1. **Project title**
SWM-EVAP: Smart Water Management in a complex environment: improving the monitoring and forecasting of surface EVAPoration

2. **Summary**
Water management in a densely populated area with a strong interplay between meteorological, hydrological and socio-economic drivers is a complex challenge. In order to guarantee the supply of water, and to avoid drought and flood damage an efficient system of weather forecasting, impact assessment and hydrological engineering is required. Even in a well-developed country as The Netherlands the current operational systems still lack skill and appropriate interconnectivity to ensure efficient water management at various time and spatial scales. Apart from precipitation, uncertainty in surface evaporation forms a strong bottleneck for water management at local, regional and (inter)national scales. The proposed research aims at enhancing the added value of available observations and medium- to seasonal range weather forecasts of particularly evaporation and related quantities (soil moisture, ground water, streamflow, lake levels). It will develop an upgraded monitoring and forecasting system for surface evaporation, using a scientific methodology to reduce existing gaps between different modelling and observational approaches. The system will be demonstrated in a case study for Lake IJssel, an area that is governed by the complex interactions determining water supply and demand.

3. **Principal applicant**
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4. **Co-applicants**
Ryan Teuling (WUR), Ruud Hurkmans (HKV)

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**Research proposal**

5. **Discipline code**
15.50.00 Atmosphere sciences
15.60.00 Hydrosphere sciences

Keywords: land surface, evaporation, hydrological modelling, water management, weather forecasting

6. **Compartment**

- Delta technology and Water technology

7. **Lay summary (in Dutch)**
Waterbeheer in een dichtbevolkt land is een complex probleem. Om verzekerd te zijn van voldoende zoet water en om problemen met droogte of overstromingen te voorkomen is een efficiënt systeem van monitoring, voorspelling en besluitvorming nodig. Zelfs in een ontwikkeld land als Nederland is de kwaliteit van de bestaande systemen, en de manier waarop ze op elkaar aansluiten nog verre van optimaal. Dit onderzoek richt zich op de ontwikkeling van een verbeterd monitoring- en voorspelsysteem voor verdamping en afgeleide grootheden als bodemvocht en waterstanden.

8. **Period of funding**
4 years (mar 2017 – mar 2021)

9. **Composition of the research team and the participating partners**

Please indicate the composition of the consortium and the research team in enclosed tabular form:

a) the principal applicant;
b) the co-applicant(s) from academia (optional);
c) the partners from academia and private and public sector;
d) the scientific and non-scientific staff who will carry out the research; if the names are not yet known, you can suffice by mentioning their positions.

Note: a principal and/or co-applicant cannot be the person carrying out the research.
Note: also indicate the persons whose contribution is intended as in kind matching.

Indicate, for all persons involved: their name, affiliation (university, institution, company, organisation, etc.), expertise and their role in the project. For the staff who will carry out the research, please indicate the duration (in months) and intensity/scope (FTE) of the requested appointment as well. In case of postdoc research you should indicate who will be the supervisor. In case of a PhD position the name of the promotor should be included.

<table>
<thead>
<tr>
<th>Consortium partners from academia and private and public sector</th>
<th>Name &amp; title</th>
<th>Affiliation</th>
<th>Expertise</th>
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<td>KNMI</td>
<td>Land surface data assimilation</td>
<td>scientific research</td>
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<td>5. Consortium partner</td>
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<td>HKV</td>
<td>IT, hydrological modelling</td>
<td>prototype service development</td>
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<td>6. Consortium partner</td>
<td>Dr D.M.D. (Dimmie) Hendriks</td>
<td>Deltares</td>
<td>Hydrological modelling, Expertise on groundwater and drought</td>
<td>link to operational implementation</td>
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<td>Deltares</td>
<td>Hydrological modelling</td>
<td>link to operational implementation</td>
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<td>8. Consortium partner</td>
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<th>Expertise</th>
<th>Duration (months)</th>
<th>Intensity (FTE)</th>
<th>Supervisor and/or promotor</th>
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<td>Land surface processes</td>
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<td>Dr Ryan Teuling, Prof Bart van den Hurk¹</td>
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<td>KNMI</td>
<td>Monitoring and prototype service development</td>
<td>36</td>
<td>1.0</td>
<td>Prof Bart van den Hurk, Dr Ruud Hurkmans</td>
</tr>
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</table>

¹ Ryan Teuling is currently in the Tenure Track system at Wageningen University and aims to have promotion rights before the end of the proposed PhD project. Alternatively, Prof. Remko Uijlenhoet of the Hydrology and Quantitative Water Management Group will act as promotor.
10. Description of the proposed research

Context: Smart Water Management (SWM)

In densely populated and hydrologically sensitive areas, such as the low-lying Netherlands, effective water management is of vital importance. Safety, economic development and the wellbeing of citizens depends critically on adequate management of river flows, storage reservoirs and extreme conditions related to intense precipitation and drought. An efficient water management system is required to guarantee ample access to high quality fresh water, and to avoid or alleviate negative consequences of droughts and floods.

Recently, a comprehensive Delta Programme has been designed and is being implemented. This programme ensures protection against hazards, availability of critical water resources, and robust governance of the water system in The Netherlands. Apart from implementation plans for reviewing, upgrading and expanding the water management infrastructure, a strong focus is put on improving the operational water management by optimizing current tools and practices. In the context of the program “Smart Water Management” (SWM) targeted actions are planned and implemented to improve the utilization and performance of current monitoring, forecasting and decision support systems. The lack of a comprehensive monitoring of important hydrological variables at all relevant spatial and temporal scales, the limited skill of forecasting systems at medium-range and seasonal time scales, and the ineffective use of all information in water management decision support all hinder an efficient near real-time management of water resources. SWM aims to improve the management of the physical water system without building new physical infrastructure, but instead by optimizing and enhancing current tools and procedures to increase the resilience of the country, to ensure cost-efficiency, and reduce emergency response to a minimum. This research proposal contributes to the objectives of SWM by improving monitoring, forecasting and tailoring of hydrometeorological information, in particular surface evaporation and soil water.

Scientific content and conceptual framework

Monitoring and forecasting of hydrological quantities such as precipitation, evaporation, river flow, soil moisture, lake levels etc. have seen a rapid development over the recent decades driven by both technological and scientific developments. Traditionally, the (land) surface interface is seen as a divide between hydrological and meteorological approaches. Hydrological monitoring and modelling systems are used to take elementary meteorological drivers (precipitation, temperature) driving hydrological budget equations in the soil/lake/snow system. Numerical Weather Prediction (NWP) usually takes a (land) surface flux as input to generate analyses and forecasts of the atmosphere, treating land surface properties merely as entities affecting these fluxes. As a consequence, divergent observational and model development has taken place, and strong simplifying approximations dominate the interaction between the hydrological and meteorological components at the (land) surface interface. Hydrological models frequently use a concept of regulated potential evaporation to incorporate the atmospheric influence on the surface water budget, ignoring active feedbacks and non-linear responses of the atmosphere. On the other hand, the level of sophistication of the representation of thermohydraulic processes in the soil/snow/lake in many NWP models often is relatively poor, constrained by either available observations, model resolution or physical theory. In spite of the methodological divergence, hydrological forecasting combining hydrological and meteorological applications is a very active field of research (Alfieri et al, 2012) leading to various (semi-)operational services in the area of flood and drought early warning, local and regional water management tools, and climate change impact studies (e.g. Reggiani & Weerts, 2008; Hurkmans et al., 2010).

The applicability of hydrometeorological monitoring and forecasting to SWM in the Netherlands is particularly limited by:

1) **Sub-optimal use of surface observations**: high quality high resolution datasets for precipitation (Overeem et al, 2010) alone do not guarantee a good knowledge on the current state of the hydrological system. Routine continuous area-covering observations of surface evaporation are nonexistent: sparse in situ data from lysimeters, meteorological towers or scintillometers lack spatial coverage, while remote sensing products are absent under cloudy conditions and rely on reliable ancillary information. Similar arguments apply to soil moisture. Combination of various novel and existing products, and assimilation of observations into routine NWP and/or hydrological applications will improve the quality of the monitoring of the hydrological budget;

2) **Lack of performance of the hydrometeorological forecasts**: although predictability of meteorological phenomena, and certainly of meteorological extremes is fundamentally limited, improvement of the predictability of hydrological extremes at various timescales can be expected

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from better initialization of forecast models, improved physiographic data, bias correction and improved post processing of probabilistic forecast outputs. Particularly the use of upgraded evaporation and soil moisture observations and representations in forecast models will improve the near-realtime forecasting of the surface hydrological budget, and the assessment of risk for extreme hydrological conditions at the weekly to monthly timescales;

(3) **Insufficient forecast output processing for water management decision support:** water management decisions rely on simultaneous assessment of information at a wide range of spatial and temporal time scales and of different nature. Monitoring products and forecast outputs need to be integrated in a multi-dimensional decision framework. Integration of all relevant information into a reference decision support toolkit is improving the quality of the information.

The key objective of this research proposal is to **improve the monitoring and forecasting of surface evaporation and related hydrological quantities** such as soil moisture, (ground)water levels and streamflow. For this it will focus primarily the spatial and temporal variability of surface evaporation including evaporation from large bodies of open water, reflecting the present and expected evolution of the surface hydrological budget and its impacts on risks for droughts and flooding.

![Integrated monitoring- and forecasting system for actual evaporation](image)

**Figure 1:** Conceptual picture of an optimized system for surface evaporation and soil moisture.

The key output of the project is a **unified monitoring and forecasting system** for surface evaporation and soil moisture, by integrating available products and tools (see Figure 1 for a schematic overview). The research will follow 3 branches. In the **Monitoring branch** available in situ and remote sensing data will be compared and integrated in order to develop an operational near-real-time area-covering evaporation monitor. Backbone of the service will be an offline hydrological model system (the Netherlands Hydrological Instrument NHI, www.nhi.nu) which will be forced using output from different evaporation algorithms driven by station data and satellite-derived surface radiation data, complemented by in situ data at well-equipped test sites for parameter optimization and calibration. In the **Modelling branch** a redesign of the modelling and data assimilation of the land surface component of the operational regional NWP model Harmonie will be carried out, leading to enhanced utilization of available information from both existing observations and (semi)operational offline land model simulations. Based on an improved initialization procedure, probabilistic forecasts of up to 2 days ahead will be produced and evaluated for skill in surface hydrological budget terms. The **Risk assessment branch** will explore options to improve outputs of operational probabilistic ECMWF (sub-)seasonal forecasts, by calibration and post-processing forecast products using existing climatological observational and model datasets. This will lead to improved discharge simulations from major river systems, entering the water balance of downstream areas and affecting the lead time of drought risk assessments.
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Approach and solution

The Monitoring branch

The Netherlands Hydrological Instrument (NHI), recently named LHM (Landelijk Hydrologisch Model), comprises a suite of coupled model components and is used by the Dutch federal water authority for scenario assessments and forecasting purposes (www.NHI.nu; De Lange et al., 2014). The operational application of the NHI functions within the operational Dutch federal water authority (RWSD, DelftFEWS) and is fed by operational Rhine and Meuse discharge (forecasts). Particularly for drought conditions it serves as a tool to evaluate and optimize drought mitigation measures.

The NHI consists of hydraulic models for surface water on the national scale (Distribution Model; DM) and on the regional scale (Mozart), which are coupled to a groundwater model (iModflow) that is fully integrated with an unsaturated zone model (MetaSWAP) and has a spatial distribution of 250x250m and a temporal scale of one day. The NHI is driven by (interpolated) meteorological data and discharge information for the Rhine and the Meuse, as well as information on local water management practices. Surface evaporation is an important term in the hydrological budget, and in NHI it is derived from a simple regulated potential evaporation formulation using locally tuned crop factors and an estimate of potential evaporation based primarily on global radiation data.

Alongside the NHI, several regional scale groundwater models have been developed that are used by regional water authorities for scenario assessments. Compared to the NHI, these models have more location-specific schematisations and a spatial distribution of 25x25m on a daily time step. An example of a regional is AZURE3, which comprises the areas surrounding Lake IJssel. The coming years, all regional models and their location-specific databases will be integrated in the NHI.

In the Monitoring branch the NHI models will be used as carrier for remote sensing and in situ evaporation information. A range of available data sets and methodologies will be compared and applied in order to construct high-resolution datasets of actual ET. These will be evaluated and integrated into NHI. Whereas many recently developed methodologies have previously seen application at continental to global scales, they have not been tested for water management application at national levels. In addition, the information contained in sparse available observations of actual ET (Elbers et al., 2009) over different land cover conditions (including urban areas, see Jacobs et al. 2014) by eddy covariance is not used for ET estimation. We will investigate the following methods:

- The current standard NHI procedure: this is based on the FAO crop factor method (Allen et al., 1998; 2005), where a reference evaporation is derived using a Penman-Monteith or Makkink method assuming well-watered conditions, and a time/space-varying crop factor represents effects of vegetation and soil moisture dynamics;
- Remotely sensed soil moisture/vegetation: routine data from e.g. passive and active microwave satellite data products instead of prescribed crop factors is used to modulate the FAO reference evaporation, including GLEAM4 (Miralles et al, 2011) and a multi-sensor microwave product (Enenkel et al, 2015);
- Random forest analysis: statistical relationships calibrated to local/regional conditions, is used to extrapolate high quality flux tower observations available in The Netherlands (Elbers et al., 2009, and the KNMI Cabauw site) in time and space using remote sensing products and meteorological conditions (similar to the Multi Tree Ensemble MTE by Jung et al. 2010) and applied by several others (e.g. Stegehuis et al. 2014)
- Inference of surface conductance and ET from relative humidity profiles (Salvucci and Gentine, 2013; Rigden & Salvucci et al, 2015) using routine observations and community data5;
- LSA SAF product6: data from this Satellite Application Facility are based on merging MSG data with ECOCLIMAP physiography into a Soil-Vegetation-Atmosphere-Transfer (SVAT) model, thus combining a physical model with high frequency remote sensing information.

An important uncertain element in current hydrological analysis is open water ET, which is surprising given the abundance of open water in The Netherlands (>20%). While useful algorithms exist for application in climate models (e.g. FLAKE see Lazhu et al. 2016), these have seen limited application in hydrological models due to the need to include lake temperature. We will monitor evaporation over Lake IJssel by scintillometry over 2 summer seasons and use the data to test and further develop open water routines for hydrological application. The routines will be used in conjunction with the methods described above to derive spatially continuous ET maps for The Netherlands.

3 www.azuremodel.nl
4 www.gleam.eu
5 http://www.metoffice.gov.uk/
6 http://landsaf.meteo.pt
Above mentioned methods will be used to estimate actual ET, and (cross-)validated using independent flux tower data. These routines will be used to create spatially continuous maps of daily ET at the 250 m scale for use in NHI. For the interpolation we will make use of tools developed by KNMI. In a final step, the gridded evapotranspiration estimates will be compared, evaluated, and the potential for creating a single ensemble-mean product (for which the weights can vary between gridcells) including open water evaporation will be investigated. Particular attention will be paid to effects of spatial and interannual variability, since different ET estimation methods deal with these aspects in fundamentally different ways. The result, an optimized multi-method surface evaporation product, used as forcing for NHI, will provide a strongly improved representation of the historical and actual hydrological budget within the NHI domain. Output from NHI simulations representing the hydrological state of the land surface will be used as input for the land surface data assimilation system of the Harmonie NWP system (next branch).

This work is the central topic of the PhD-position at WUR.

The Modelling and data assimilation branch

The Harmonie regional NWP system suffers from systematic biases in land surface hydrological characteristics, and consequently has a poor forecast performance for situations that are strongly related to these land surface properties, such as temperature during dry spells (see Figure 2). The upper six plots of figure 2 represent time series of the 3-hourly mean, the daily mean and the difference of the collocated observed and modelled latent heat flux (LH) at Cabauw and Loobos for the spring and summer of 2015. The observations at Cabauw are based on 10 min flux-tower data resampled to 3-hourly means, the cycle time for data assimilation. At Loobos observations are based on 30 min data. The +3H model forecast data is from ISBA in Harmonie v38h1.2. The plots show that the model forecasts of the LH flux significantly underestimate the observations as the model does not take into account the influence of the elevated water table. At Loobos the model fluxes are similar to the observations if not slightly higher. A spike is evident at Loobos on July 5th. The lower left plot in figure 2 shows the verification of the LH flux forecast as a function of range. The bias at Cabauw is severe and of similar size to the standard deviation of the random error. At Loobos the bias is small and slightly increasing with range. The random error is similar to that at Cabauw. The data assimilation has opposite effects on the bias at Cabauw and Loobos, but it has a negative effect (!) on the size of the random error. In general the systematic and random error are fairly constant during the forecast. The first of the maps on the lower right of figure 2 shows that the unrealistically large spike at Loobos on July 5th is part of a spatial structure associated with a passing weather front that day (not shown). The maps for the daily maximum near-surface temperature show that forecasted temperatures are higher than actually observed.

Figure 2: Illustration of surface evaporation related bias in the Harmonie NWP model system.
Upgrades to the model performance will be applied by (a) optimization and further development of the land surface module and land surface physiography and (b) assimilation of both conventional and non-conventional observations, making use of state-of-the art data assimilation and parameter optimization techniques.

A large part of the systematic bias in the land surface module of Harmonie is attributed to the use of a Force-Restore method (Noilhan & Planton, 1989) for soil temperature and moisture transport. This scheme is unable to properly represent the temporal dynamics and ingest the information from the assimilated data. A newer diffusion based thermo-hydraulic transport model for the soil (Decharme et al., 2011) is being implemented and evaluated. This scheme is more realistic in terms of soil water transport to and from the root-zone, soil water availability to vegetation of different types and the dispersion of soil moisture analysis increments from the data assimilation.

Currently the soil moisture state of the land surface model is adjusted based on a linear relation between soil moisture increments and near surface atmospheric temperature and humidity differences between the model and observations. This relation is an approximation and not valid if near surface temperature and humidity depend on conditions other than soil moisture, i.e. when surface fluxes are weak, such as during strong advection (wind), overcast conditions, precipitation and snow cover. A more direct approach to influence both the soil moisture state of the model and its evaporation output is through assimilating (surface) soil moisture observed by satellites (Draper 2007, Mahfouf 2010). These area-averaged observations retrieved from passive and active microwave sensors, such as AMSR, SMOS, SMAP and ASCAT have a 10 kilometre-scale footprint and are not sensitive to cloud cover.

In addition, analysis constraints will be provided by output from the NHI system. Particularly NHI-outputs of soil moisture and vegetation state are suitable quantities to update the state of Harmonie. Volumetric root-zone soil moisture estimates from the hydrological module in NHI (MetaSWAP) will be used to nudge the soil moisture state in Harmonie towards the analyzed state of MetaSWAP, employing Newtonian relaxation (Stauffer, 1990). Actual canopy transpiration and bare soil evaporation estimates can be used to verify analyzed and forecasted actual evaporation in Harmonie.

To overcome systematic inconsistencies between observational and modelling approaches, merging these information sources into the NWP model requires a new and more advanced assimilation system. This requirement also allows for the consideration of uncertainty in both the state of the model and in the soil and vegetation parameters simultaneously. Pragmatic assumptions on the dynamic evaluation of these parameters used in operational model implementations are highly uncertain and require reassessment. Traditionally parameter estimation (model calibration) and state estimation are treated separately, which leads to inconsistency between errors in the forecast and observations, subsequently leading to biased model predictions. Simultaneously estimation of model parameters and states may reduce systematic model biases and enhance predictive skill. Monte Carlo methods will be explored as a flexible means to handle uncertainty in simultaneous state and parameter estimation (Moradkhani 2005, Nie 2011). Changes in the similarity in character and strength of the soil moisture-evaporation feedback in the model compared to observational references (Dorigo 2010, Crow 2015) will be used as a measure of improvement relative to the current model performance.

This work package is closely linked to Harmonie land surface development effort currently in progress at KNMI. The current research proposal will focus on the assimilation of NHI model output into the Harmonie system, and its evaluation of forecast skill and consistency of the estimated hydrological budget terms.

The Risk assessment branch
Adequate assessment of the risk for hydrological hazards requires access to calibrated (probabilistic) forecasts with sufficient lead times that allow timely measures. For the water management of the Netherlands an appropriate forecast of the Rhine (and Meuse) discharge is essential. Forecast skill of meteorological forecasting systems deteriorate with lead time (Bauer et al, 2015), and at monthly to seasonal time scales only generic information can be provided about quantities that are predictable at this time scale due to a physical relationship with slow (and predictable) components in the atmosphere/ocean system, such as ocean temperatures, large anomalies in soil hydrology or snow/ice cover. Years of development of the ECMWF monthly and seasonal forecasting system have led to a gradual progress in forecast skill (Vitard et al, 2014), but for most of the Western European area this forecast skill is generally lacking after about 2 to 3 forecast weeks. However, slowly varying characteristics such as large scale droughts or persistent wet episodes generally are picked up better by these forecasting systems, particularly when systematic bias is removed and additional model output post-processing is applied.
In this study ensemble hindcasts of streamflow for the Rhine basin will be created using different evapotranspiration estimates from global datasets. This will lead to an assessment of the potential increase in predictive skill at longer lead times that can be attributed to improved representation of the land surface evaporation and soil moisture budget. Current research at WUR is already devoted on modeling the Rhine and Meuse basins using traditional hydrological methods to describe the surface evaporation forcing. In the current study this evaporation forcing will be replaced by available (global) datasets of evaporation at the 0.25 degree resolution, including GLEAM (Miralles et al 2011) and the MTE dataset (Jung et al, 2012). This study will provide the boundary condition for the Lake IJssel case, described in more detail below.

Application to Lake IJssel
The degree to which the research complies with request for upgrades in hydrometeorological information by the Smart Water Management (SWM) program will be demonstrated through a case study proposed by the SWM team, and carried out at HKV. Operational water management of the artificial Lake IJssel, with 1100 km² the largest lake in Western Europe, includes a seasonally varying target lake level, associated with a "safe operation margin" that allows to use Lake IJssel as a buffer to accommodate both high and low water levels and/or demands (see Figures 3 and 4). The lake level depends on influx from the IJssel-river (governed by the hydrological balance of the upstream Rhine river), regional water supply and demand from the areas surrounding the lake (and dependent on water consumption in that regional area), and lake evaporation/precipitation. The lake evaporation in particular is a large source of uncertainty which we address in the monitoring branch.

The case study will be addressed using the NHI model suite, in which newly developed components and data sets are integrated. The full model chain, that will be run operationally, comprises:

- Regional hydrological models surrounding Lake IJssel, where necessary supplemented by the national hydrological model;
- Regional surface water model;
- National surface water model, including Lake IJssel;

In the system the hydrological models discharge into or extract from the regional surface water model. The regional systems in turn can extract from or discharge to the national water system. The hydrological models calculate a water demand (largely based on evapotranspiration), which via the regional system extracts water from the Lake IJssel, or a water surplus which adds to the Lake IJssel. The regional models are preferred above the national model because they have more local knowledge incorporated. In addition, this has the advantage of the end-product being directly usable by the regional water boards.

The model chain will integrate the following data created during the project:

- Gridded ET datasets and improved open water evaporation for the Netherlands from the Monitoring Branch;
- Improved HARMONIE-evaporation forecasts from the Forecasting Branch; for this a reformulation of the NHI model structure has to be applied;
- Hindcast ensembles of streamflow at Lobith from the Rhine discharge evaluation carried out at WUR.

To assess the impact of the improved evaporation forecast, twin experiments with the default and updated model chain will be executed for a historical validation period. Based on measurements of
multiple variables (lake levels, discharges) we will assess the effect of the new evapotranspiration estimates.

The operationally coupled system will provide spatially detailed maps of water shortages, that can be converted to 'potential economic damage'. Several approaches exist to do this. A straightforward approach is to use the so-called 'HELP-tables' (STOWA, 2005). Alternatively, more sophisticated crop yield models can be used to assess the damage. One of the final products and the main outputs of the model suite will be a risk map: where does currently (and in the near future) the greatest damage occur, i.e., where should available water be allocated? This is of great interest to both the national and regional water authorities.

All models will have to be run operationally, and data flows to, from and between the models need to be properly configured. The Delft-FEWS package is widely used to accommodate such operational applications, and HKV is experienced in the configuration of those. The current operational setup of the NHI models is also configured in Delft-FEWS.

The expected effect of the upgrade of the surface hydrological budget instruments include:

- Lake IJssel: near-realtime monitoring of evaporation from the lake will lead to improved representation of lake dynamics
- the areas surrounding Lake IJssel: improved monitoring and short-range forecasting of precipitation, evaporation and soil moisture will lead to improved assessments and forecasts of hydrological discharge to Lake IJssel
- the river IJssel headwaters: both improved monitoring and short-range forecasting of the Dutch part of the IJssel area, and monthly-seasonal forecasting of the international headwaters (including the Rhine river area) will improve the assessment of risks for periodic or extensive low/high flow conditions.

This work will largely be carried out at HKV, and used as a demonstrator for the upgraded NHI.

Existing infrastructure

Routine observational products (remote sensing, in situ) and models

The main project partner KNMI will provide access to a wealth of meteorological observations and models, including: the ECMWF monthly/seasonal forecast archive, the Dutch national archive of meteorological observations, the Cabauw experimental site including long-term eddy covariance data, the Harmonie model and the HTESSEL offline land surface model. In addition, KNMI provides access to the high performance cluster (HPC).

Operational System for monitoring and forecasting water resources (RWsOS Waterbeheer)

The available data and models will be coupled in a stand-alone version (i.e. copy) of the operational forecasting for monitoring and forecasting of water resources, RWsOS Waterbeheer (Figure 4), used by the in-cash contributing consortium partner RWS-WVL. RWsOS Waterbeheer is an implementation of Delft-FEWS. Delft-FEWS is freeware and developed and maintained by Deltares and it is already used widely both nationally and internationally. We will use a copy of the operational systems to work with and implement the improved evaporation estimates. This will also make it easy to compare our results with the current operational system and evaluate skill improvements.

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7 [http://help200x.alterra.nl/](http://help200x.alterra.nl/)
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Team structure and collaborations

Project partners
KNMI is the central partner in the project. The postdoc will be employed by KNMI, and both the postdoc and PhD student will spend part of their time at KNMI. During the practical work, the postdoc will be based at HKV. The PhD student will be employed by WUR, but will spend part of the time at KNMI to interact with Bart van den Hurk (co-promotor and project PI). Daily supervision at WUR will be the responsibility of Ryan Teuling. The PhD student will be part of a larger group (>10) of PhD students in the Hydrology and Quantitative Water Management Group, and is expected to benefit from the interaction between students in different phases. In addition, the central role of KNMI is strengthened by the involvement of John de Vries, who will work on the project as part of his PhD research (in kind contribution by KNMI, see Budget).

The postdoc will be co-supervised by Dr. Ruud Hurkmans at HKV. It should be noted that close ties exist also between HKV and the Hydrology and Quantitative Water Management Group, since Ruud Hurkmans obtained his PhD in this group. Both the postdoc and PhD student will spend a smaller part of their time at Deltares, which will allow for efficient collaboration with project partners Dimmie Hendriks and Albrecht Weerts on the use of NHI and data assimilation.

Routine collaborations with external partners

- Scientific experts: The WUR PhD candidate will have several extended visits to labs that have developed one of the ET methods: Ghent University (GLEAM, collaboration with Diego Miralles), Boston University (ETRHEQ, Guido Salvucci), and MPI Jena (Random forest-based upscaling of eddy covariance data, Martin Jung). Good contacts and/or routine collaborations exist with all of these groups.
- There are ongoing collaborations with Smart Water Management partner board, led by Bas de Jong (RWS-WVL), likely leading to an additional collaboration between RWS and HKV outside the scope of this proposal.
- Both PhD and post-doc will be stationed parttime at Deltares during the period they are actively working with the NHI, regional model and/or RWSoS. They can make use of Deltares’ hydrological tools and software, as well as expertise and guidance by dr. Dimmie Hendriks and prof. Albrecht Weerts

b) Economic and/or societal value, utilisation potential

Economic and societal value of the research
The proposed research will address provide an important contribution to water management in delta regions through improved representation and forecasting of evaporation. For The Netherlands and in particular for the northern provinces, water supply during long dry spells and severe droughts depends critically on the management of water levels in other parts of the country, which in turn depend heavily on hydrologic forecasts in which evaporation is a key source of uncertainty. By improving water supply during drought, a fundamental service not only for drinking water supply but moreover for agricultural production, significant yield losses and associated damage can be reduced. The proposal thus contributes to optimizing the adjustment between water supply and demand of precious fresh water resources, and it does so by making more efficient use of current expertise and infrastructure.

Applicability of results
The project results will have direct application at RWS and Waterboard level, which is also reflected in the strong in-cash and in-kind contribution of the different partners. The project will not only improve the representation of accuracy of evaporation in models used for operational hydrological forecasting and water management, it will also generate knowledge and datasets that will see application in other sectors both nationally and internationally. Only few studies have focusses on the parameterization of open water evaporation, and this project can contribute to the management of open water bodies globally. The high-resolution gridded datasets of actual evaporation are expected to see widespread application in hydrological analysis and modeling.

Team experience with application-oriented research
The projects partners have a strong track-record in application-oriented research. As a private company, HKV critically depends on maintaining the link between innovation and application. HKV has a strong track record of knowledge-intense consultancy contracts, and has a strong network in the regional and national water governance circuit. For KNMI, operational NWP using a suite of techniques and methods is
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core business. KNMI is also involved in many application driven projects for water authorities at regional and national levels. While the primary focus of the HWM group at WUR is on fundamental research, there are strong ties with users of hydrological knowledge and models. As an example, the group has recently developed a hydrological model (WALRUS, see Brauer et al. 2014) for application in Delta- and lowland regions, which is now being further developed in close collaboration with, and funded by, users from different water boards.

Contribution to themes described in the call

Our proposal contributes to the Watermanagement, Water and ICT, and Sustainable Delta cities KICs (Knowledge and Innovation Clusters). Within the first cluster, Watermanagement, our proposal contributes specifically by:

- Developing and improving effective instruments for monitoring of hydrological budgets to be used in decision support systems.
- Developing a Rapid Assessment Tool for surface evaporation (ensured by taking NHI as integrating platform)
- Optimizing water management, including exploring options for land surface storage and open water storage as management options

Within the second cluster, Water and ICT, our proposal contributes specifically by:

- Extension of the current NHI implementation with improved surface evaporation
- The coupling of regional and national high-resolution datasets and models
- Providing public access to evaporation datasets produced in the project

Within the third cluster, Sustainable Delta cities, our proposal contributes specifically by:

- Improved management of fresh water resources and assessment of evaporation over cities.

c) Cohesion and focus of the project

The project is targeted at improving the monitoring and forecasting capability of both hydrological and meteorological features in order to improve water management under water scarce conditions. It makes full use of the complementary functions of the involved modelling systems, and synergetic expertise of the associated institutional experts. We need KNMI for their operational Harmonie operation, WUR for their knowledge development track record, monitoring experience, and experience in PhD supervision, HKV for their expertise in running operational systems and the network with stakeholders, and Deltares for their knowledge and management of NHI. The proposed work also builds on existing ties and collaborations between the different institutes.

The project will be managed by KNMI, which will allow for a further strengthening its position as a national key player in evaporation monitoring and forecasting. Extensive collaboration, both in the framework of the proposed work as well as ongoing projects, ensures effective communication between the partners. For example, consortium partner Albrecht Weerts has a 0.2 FTE appointment as Personal professor in Wageningen in the group of co-PI Ryan Teuling. The PhD student will have offices both at Wageningen University and KNMI, enabling efficient communication between partners. The same holds true for the PostDoc, who will have offices at public partner KNMI and private partner HKV. Ryan Teuling will also supervise a PhD student working on related topics directly funded by RWS, who is envisioned to collaborate closely the proposed PhD student.

The project will have yearly progress meetings at KNMI, in addition to a kick-off meeting, at which all project partners will be present. In the final 2 years of the project, this meeting will be combined with a public seminar on the role of evaporation in hydrological modeling and forecasting. Of key importance is the monitoring of the progress of the PhD student. At Wageningen University, PhD students face an official go/no-go evaluation after 15 months, which is based on output over the first period. At the Hydrology and Quantitative Water Management Group, PhD students are expected to present after 15 months: a) a PhD proposal approved by the graduate school, b) a draft manuscript of the first study.

Reporting of the project results will primarily take place via peer-reviewed scientific publications in open-access journals such as Hydrology and Earth System Sciences. Additional dissemination of projects results will take place via news items on partner websites (i.e. WUR, KNMI), in particular in case extreme dry conditions will occur during the project which can illustrate the potential of the products and methodologies.
References
11. Work programme

1 fulltime PhD and 1 postdoc positions supplied by the NWO program will ensure continuity and interlinkages. 1 Staff member at KNMI will be devoted to the NWP development and evaluation, and not be funded through the NWO program. One technician (Pieter Hazenberg, working for the Hydrology and Quantitative Water Management Group at WUR) will assist with the monitoring of open water evaporation over Lake IJssel and will be funded by the programme.

The table below lists the main activities and the periods over which these activities will take place.

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</table>

12. Brief curriculum vitae of the principal applicant and the co-applicant(s)
Curriculum Vitae

Name: Bartholomeus Johannes Josephus Martinus van den Hurk
1st Affiliation: Royal Netherlands Meteorological Institute, KNMI
PO Box 201
3730 AE De Bilt
The Netherlands
hurkv@knmi.nl
Position: Department Head R&D Weather and Climate Modelling

2nd Affiliation: Institute for Environmental Studies (Vrije Universiteit Amsterdam)
De Boelelaan 1085
1081HV Amsterdam
The Netherlands
Position: Professor

Bart van den Hurk has a PhD on land surface modelling, obtained in Wageningen in 1996. Since then he has worked at the Royal Netherlands Meteorological Institute (KNMI) as researcher, involved in studies addressing modelling land surface processes in regional and global climate models, data assimilation of soil moisture, and constructing regional climate change scenarios. He is strongly involved with the KNMI global modelling project EC-Earth, and is co-author of the land surface modules of the European Centre for Medium Range Weather Forecasts (ECMWF). Since 2005 he was part-time professor "Regional Climate Analysis" at the Institute of Marine and Atmospheric Research (IMAU) at the Utrecht University, and from 2014 holds a chair "Interaction between climate and the socio-ecological system" at Institute for Environmental Studies (IVM) at VU University Amsterdam. There he teaches masters students, supervises PhD-students and is involved in several research networks. Between 2005 and 2010 he was chair of the WCRP-endorsed Global Land-Atmosphere System Studies (GLASS) panel, between 2006 and 2012 member of the council of the Netherlands Climate Changes Spatial Planning program, and since 2008 member of the board of the division "Earth and Life Sciences" of the Dutch Research Council (NWO-ALW). He is convenor at a range of incidental and periodic conferences, and editor for Hydrology and Earth System Science (HESS). At KNMI he was member of the Coregroup Institute Reorganisation between 2011 and 2013. He now leads the R&D department on Weather and Climate modelling at KNMI. He is also leading the European Horizon 2020 project IMPREX (Improving Predictions and Management of Hydrological Extremes, 2015-2019).

PhD thesis

Selected papers (Scopus H-index 2015: 39).


CURRICULUM VITAE  Dr. Adriaan J. (Ryan) Teuling

Current position
Assistant professor (TT), Hydrology and Quantitative Water Management Group, Wageningen University

Professional experience/employment
Ryan Teuling received both his MSc (2002) and PhD (2007) degrees from Wageningen University. Both degrees were obtained with distinction (cum laude). From 2007 to 2010, he worked as a postdoc in the Land-Climate Interactions group of Sonia Seneviratne at the Institute for Atmospheric and Climate Science (ETH Zurich) on the interaction between land surface hydrology and climate. This postdoc was partly financed through a NWO Rubicon grant. In 2010, he received a NWO Veni grant for his research on the effect of forests on heatwaves. At the same time, he started as a tenure track assistant professor at Wageningen University. His main research topics are 1) land-atmosphere interactions from diurnal to decadal timescales, 2) flood and drought synthesis at the catchment scale, and 3) topographic signatures on hydrological processes. Ryan Teuling has published 54 peer-reviewed papers, among which several first author and co-author papers in highly-ranked journals (Nature Geoscience 3x, Nature Climate Change, Nature Communications, Scientific Reports, Geophysical Research Letters 13x). He is involved in the supervision of several PhD students (in Wageningen as well as in collaboration with LSCE in Gif-s-Yvette, France and MPI Jena, Germany) and one postdoc. In addition, he supervised a total of 45 MSc students for their thesis or internship. In addition, Ryan Teuling has been active a convener of a successful session at the yearly General Assembly of the EGU, as a contributing author to the 5th assessment report of the IPCC (WG1), and as a regular reviewer for over 35 different journals and funding agencies. Since 2016, he is an associated editor with Vadose Zone Journal with the specific task to increase the number and quality of evapotranspiration-related papers.

Key publications for this proposal


Citation overview

<table>
<thead>
<tr>
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<th>Web of Science</th>
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</table>
13. Publications
Selection of publications. Please specify a selection of up to 10 key publications in total by the applicant and co-applicants.


8. **Teuling, A. J.;** S. I. Seneviratne; R. Stöckli; M. Reichstein; E. Moors; P. Ciais; S. Luyssaert; **B. van den Hurk;** C. Ammann; C. Bernhofer; E. Delpierre; D. Gianelle; B. Gielens; T. Grünwald; K. Klumpp; L. Montagnani; C. Moureaux; M. Sottocornola & G. Wohlfahrt (2010), Contrasting response of European forest and grassland energy exchange to heatwaves. *Nature Geosci.* 3(10), 722-727, doi:10.1038/ngeo950.


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Financial details

14. Research Budget
Please use the table 'Project Budget' for the description of the personnel and material resources required for the entire duration of the total project. It's important to take good note of 'What can be applied for' (call paragraph 3.3).

Please also provide (in a separate text box with reference to entries in the table):
- a) a specification for all the requested material resources;
- b) a description of the contribution from the partner(s).

It is possible to apply for NWO grants up to €500,000 (Maritime technology) or €550,000 (Water technology and Delta technology). Given the obligatory matching by private and/or public partners, the NWO financing is maximally 90% of the whole project.

The budget can be composed of three different types of funding: 1) the NWO grant applied for, 2) cash contributions from consortium partners, and 3) in-kind contributions from consortium partners. All three types of funding can only include costs and contributions directly and exclusively related to the research proposal. Cash contributions have to be settled with NWO. After receiving cash contributions, NWO will designate the funds to the applicant(s).

Personnel costs are funded in accordance with the most recent VSNU–NWO contract, which you can find on [http://www.nwo.nl/financiering/hoe-werkt-dat/Salaristabellen](http://www.nwo.nl/financiering/hoe-werkt-dat/Salaristabellen). The maximum amounts are: PhD 4 years - €209,474; postdoc 3 years - €207,663 (amounts as of 1 July 2015, including €5,000 bench fee). Costs to be covered by the NWO grant and the cash contributions from consortium partners must both adhere to the VSNU–NWO contract. In-kind contributions must follow the rules explained in the call document entitled "Regulations governing in-kind contributions". For all personnel costs, please indicate (1) the nature of the proposed appointment (postdoc, PhD student, technician), (2) the duration of the appointment and (3) intensity/scope of the appointment (in FTE).

For each cost category (personnel and material) please indicate the funding recipient, i.e. the partner (either principal applicant or one of the co-applicants) that will receive the NWO funding.

Statements

15. Statements by the applicant

YES I endorse and follow the Code Openness Animal Experiments (if applicable).

YES I endorse and follow the Code Biosecurity (if applicable).

YES By submitting this document I declare that I satisfy the nationally and internationally accepted standards for scientific conduct as stated in the [Netherlands Code of Conduct for Scientific Practice 2012](http://www.nwo.nl/nl/financiering/hoe-werkt-dat/Salaristabellen) (Association of Universities in the Netherlands (VSNU)).

YES The consortium partners have read the NWO Framework for Public-Private Partnerships and will adhere to this if the proposal is awarded.

YES I have completed this form truthfully.

Name: Prof. Bart van den Hurk  
Place: De Bilt  
Date: 06-06-2016

Please submit the application to NWO in electronic form ([PDF format is required!](http://www.nwo.nl/nl/financiering/hoe-werkt-dat/Salaristabellen)) using the ISAAC system, which can be accessed via the NWO website (isaac.nwo.nl). The application must be submitted from the account of the main applicant. For any technical questions regarding submission, please contact the ISAAC helpdesk ([isaac.helpdesk@nwo.nl](mailto:isaac.helpdesk@nwo.nl)).
If the project is carried out at several universities or knowledge institutions, and you want the project to be split into several sub-projects if granted, you must submit the same application multiple times (e.g. 2 sub-projects: submit the same application 2 times).
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<tr>
<th>Project budget (EUR)</th>
<th>Total costs</th>
<th>NWO grant</th>
<th>Cash contribution will be added to NWO grant</th>
<th>In kind contribution</th>
<th>Funding recipient * Principal applicant or co-applicant(s)</th>
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<td>Personnel costs</td>
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<td>Material costs</td>
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</table>

* Only applicable for larger projects (2 or 3 PhD students/post-docs). Please indicate to which partner (applicant, co-applicant 1 or co-applicant 2) the budget applies. If the project is awarded funding will be split over the applicant and co-applicants accordingly.
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**Specification of the requested material costs:**  

**Travelling costs PhD + AJT + technician:** This budget covers the traveling costs for the PhD student to international conferences and one national conference or summer course (once a year, total 2 kEuro p/y), as well as extended visits to Jena, Ghent, and Boston (see proposal, total 6 kEuro). One international conference visit (2 kEuro) is planned for co-PI AJT. The remaining budget (4 kEuro) covers for the costs of traveling by the PhD student, AJT and technician Pieter Hazenberg to the experimental site at the IJssel-lake, lodging, and rent of boot depending on selected location of scintillometers.  

**Travelling costs Postdoc:** Budget for attending one large international conference (e.g. EGU, AGU) and one national per year, estimated costs 2 kEuro per year for 3 years.  

**Description of the contribution from the matching partner(s):**  

**NHI support:** Deltares will assist with implementation in a standalone version of RWsOS Waterbeheer (including the assimilation with OpenDA) for offline testing and reforecasting to measure skill improvements. Deltares will also contribute to scientific publications as a result of these activities. The contribution is equivalent to 300 hours, which will be split between Albrecht Weerts and Dimmie Hendriks.  

**KNMI:** The in kind contribution is 500 man hours from the PhD-work of John de Vries representing a value of € 50,000.  

**HKV:** The in kind contribution is 37.5 man days representing a value of € 30,000. and will mainly be delivered by Durk Klopstra.  

**WVL:**
Letter of support to the NWO Topsector Water call 2016

Dear,

Deltares is very much interested in the project "SWM-EVAP: Smart Water Management in a complex environment: improving the monitoring and forecasting of surface evaporation". This project aims at improving estimation of actual evaporation which plays a large role in drought periods and improving water management, which will be beneficial for the The Netherlands, but the knowledge developed can also be used in other delta areas worldwide.

With this letter I support this project. When granted, Deltares will contribute in kind to this project. The value of this contribution is 40 keuro. We will work in close collaboration with both the PhD and Postdoc.

When the project is granted I would be very happy to become a consortium partner and attend the consortium meetings as indicated in the proposal, to guide the project in order to ensure its impact is maximised, and to help establish potential end uses of the project results.

Yours sincerely,

ir. C. Blom
Director Inland Water Systems
Dear Professor Van den Hurk,

HKV is very much interested in the project "SWM-EVAP: Smart Water Management in a complex environment: improving the monitoring and forecasting of surface evaporation". This project aims at improving estimation of actual evaporation which plays a large role in drought periods and improving water management, which will be beneficial for The Netherlands, but the knowledge developed can also be used in other delta areas worldwide.

With this letter I support this project. When granted, HKV will contribute in kind to this project. With this in kind contribution, being a boutique consultancy firm, we specifically aim to bridge the gap between the scientific results of the SWM-EVAP project and the requirements, both in the field of policy making and operational water management, of the Dutch Water boards and Rijkswaterstaat, being the end-users of evaporation data. The value of this contribution is 37.5 man days representing a value of € 30,000.=. The in kind contribution will mainly be delivered by Durk Klopstra. He will work in close collaboration with both the PhD and Postdoc.

When the project is granted I would be very happy to become a consortium partner and attend the consortium meetings as indicated in the proposal, to guide the project in order to ensure its impact is maximized, and to help establish potential end uses of the project results.

Yours sincerely,

Durk Klopstra
Director
Date 21 June 2016
Subject Letter of support to the NWO Top Sector Water proposal

Dear Dr. Pauw,

As principal applicant I would like to express the keen interest of KNMI in the project “SWM-EVAP: Smart Water Management in a complex environment: improving the monitoring and forecasting of surface EVAPoration”. The project provides the opportunity to remove inconsistencies in, and improve the quality of the monitoring and forecasting of surface evaporation and related hydro-meteorological quantities. The realization of a unified monitoring and forecasting system that includes risk assessment is expected to benefit the decision-making process in operational water management.

By means of this letter KNMI confirms that it will supports this project, when granted, with an in kind contribution of 500 man hours for KNMI staff that will be involved in the required upgrade of the land surface model in Harmonie and in the assistance of the PhD student and post-doc in meteorological aspects of their research. The contribution is spread over the duration of the project (4 years) and represents a value of 50 000 euro.

When the project is awarded KNMI will be happy to lead the consortium in close cooperation with its partners as well as organise consortium meetings and public seminars as indicated in the NWO Top Sector Water proposal.

Yours sincerely,

Prof. Dr. B.J.J.M. van den Hurk
VU University / Lead R&D Weather and Climate Models at KNMI.
Dear Prof Van den Hurk,

Rijkswaterstaat is interested in the project "SWM-EVAP: Smart Water Management in a complex environment: improving the monitoring and forecasting of surface EVAPoration". The Delta Decision on Freshwater have led to the programming of a number of new measures, knowledge issues, further studies and pilot projects, the elaboration of new tools and instruments and, especially to preparatory activities to be able to programme and implement new measures. The measures and studies have been brought together in the Delta Plan on Freshwater. Smart water management (SWM) is one of those studies and focused on water shortages, flooding and energy use in the operational water management. It is thereby not focused on new infrastructure measures, but to make better use (optimization) of the existing water infrastructure.

The proposed research focuses on enhancing the added value of available observations and medium- to seasonal range weather forecasts of particularly evaporation and related quantities. This is important for the determination of the water demand and hence for SWM.

With this letter I support this project. When granted, Rijkswaterstaat will contribute in cash to this project. The value of this contribution is 40,000 euro, spread over the duration of the project (4 years). When the project is granted Rijkswaterstaat will be happy to become a member of the user committee as indicated in the NWO Topsector Water proposal.

Yours sincerely,

directeur Veiligheid en Watergebruik
Rijkswaterstaat Water, Verkeer en Leefomgeving

R. Allewijn