess the impact of crop yield reduction and higher irrigation costs on the national welfare, by calculating the change in consumer and producer surplus. The price
145 elasticities in this tool are based on observed price changes during historic droughts (Briene et al., 2019) and information on the Netherlands' market share, which determines the influence on crop prices in the regional, national, or international market.

Inland water transport

The impact of droughts on inland water transport was estimated using the Dutch inland transport analysis model BIVAS
150 developed by the Ministry of Infrastructure and Water Management (Rijkswaterstaat, 2019) and an economic tool. BIVAS calculates annual transport costs based on a daily time series of water levels in the main waterways (simulated by the National Water Model), a database with actual daily shipping movements for various types of vessels, and assumptions on draught. Reduced water levels will result in reduced load of vessels and therefore more trips, as well as increased travel times due to detours and increased waiting time at sluices, which all results in higher transport costs. The economic module adds the costs
155 of temporary storage of goods or transportation by other modalities. The total additional costs due to droughts were calculated by taking the difference with the total costs in a simulated year without water level restrictions. Finally, a correction was made for the costs of foreign vessels or costs paid by consumers in other countries (about 50% in the current situation), since societal cost-benefit analyses for the Dutch Delta Program only consider welfare effects for the Netherlands.

160 *Drinking water and industry*

Droughts may affect drinking water production and industrial use by deteriorating water quality. Drinking water companies in the Netherlands are obliged by the Dutch drinking water law (Article 32-38) to provide drinking water with 100% reliability. The drinking water production companies are therefore well-prepared for periods of droughts by maintaining sufficient buffer capacity and diversifying drinking water resources (surface water, groundwater, river bank infiltration). However, future
165 droughts may reduce the long-term reliability of drinking water supply and therefore requires additional investments. The costs of drought adaptation to maintain the supply reliability represent the economic impact of (future) droughts on drinking water supply.

A similar approach was taken for industries (e.g., paper, steel, chemical), which rely on water for production or for cooling
170 purposes. It is assumed that industry will timely invest to avoid production stops in the future, to keep the probability of
production stops very low. The probability of production stops due to droughts has been estimated at 1/100 per year, based on
historic measurements and interviews with the sector (Briene et al., 2018). For the risk analysis we have assumed that
adaptation investments are aimed at maintaining this failure probability under future scenarios.

175 To estimate the required adaptation investment under future change, we first calculated the additional treatment capacity
required by estimating the additional exceedance (in comparison with the current situation) of the concentration of six
indicating substances at water intakes for water supply and industry. As a proxy for adaptation costs it has been assumed that
drinking water companies and industries will implement reverse osmosis treatment as an additional step to cope with the
drought-induced deterioration of water quality. In line with the agriculture and shipping impact models, we do not include the
180 potential impact of events smaller than 1/100 per year. Furthermore, because the demand for drinking water is inelastic, the
semi-public drinking water companies will increase the consumer prices to cover for the adaptation costs. For industry supply,
we also used the adaptation costs as a proxy for the welfare effect of drought.

Other effects
185 Droughts may have other societal, economic and environmental impacts, such as the impact of reduced surface water quality
causing deterioration of aquatic biodiversity, and the impact of lower (ground) water levels on terrestrial nature, infrastructure,
stability of embankments, and CO_2 emissions in peat areas. These impacts are monetized by multiplying the simulated water
shortages for flushing and water level management in the polder systems with a shadow price of water. The shadow price of
water can be defined in different ways, for example by the value of water based on all (opportunity) costs and externalities, by
190 the value of alternative use of water, or by the marginal value of water for the farmer (Bierkens et al., 2019; Young and Loomis,
2014). In this paper, we defined the shadow price of water as the marginal value of an additional cubic meter of water during
periods of water shortage. The shadow price was derived from the agricultural impact model outcomes, as a regression between
crop evapotranspiration and crop yield minus the additional costs of irrigation, which represents the additional yields that can
be obtained by adding one m^3 of water. The shadow price has been calculated for five different regions in the Netherlands
195 averaged over all irrigated crops. The implicit assumption is that the value of water for nature, infrastructure and other functions
is equal or higher than the value of additional irrigation water for the agricultural sector. This assumption is supported by the
Dutch national prioritization rules for water allocation during periods of water shortage, which states that flushing and water
level control should be prioritized over irrigation. The monetized other effects were only considered in the evaluation of policy
actions.
200

Additionally, stakeholders provided qualitative scores on effects that could not be monetized with the above modelling
framework.

2.3 Future scenarios

Long-term drought risk may change due to climate change and socio-economic developments. To take this into account in
205 policy making, the Dutch Delta Program develops and frequently updates so-called 'Delta scenarios' (Wolters et al., 2018),
which combine climate change scenarios from the Royal Netherlands' Meteorological Institute (Lenderink et al., 2014) with
population and economic growth projections by the Netherlands planning agencies (CPB/PBL, 2015). Lenderink et al. (2014)
distinguishes four climate change scenarios: a moderate (G) or fast (W) temperature rise, combined with either low (L) or high
(H) change in the circulation patterns over Western Europe, resulting in dryer summers. G_L and W_H were combined with two
210 socio-economic scenarios and used in the model analyses. The moderate/wet climate scenario G_L is combined with low
respectively high socio-economic growth in the Delta scenarios 'Rust' and 'Druk'; the warm/dry climate scenario W_H is
combined with low and high growth in the Delta scenarios 'Warm' and 'Stoom' respectively (Table 1). The scenarios provide
qualitative and quantitative data on the climate, water systems, water demand, and the use of land. Each scenario has its own
map with projected land use. The qualitative information consists of narratives that describe the backgrounds and the
215 interconnectivity of the issues. The quantitative data include time series for various factors, including temperature,
precipitation, and river discharges as well as degree of soil subsidence, and salinization. To limit the number of model
simulations, the effect of policy actions was analysed for the reference and Stoom scenario only. The reference scenario was
assumed to represent the lower value of the bandwidth of future drought risk and Stoom represents its upper value.

220 Table 1 Overview of scenario assumptions in the projections for 2050 (adapted from Wolters et al. (2018)). Climate change
is relative to the average climate over the period 1981-2010.

Delta scenario	Rust	Druk	Warm	Stoom
Climate change scenario	GL		WH	
Global temperature change (degrees Celsius)	1		2	
Sea level rise (cm)	+15		+40	
Change in annual precipitation (current climate: 851 mm)	+4%		+5%	
Change in annual evapotranspiration (mm)	+3%		+7%	
Socio-economic change	low	high	low	high
Population (current: 17 million people)	16	19	16	19
Economic growth per year	+1%	+2%	+1%	+2%
Agricultural land use (% of total area; reference = 60%)	58	54	57	53
Nature and recreation (% of total area; reference = 23%)	24	26	24	25
Urban area (% of total area; reference = 18%)	18	20	18	21
Hydrological model input				
Change in irrigation area (reference = 424.000 hectare)	+8%	+4%	+60%	+55%
Change in water extraction for industry	-40%	-30%	-10%	+15%
Change in drinking water extraction	-10%	+10%	0%	+35%
Change in water demand for flushing of salinized polder systems	-10%	-25%	+20%	+100%

2.4 Model input data

As input for the hydrological model, 100-year time series of precipitation, evapotranspiration, river discharge and sea level
225 were used (overview of data sources given in Table 2). Historical meteorological data consist of daily time series of gridded
precipitation (1911 – 2011) and reference (Makkink) evapotranspiration calculated from sunshine duration (1911 – 1981) and
radiation (1981 – 2011), developed by the Royal Dutch Meteorological Institute (KNMI). River discharge for the Rhine and
the Meuse was obtained from the national monitoring network of Rijkswaterstaat. For future projections, the historical time
series were transformed with a transformation tool (Bakker, 2015; Bakker and Bessembinder, 2012), which applies a change
230 factor consistent with each climate change scenario (Section 2.3) and takes into account that the change in the median may
differ from the change in the extremes.

Table 2 Overview of measurement data sources used as model input

Variable		Resolution	Source
Precipitation	[P]	Daily; gridded	https://api.dataplatform.knmi.nl/open-data/v1/datasets/RDH_REF/versions/2/files
Reference evapotranspiration (Makkink)	[ETref]	Daily; gridded	https://dataplatform.knmi.nl/dataset/evh-ref-2
River discharge Rhine	[Q]	Daily; at station Lobith	https://waterinfo.rws.nl
River discharge Meuse	[Q]	Daily; at stations Amay, Chaudfontaine and Sauheid	http://voies-hydraulique.wallonie.be

235 ## 2.6 Costs and benefits of policy actions

Limiting the economic and societal impact of water shortages requires collective efforts from all the government authorities
with water-related tasks and freshwater users. Within the national Delta Program, these parties (stakeholders) jointly identify
policy actions that contribute to increase long-term drought resilience. In a six-year policy cycle, these stakeholders discuss
the current and future drought risk based on the national risk analysis, build a long-term strategy, and propose short-term policy
240 actions that will be implemented during the next policy cycle. The national government has to endorse the changes to the
strategy and approve the new policy actions for the short term in order to release the required funds for implementation. In a
funneling process a long list of possible measures is narrowed down to a shorter list of preferential measures. The selection of
preferential measures is not only based on the efficiency of the policy actions in terms of drought risk reduction. Other societal
goals (such as solidarity, sustainability) are to be achieved as well as (political) support. The final short list of proposed actions

245 is used in the societal cost-benefit analysis. The stakeholders provide information on investment costs, operation and maintenance cost, potential hydrological effects and a variety of other benefits which are scored qualitatively. The provided data were tested for consistency and when information was lacking estimates were based on previous societal cost-benefit analyses or additional information provided by cost experts from Rijkswaterstaat.

250 The cost estimates were translated into the equal annual annuity (Eq. 1), i.e. a series of equal cash flows over the life time of the measure, in order to equally compare measures with different life spans, investments and annual operational and maintenance costs.

$$equal\ annual\ annuity\ (EAA) = \frac{r*(I)}{1-(1+r)^{-n}} + C \qquad (1)$$

255 Where:

   r = yearly discount rate (percentage),

   n = life span (years),

   I = investment costs (euro),

260   C = annual costs for operation, management, and maintenance (euro per year).

A standard discount rate of 3% - 4.5% is prescribed by the Dutch government, where 4.5% is for public infrastructure investments with substantial fixed costs. A rate of 4.5% was used for all actions and a sensitivity analysis was carried out with 2.25% and 3.0%.

265

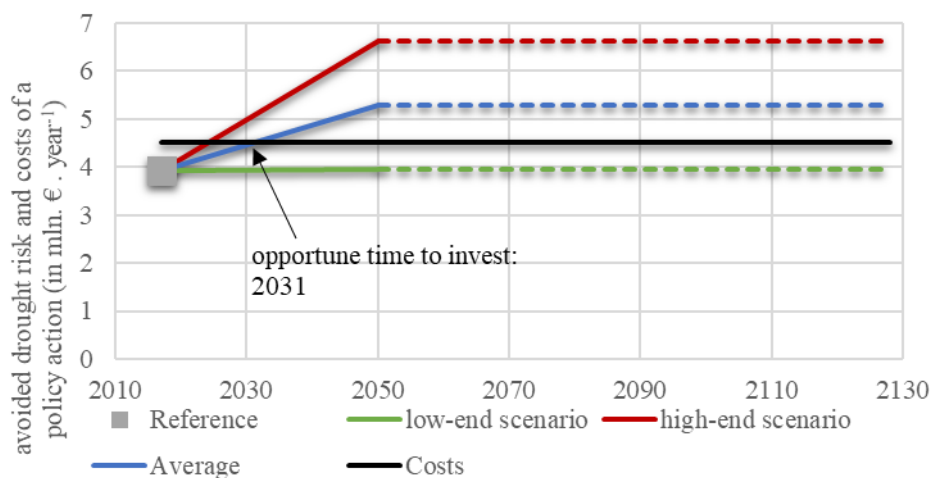
The quantified risk reduction per scenario was compared with the annual cost for each policy action. With a positive balance (the avoided drought risk ≥ costs), the policy action is positively evaluated from a societal welfare perspective. Both monetized effects based on calculated change in drought risk and non-monetized effects provided by the stakeholders were included. For each policy action, three evaluation outcomes are possible:

270   1. Cost-effective, when costs are smaller than monetized effects and non-monetized effects are either positive or slightly negative;

   2. Indecisive, when a) costs are slightly larger than the monetized effects and non-monetized effects are positive, or b) costs are smaller than monetized effect and non-monetized effects are (slightly) negative;

   3. Not cost-effective, when costs are larger than monetized benefits and non-monetized effects are either negative or 275   slightly positive.

2.7 Building an adaptive strategy

A drought risk management strategy is a combination of several short-term and long-term policy actions. The short-term actions involve a decision by Dutch Government, but the long-term actions are planning options that need a decision at the end of the next policy cycle or later. Whether a policy action is included in the advised strategy for the coming 6 years (2022-
280 2027) depends on its cost-benefit evaluation as well as its opportune time to invest. The balance of costs and benefits depends on the scenario. When policy actions are not cost-effective now but may become cost-effective under the Stoom scenario, the opportune time to invest is determined by first interpolating the results between Reference and Stoom and then averaging the effects over these low-end and high-end scenarios (see Figure 3). When costs and averaged effects intersect, it is assumed to be the opportune time to invest. An investment done before the opportune time means that costs may be higher than the benefits
285 for some years, while investing after the opportune time may result in missed benefits. If the opportune time to invest was in or before 2028, the action was included in the preferred strategy for the period 2022-2027.

290 Figure 3 Determination of opportune time to invest based on when the average avoided drought risk of the low-end and high-end scenario intersect with the annual costs (EAA)

3 Results

3.1 Changing drought risk when current policy is continued

A warmer climate will result in an increase in annual precipitation and reference evapotranspiration, however large uncertainty
295 exists about the change in precipitation patterns during the growing season (April – September) and thus about increasing droughts, determined by the frequency and intensity of precipitation deficit as well as the frequency and duration of low river

flow periods (Figure 4). Based on the model simulations, the current drought risk in the Netherlands is estimated at 372 million euro per year and may increase to 611 million until 2050 according to the worst-case scenario Stoom (Table 3). Drought risk in the Warm2050 scenario, with a similar climate change scenario but assuming limited socio-economic growth, was estimated

300   at 607 million euro per year. In the moderate scenarios Rust and Druk, the drought risk is estimated to remain similar to the current situation.

The drought risk is dominated by the effect on agriculture, but the relative increase in Stoom is higher in the other sectors. The risk for agriculture may increase by 155 million euros in 2050. Increased drought and related salt water intrusion affects all

305   regions. The highest absolute increase of about 70 million euro per year occurs in region North, one of the largest regions. This increase is largely due to the extra costs of irrigation in response to a warmer climate.

Drought risk for the shipping sector is projected to double in the next 30 years in the Stoom scenario, an increase of 72 million euro per year. This is mainly due to the increase of low flow periods in the Rhine river. Drought risk for drinking water supply

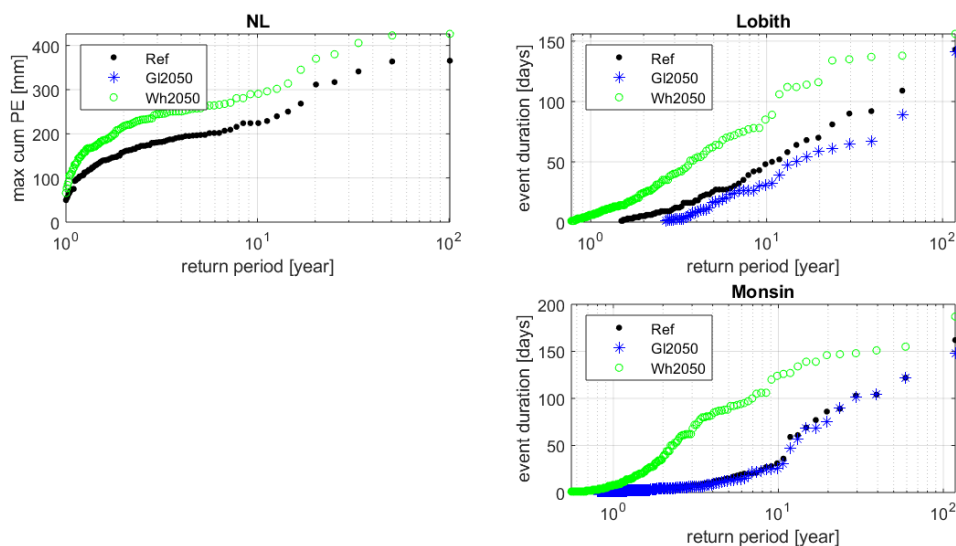
310   is estimated to increase with about 9 million euros per year in the Stoom scenario, and industrial risk with 3 million euro per year. The current risk for industry of 1 million euro per year is caused by one of the largest industrial areas of the Netherlands, located in region Southwest, which depends on a small fresh-water lake (Brielse Lake, see Figure 2) that is vulnerable to salt water intrusion from the North Sea.

315   Figure 4 Change in meteorological and hydrological drought probability in the two climate scenarios G_L and W_H, measured as the maximum cumulative precipitation deficit in mm (upper left) and the duration of low flows in the Rhine river (upper right) and Meuse river (lower right) in days. Only periods with a minimum duration of 7 days are considered.

Table 3 Current and future drought risk (in million euro per year, excluding VAT) in the Netherlands and the two focus regions when continuing current policy, broken down by sector.

Sector	Reference			Stoom2050		
	Netherlands	Region Southwest	Region North	Netherlands	Region Southwest	Region North
agriculture	305	32	149	460	51	217
shipping	66	n/a	n/a	138	n/a	n/a
drinking water	-	-	-	9	7	2
industry	1	1	-	4	3	-
total	372	33	149	611	62	219

3.2 Costs and benefits of policy actions in region North

Three policy actions were considered in region North: N-1) water demand reduction for flushing of sluices in the Afsluitdijk (the dam between the Wadden Sea and the IJssel Lake), N-2) increased water supply for the eastern part of region North through increased capacity of the inlet from the IJssel Lake as well as the supply canals, N-3) increased supply by an additional emergency supply route from further downstream the Rhine river towards the IJssel Lake (see Figure 2), which can be used during extreme drought events when the IJssel discharge is insufficient to timely refill the IJssel Lake buffer.

The evaluation of individual policy actions revealed a positive cost-benefit ratio for all actions in the Stoom scenario, but only policy action N-2 is already cost-effective in the reference (Table 4). Policy action N-3 will become cost-effective under the Stoom scenario. N-3 extracts water from Waal river which has a negative effect on shipping in Stoom of about 0.02 million euro per year, but this effect is much smaller than the positive effect of extra water supply for agriculture (2.16 million per year in Stoom). Because it is likely to become cost-effective before 2028 (opportune time to invest is 2021) and there are considerable positive non-monetized effects, it was advised to include it in the strategy. Policy action N-1 is not cost-effective before 2028, but it can be divided over several phases. Investing in one of the four sluices in the Afsluitdijk will reduce the water demand for flushing by 25%. This will reduce the costs while the risk reduction in the reference remains the same. This can be explained by the fact that the calculated water shortage in the reference is small and investing in four sluices would imply overdimensioning.

It was advised to build a strategy with all actions, but only one sluice (N-1) until 2028. Figure 5 shows the combined cost and avoided drought risk of this strategy for three points in time. The avoided drought risk in 2050 is based on the Stoom scenario

assuming all actions will be implemented (including the other three sluices). The lower estimate of avoided drought risk for 2050 is estimated at 7.06 million euro/year, equal to the avoided risk in the reference.

345 3.3 Costs and benefits of policy actions in region Southwest

Two policy actions were considered in region Southwest: S-1) increased supply by enlarging the capacity of the emergency supply route, and S-2) changed river distribution thereby increasing the discharge in the river Lek. This redistribution will reduce the risk of salt water intrusion for drinking water inlet points along the river Lek, but it will reduce water levels for economically important shipping routes. The evaluation of the individual policy actions revealed a negative balance for S-1

350 for both scenarios, and a positive balance for S-2 only under the Stoom scenario. S-1 reduces the monetized risk (agriculture and other effects) and has considerable positive non-monetized effects. These non-monetized effects were scored by the stakeholders and involve an increase in recreational value and supply reliability as well as a reduction in urban heat stress. It is however uncertain whether the sum of effects is sufficient for a positive evaluation. S-2 mainly reduces the risk for drinking water, but it is also conditional for S-1, since the alternative supply route extracts water from the Lek. Both actions increase

355 the risk for shipping by 0.10 to 0.20 million euro per year, depending on the scenario. Based on the evaluation of individual policy actions, it was advised to invest in S-2 in the coming period until 2028 (phase 1), because it is likely to become cost-effective (opportune time to invest was estimated to be in 2018), it has positive non-monetized effects, and it is conditional for S-1. It was further advised to postpone the investment in S-1. The resulting strategy thus includes implementing S-2 until 2028 and both actions for the period after 2028 (Figure 5).

360

Table 4 Costs, benefits, and opportune time to invest for the individual policy actions in region North (N-1 to N-3) and Southwest (S-1 and S-2)

ID	Policy action	Costs [million € year⁻¹]	Drought risk reduction [million € year⁻¹]		Benefit - Costs [million € year⁻¹]		opportune time to invest [year]
			Reference	Stoom	Reference	Stoom	
N-1	Demand reduction at all sluices in Afsluitdijk	4.8	2.19	9.45	-2.65	4.62	2029
N-2	Increase supply capacity at inlet point and main canals	0.8	4.86	18.25	4.11	17.50	2017
N-3	Increase supply by implementing an emergency supply route	0.2	0.01	2.14	-0.23	1.89	2021

S-1	Increase capacity of the emergency supply	1.2	-0.02	0.30	-1.22	-0.90	unknown
S-2	Redistribution of water towards the Lek river	0.2	-0.05	7.89	-0.28	7.66	2018

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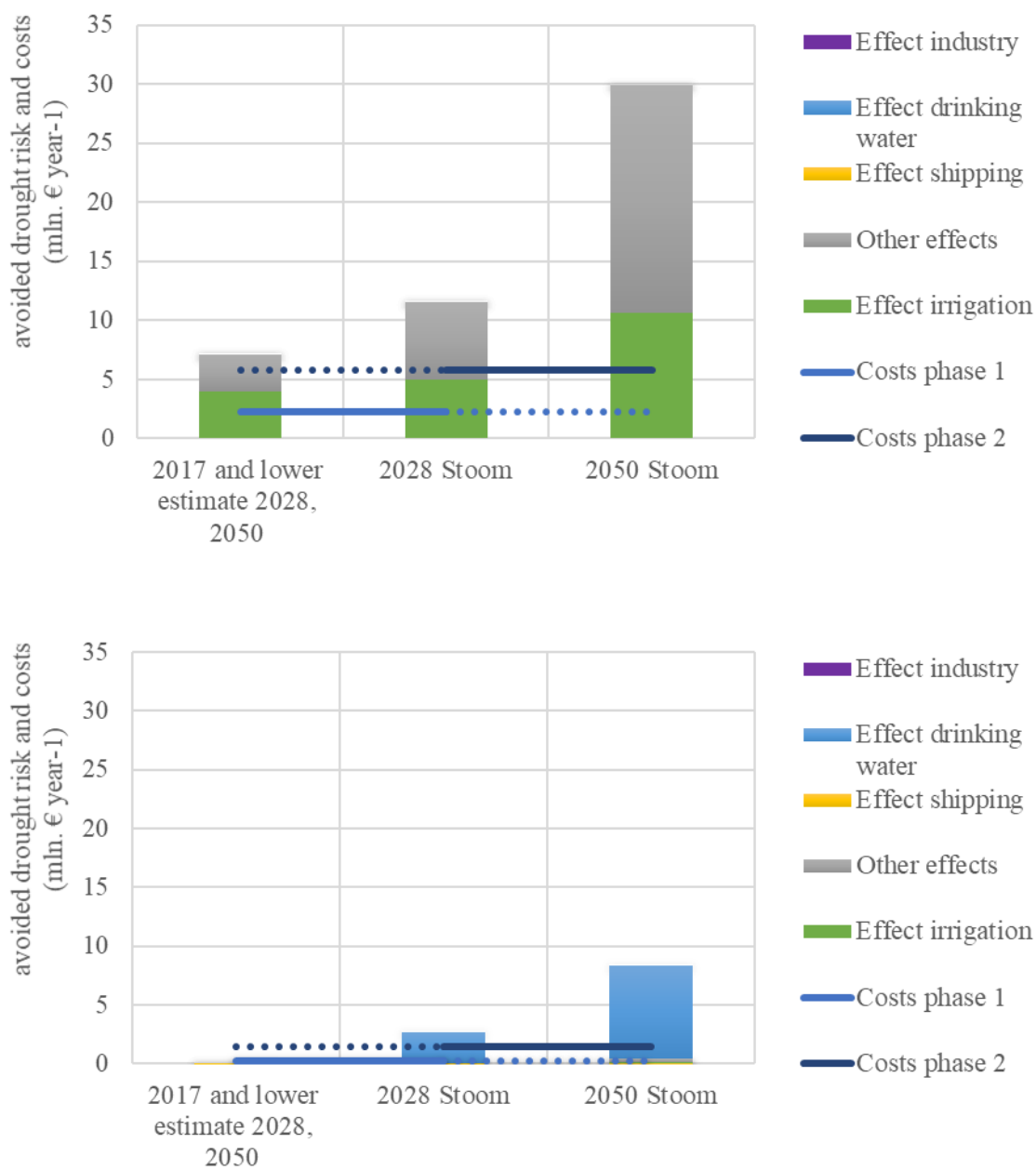
Figure 5 Comparison of costs and avoided drought risk of the advised strategy in region North (upper panel) and Southwest
370   (lower panel)

4 Discussion

4.1 Process-based drought impact modelling

This paper presents a framework for process-based, integrated drought risk assessment, and illustrates it with an application
375 for the Netherlands. The framework combines a time-series analysis with process-based hydrological models and impact
models as well as economic cost-benefit analysis to quantify the change in drought risk due to changes in climate, land use,
population, and policy actions. This dynamic simulation approach required the coupling of several impact models with the
hydrological simulation model. This approach acknowledges the complexity of drought propagation to societal impact, but it
is also data- and computation-intensive. The impact models use different market valuation techniques. For agriculture and
380 shipping we used market price methods to estimate direct costs from simulated production losses and resulting changes in
market prices. For drinking water and industry, we used the avoided cost approach to estimate the investments that would be
needed to avoid future cost to deal with more frequent or severe drought. Other effects, for which impact-models were not
available, were monetized by multiplying modelled water shortage with an assumed shadow price of water. This category
represents a range of drought impacts related to soil subsidence (carbon emissions, biodiversity as well as damage to
385 infrastructure and buildings), urban water supply (e.g. heat stress), and water quality (aquatic biodiversity). It is recommended
to further improve the impact calculation for drought-induced soil subsidence, by developing a subsidence model combined
with carbon prices for soil subsidence and replacement costs for buildings and infrastructure. It is further recommended to
develop a method to better incorporate the impact on ecosystems and biodiversity. Literature suggests that a more complete
understanding of how droughts impact ecosystems will lead to more effective plans and more sustainable communities
390 (Crausbay et al., 2017). However, valuation of ecosystem impacts is not straightforward and broadly accepted assessment
methods are lacking (Bartkowski et al., 2015; Victor, 2020). More research is thus needed to incorporate ecological drought
in integrated drought risk assessment.

Compared to index-based approaches to drought risk assessment (Carrão et al., 2016), we have shown that dynamic simulation
395 of drought risk allows the quantitative evaluation of costs and benefits of planned drought adaptation investments.
Additionally, the assessment provided insight into the distribution of drought costs and benefits over different waters users
and regions. For example, the emergency supply route for region North could further increase water shortage in region
Southwest, and adjusted distribution of river water significantly reduces the adaptation costs of the drinking water sector but
increases drought risk for shipping. Insight into distribution effects could be further improved, for example by including the
400 impact on farmers' livelihoods in addition to the quantified welfare effects for the Netherlands. This would require additional
information on the financial and economic resilience of the agricultural sector. Finally, the uncertainty in quantified benefits
due to the different future scenarios was translated to the opportune time to invest, which supported the decision on both short-
term actions and the long-term strategy.

4.2 Model limitations

405 Limitations of the hydrological model are related to the large spatial scale and level of detail of the processes that are included. Considering the purpose of the national-scale model, i.e. to assess long-term scenarios and strategies, some degree of uncertainty can be accepted. On the other hand, more detail is often required for the cost-benefit evaluation of short-term policy actions. The National Water Model is relatively complex with long computation times, which limits the number of strategy-scenario combinations of policy actions that can be explored on a national scale (Mens et al., 2021). It is recommended to

410 further improve the framework to better deal with different time scales for short-term actions and long-term strategies.

Besides uncertainties resulting from the chosen model-representation of the hydrological system and from the future developments assumed in the scenarios, uncertainties are introduced in the economic impact models and cost-benefit analysis. For example, the agricultural impact model does not include the impact of lower agricultural production and resulting price

415 changes due to simultaneous droughts in neighbouring countries. This effect may be significant. A recent inventory of farmers' income effects of the 2018 and 2019 drought in the Netherlands showed that for some crops and regions the price increase compensated the yield reduction (Van Asseldonk et al., 2021). Secondly, the cost-benefit analysis is carried out with a discount rate of 4.5%. For some effects a lower basic discount rate of 3% would have been more appropriate as advised by the Dutch Economic Planning Agency at the time of the study. A sensitivity analysis with a discount rate of 3% showed that the preferred

420 strategy did not change, although absolute cost-effectiveness of the policy actions slightly improved.

5 Conclusion

In this paper we developed and applied a process-based method for integrated drought risk assessment in the Netherlands. By coupling hydrological models with socio-economic impact functions, we were able to monetize the impacts of drought-induced water shortage for agriculture, shipping, drinking water production, and industrial water use, urban water supply, water quality,

425 and soil subsidence. The modelling framework allowed us to quantify how drought risks will evolve under various future scenarios, and to what extent proposed policy actions are able to reduce the risk against acceptable cost. We showed how this information can be used to support the development of adaptive strategies through determining opportune time to invest, considering the uncertainty about future developments in both water supply and demand. Because drought may have an impact on a wide range of water users, it is important to couple the socio-hydrological system model with economic impact models.

430 This allows exploring combinations of policy actions that aim at water supply increase, demand reduction, and impact reduction for the various sectors. Furthermore, the national-scale risk assessment provided insight into how costs and benefits are distributed over the different regions and sectors.

With the application we have shown that it is possible to use a process-based drought risk assessment method to support

435 decision-making under future uncertainty. Similar methods can be developed for other countries, but this requires hydrological

models and preferably process-based impact models for a variety of water use sectors that can be connected. If process-based impact models are not available for all sectors, we showed that using shadow prices is a useful alternative to monetize societal and ecological drought impacts.

Competing interests

440 The authors declare that they have no conflict of interest.

Author contributions

Marjolein Mens managed and supervised the model analyses and was responsible for the draft preparation.

Femke Schasfoort coordinated the impact model development and contributed to the original draft preparation.

445 Gigi van Rhee coordinated the societal cost benefit analysis and opportune time to invest and contributed to the original draft preparation.

Neeltje Kielen coordinated the stakeholder input and contributed to the discussion of results and editing the manuscript.

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