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Standard years for large-scale hydrological scenario simulations

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ABSTRACT

Scenario analyses are regularly characterised by a large number of degrees of freedom. It is usually unfeasible to perform sophisticated hydrological simulations with continuous long-term meteorological time series for all combinations of scenarios and adaptation strategies. To reduce computation time while retaining sufficient degrees of freedom, a so-called “standard year” has been developed. Average hydrological conditions according to simulations driven by this standard year should optimally resemble results from full 30-year simulations. Therefore, the standard year should optimally represent intra-annual variability. The objective of this paper is to explore how the errors, introduced by using standard years compare to natural variability. In addition, the standard year was also tested for future climate scenario simulations.

The standard year was constructed by perturbing meteorological quantities recorded during a selected meteorological year. The selection of this year was based on precipitation (P) and reference crop evapotranspiration (E_{ref}) in 1967, due to the good resemblance of the potential cumulative precipitation deficit in the Netherlands ($E_{ref} - \mathrm{P}$) during April–September in this year with the mean climatology. Subsequently, the 1967 precipitation and reference crop evapotranspiration was modified such that the standard year optimally captured intra-annual modes of variability. This is done by the application of spatially varying correction factors, which set the 2-monthly precipitation and reference crop evapotranspiration sums equal to climatology.

As a standard year only contains one year of meteorological data, it has no interannual variability by construct. As a consequence, extreme daily events are biased and small but systematic errors are simulated in the major hydrological budget terms. Surface runoff appeared oversensitive to the underestimated number of heavy rainfall events and was considerably underestimated by standard year simulations. The simulated climate change response of the major hydrological terms was reproduced very well and the error introduced by the standard year methodology appeared much smaller than the climate change signal.

1. Introduction

Scenario studies are popular tools to explore effects of climate variability at multiple time scales (Houghton et al., 2001). Careful selection of a representative number of scenarios is used to sample a wide range of possible conditions. Climate change scenarios (e.g. Van den Hurk et al., 2006; Hulme et al., 2002) are developed for this goal, and used for many assessments of adaptation studies (Jacob and Van den Hurk, 2008). However, the full evaluation of current and anticipated management options under even a limited number of climate change scenarios is still a major challenge, given the abundant number of degrees of freedom when considering all relevant interactions at a regional level. In a water managed country like the Netherlands hundreds of small scale watersheds exist, mutually connected and organised in regional structures with a wide variety of governing hydrological processes (proximity of rivers, spatial and temporal gradients of precipitation/reference evapotranspiration, land use, water management and soil type). For assessments of climate change impacts and adaptation options, reduction of the number of degrees of freedom is the rule rather than the exception.

Detailed hydrological assessments are routinely applied in the Netherlands. For this, a National Hydrological Instrumentation (NHI-projectgroep, 2008) has been developed. This instrumentation couples various existing models for the saturated and unsaturated zone and surface water distribution, connecting precipitation, actual evaporation, seepage, water management and groundwater at the plot scale using grid resolutions of up to 50 m. To put effects of anomalous episodes (like the 2003 heat wave;

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Beersma et al., 2004) into a climatological perspective, mean conditions over a 30-yr period are used as reference. Scenario studies are used to evaluate a wide range of water management practices under a wide range of present-day and future climate conditions. Tools that can rapidly generate quick assessments have been proven to be useful in many cases (e.g. Delta Commission, 2008). Running a continuous long-term rainfall series for a large number of scenarios is practically unfeasible.

Together with the need to reduce the number of degrees of freedom, and the large computer resources that are required for detailed hydrological applications, reference years or reference episodes are frequently used in scenario analyses. For instance for the design of hydraulic facilities, peak discharges are often estimated on the basis of simulations with design storms instead of continuous long-term time series (Froehlich and Pe, 2009; Vaes et al., 2002; NRCS, 2004). Also water resources and water quality studies regularly apply "test reference years" or typical years (Werkman and Jacobs, 2005; Wuyts et al., 2009). Obviously, a single year or episode cannot capture all relevant modes of variability, and has also lost the extreme tails of the probability distribution function (PDF) of meteorological quantities. Another drawback of a reference year is that a single year is only "typical" for a limited area and a limited number of time scales. In the Netherlands for instance, the 1973 precipitation sum is closest to the annual average precipitation, but 1967 has been identified as most typical with respect to the potential cumulative precipitation deficit ($E_{\mathrm{ref}} - P$) during April–September (Beersma et al., 2004).

Therefore, we have constructed and tested a standard year that reduces as many drawbacks as possible. The precipitation (P) and reference evapotranspiration (E_{ref}) as in the year 1967 are used as a basis and different scaling variants are compared. The main objective of this paper is to explore how the error in the hydrology introduced by using a standard year compares to (1) the interannual variability of the hydrological variables and (2) the climate change signal, imposed by a set of predefined climate change scenarios.

A well-defined standard year can be of great help in case of applications where sophisticated and computationally intensive models are used. Given the focus on the meteorological forcing in this study we use a relatively simple hydrological modelling framework, not accounting for variations in boundary conditions such as soil moisture and surface storage. Hydrological calculations, covering the entire Netherlands, are carried out using both a 30-yr historical meteorological forcing and a forcing from a standard year where the former is used as reference for the latter. The procedure is repeated for a number of future climate scenarios for 2050, and the climate change signals in both sets of calculations are compared. Three hydrological parameters (drainage, actual evaporation and surface runoff) are evaluated, covering a relevant range of modes of variability.

2. Methods

2.1. The hydrological modelling platform and forcing observations

The STONE2.1 instrumentation (Dutch acronym for Commonly Developed Nutrient Emission model; Wolf et al., 2003) is a general modelling framework originally designed for nutrient emission modelling, in which a multilayer model for the unsaturated zone and surface water bodies, SWAP (Soil–Water–Atmosphere–Plant; Kroes et al., 2002) and a deep groundwater model, NAGROM (National Groundwater Model; De Lange and van der Meij, 1994) are included. Precipitation (P) infiltrates the soil or is discharged via a surface water network directly, depending on precipitation intensity. Infiltrated water is partially evaporated/transpired, which is represented by the total actual evaporation (E_a) being the sum of transpiration, soil evaporation and evaporation from open and intercepted water. Transpiration and soil evaporation are related to the open water evaporation rate (E_o) and a prescribed, land use dependent and seasonally varying crop factor. This regulates evapotranspiration as function of available soil moisture. Daily values of P and E_o are forcings supplied to the hydrological model. Annual mean precipitation and open water evaporation averaged over the Netherlands are approximately 800 and 700 mm/yr, respectively. Surface runoff (R_s) takes place when precipitation cannot infiltrate into the soil or when the groundwater level reaches levels above the surface. Drainage (D) is the net water exchange between the groundwater reservoir and the open water bodies in a particular grid cell. Usually this transport is directed away from the soil into the open water bodies, but occasionally the reverse takes place. The modelling instrument accounts for water management as applied by the regional water boards. Prescribed target levels of open water bodies are automatically conditioned if enough water is available and tubes start to drain if a specific groundwater level is exceeded. Lower boundary conditions are governed by a prescribed annual sinusoidal cycle of seepage K with spatially varying amplitude (Massop et al., 2000), derived from long-term climatological integrations with NAGROM (De Lange and van der Meij, 1994). In the model the change of the total soil water amount V per unit time t is thus governed by

$$\mathrm{d}V/\mathrm{d}t = P - E_a - R_s - D + K \qquad (1)$$

The model is set-up at 6405 areal units (average area approximately 5 km^2) covering the Netherlands (36,000 km^2) entirely (Kroon et al., 2001; Van Bakel et al., 2007). SWAP uses subdaily integration time steps. The spin-up of each simulation consists of a two-year cycled simulation with the appropriate standard year meteorological forcing.

Daily precipitation (P) and reference crop evapotranspiration (E_{ref}) data for the reference period 1971–2000 are derived from routine meteorological observation networks of approximately 325 roughly equally spaced daily rain gauges (Heijboer and Nellestijn, 2002) and 35 automated weather stations. Daily reference crop evapotranspiration (E_{ref}) is calculated from temperature and global radiation according to Makkink (1957) – hypothetical rate of evapotranspiration of open actively growing grass land (8–15 cm) and no shortage of water. In this study, the seasonal variation in the relation between open water evaporation (E_o) and E_{ref} is neglected and E_o is defined as 1.25 E_{ref} (De Bruin and Lablans, 1998). P and E_o are spatially aggregated to 15 weather regions (on average about 2500 km^2 each), by simply averaging all precipitation station values within a region, and using a single E_o value located within the region. Every hydrological areal unit within a weather region receives the same meteorological forcing. This aggregation implies a loss of spatial and temporal variability in the precipitation forcing. Extreme values are smoothed, and the number of wet days at a given areal unit is artificially enhanced. The impact of these aggregation steps on the modelled hydrological balance terms is not investigated in detail. It may, however, be expected that the implications are smaller for relatively slow hydrological variables (actual evaporation, groundwater level, mean discharge) than for surface runoff terms responding to intense precipitation.

2.2. Construction of standard years

The construction of the standard year consists of two steps. First, a single year is selected in which the potential cumulative precipitation deficit ($E_{\mathrm{ref}} - \mathrm{P}$) during the growing season (1 April–30 September) optimally matches the 30-yr mean. This selection yields different years for different regions, but overall 1967 represents "average" conditions fairly well. Second, spatial and temporal structure was included. This is done by perturbing 2-month periods (Jan–Feb, Mar–Apr, ..., Nov–Dec) by a correction factor to match the 30-yr climatology of these 2-monthly values. The 2-month interval was chosen from a range of spatial and temporal averaging options and yielded a fair correspondence between the time series of several hydrological budget components (groundwater level, discharge, actual evaporation) between the

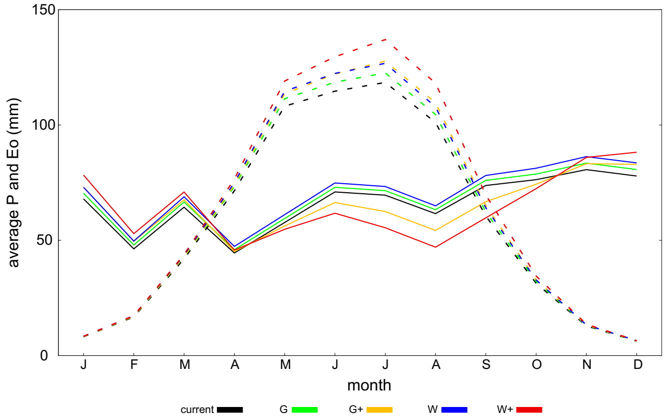

Fig. 1. Areal mean observed and projected mean annual cycle of precipitation (solid lines) and open water evaporation (dotted lines) in mm/month, for the reference climatological period (1971–2000, black line) and according to the four KNMI'06 scenarios.