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Water supply network model for sustainable industrial resource use a case study of Zeeuws-Vlaanderen in the Netherlands

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ABSTRACT

Matching regional water supply and demand can be improved by allocating local renewable water resources through decentralized water supply networks (WSNs). The feasibility of decentralized WSNs depends on the costs for the required pipeline infrastructure. The lowest costs for pipeline infrastructure depend on the local landscape characteristics. We present a model that designs decentralized WSNs to supply water with regional supply sources. The objective of the model is to include the effects of landscape characteristics on infrastructure costs and to minimize overall WSN costs. We tested the model on a case study in the fresh-water scarce region of Zeeuws-Vlaanderen in the southwestern part of The Netherlands with known (hydro)geological, geographical and climate data. The model was tested to supply a large industrial water user with groundwater resources operated within sustainable yields. The generated WSNs cover a demand between 0.5 and 5.5 million m^3 $year^{-1}$. Between 1 and 12 supply locations are needed to cover the demand. The pipeline infrastructure needed ranges from 25.1 to 114.5 km. The model determines the optimal pipeline route, the amount of water flowing over each pipeline segment, and reveals if a small increase in demand causes a relatively large increase in costs. The results can be used to determine if water transport is preferred over other water supply options, such as wastewater re-use or desalination of saline water resources.

1. Introduction

Many industrial processes are dependent on the availability of water; in some cases for the product itself, but often mainly for the production process. Industries largely rely on centralized water supply systems due to the general policy in the twentieth century to create large-scale infrastructure projects [1]. Relying on large-scale centralized systems introduces uncertainty in water supply due to the rising costs and changing availability of water resources [2–4]. Projections show that rainfall patterns will change around the globe [5,6], that the quality of water may severely diminish due to salt water intrusion in coastal areas [7], and that human alterations to watersheds affect the quantity and or quality of the available water resources [8]. Groundwater resources are often used in an

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unsustainable way, depleting water supplies and possibly leading to land subsidence and/or enhancing salt water intrusion [9]. New approaches are needed to use the available water resources in a sustainable way [10–12]. Many efforts within industry, a sector accounting for 19% of global water withdrawals [13], focus on reducing the water demand by increasing the process efficiency and by reusing or recycling water [14]. While these efforts are certainly needed, the remaining demand still needs to be supplied by extracting water from natural systems.

Alternative local sources of water, such as wastewater, harvested rainwater, surface water, and groundwater can be used to reduce dependency on remote centralized sources. The use of decentralized water supply systems is an option to alleviate future water scarcity and to deal with increasing infrastructure costs [15]. The use of decentralized networks provides flexibility to adjust water quality to the needs of the user [15] and has the potential to increase resilience when supply is diversified [16]. A comprehensive overview of water supply network design and optimization methods was created by Mala-Jetmarova [17].

Irrespective of the form of distribution, central or decentral, local extractions need to adhere to the sustainable yield of the water resource, avoid subsidence due to groundwater extraction, and prevent enhancement of salt water intrusion. The use of methods to assess all these aspects for the overall sustainability of industrial water use is currently still limited, but is needed to ensure water use remains within the limits of local water systems [18]. The appropriate design and evaluation of a water supply network (WSN) based on many small scale water resources requires a model based approach. Several models exist that can be used to evaluate the regional supply and demand of conventional and alternative water resources such as: (a) the Water Evaluation And Planning System (WEAP), which can be used to evaluate water management scenarios based on a water balance accounting principle [19], (b) the WaterCress model, which simulates the quantities and qualities of water flowing through a catchment area at equal continuous time-steps [20], (c) the RIBASIM model which links hydrological conditions with the specific water users in the basin [21], (d) or the model developed by Nobel and Allen which matches and optimizes the water reuse possibilities between industries based on their location [10]. These models are useful to evaluate and optimize the water supply and demand system when the water transport infrastructure is already present and the water resources to be used are defined. A modelling approach which can select the optimal configuration of supply locations, based on a WSN for which the transport infrastructure does not yet exist, was still lacking. Such a model can assist in a transition towards regional water self-sufficiency based on local renewable water sources.

A transition towards the use of local water resources requires an evaluation of the optimal network for water transport. Transporting large quantities of water usually occurs through pipelines. Pipeline construction costs depend on the local conditions and landscape features, such as land use, slope, required excavation depth, and subsurface soil type [12,22]. The objective of the model we present is to generate the lowest cost WSN based on the local landscape characteristics and the available renewable water resources. We combined geographic information system (GIS) methods, graph theory [23], and mixed integer quadratic programming. The GIS methods were used to include the influence of landscape characteristics on pipeline construction costs. Graph theory was used to model the relationships between objects [23,24]. The supply and demand locations in our model represent the objects and are referred to as nodes. The pipeline connections are the relationships between nodes and are referred to as edges. Mixed integer quadratic programming was then used to find the configuration of nodes and edges that leads to the lowest cost WSN.

In this paper, we present a modelling approach which generates the lowest cost WSN for a specific demand based on known supply locations in a region. We tested the approach on a case study in Zeeuws-Vlaanderen, in the southwestern part of the Netherlands.

2. Case study description

The model was tested by generating a WSN for an industrial site in Zeeuws-Vlaanderen, The Netherlands. The current fresh water supply for the site is dependent on transport of water from outside this coastal, fresh water scarce, region. Most of the surface area of the region (733 km^2) is used for agriculture. Local fresh groundwater sources are hosted within a lithologically heterogeneous aquifer and positioned on top of deeper, more saline groundwater. In this case study, we consider a maximum chloride concentration of 1500 mg Cl^-/l as a limit for use in industry, based on an accepted classification of a fresh-saline interface [25]. The fresh-saline groundwater distribution in the area was mapped in 2015 [26]. Calculated groundwater extractions should not cause the so-called upconing of the fresh-saline groundwater 1500 mg Cl^-/l interface in the deeper subsoil to avoid possible negative consequences for other water users (e.g. famers) in the area. We tested the model to generate a WSN with the available fresh groundwater resources in the region operated

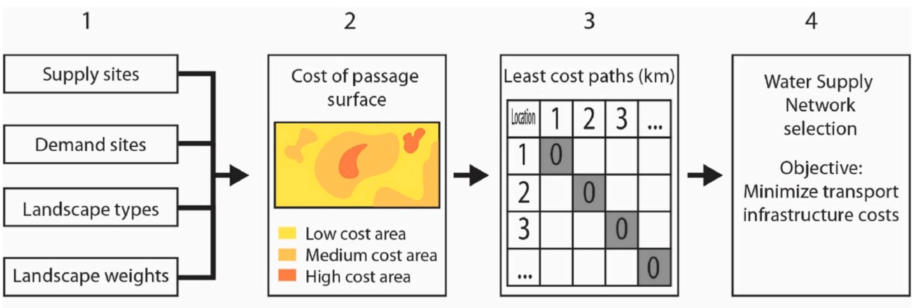

Fig. 1. Model steps to generate the water supply network with the lowest costs.

at sustainable yields. The current water supply of the industrial site is covered by importing 3 million m^3 $year^{-1}$ from outside the region. We investigated the possibility to supply between 0.5 and 5.5 million m^3 $year^{-1}$ of water with groundwater resources in the region.

3. Methodology

Transport networks, including WSNs, and their optimization have been thoroughly studied within the operations research field [17]. A water transport network can be represented as nodes and edges [27,28]. The nodes represent the water demand or supply locations, and the edges represent the pipeline connections (with associated costs) between nodes. Graph theory optimization procedures can then be used to optimize the network [29]. The presented model converts regional spatial data into a node and edge network, generates the lowest cost WSN based on the water demand of the user, and visualizes the result.

The model has four main steps (Fig. 1): (1) Input data generation, (2) Cost of passage surface creation, (3) Least cost path determination, (4) Water Supply Network selection.

3.1. Input data

The first step of the model compiles and generates the data required for step 2–4. In this section the components to generate the input data are described: the supply and demand sites with respect to water quantities and qualities, the landscape types and associated weights to determine the route of the pipeline infrastructure.

Supply sites: to generate a decentralized WSN, possible sources of water need to be identified. The supply site input data are the locations (coordinates), and the amount of water which the wells can supply sustainably (m^3 $year^{-1}$). Criteria such as the natural recharge of an aquifer [30], the environmental flow requirements of an area [31], or the overall sustainable water footprint of a river basin [32] can be used to determine the sustainable yield for water extractions. For this case study fresh groundwater sources in the Zeeuws-Vlaanderen region were modelled. A maximum drawdown of 50 mm [33] of the phreatic groundwater level (the change in water level at the extraction wells relative to the initial situation) was set as the boundary condition for the allowed extraction rate. In Zeeuws-Vlaanderen brackish and saline groundwater is present below fresh groundwater, therefore saline groundwater upconing can occur as a result of lowering the piezometric heads due to extraction and saline groundwater flowing to the extraction well. Extractions are dimensioned in such a way that the position of the 1500 mg Cl^-/l interface between the fresh groundwater above and the brackish groundwater below should not move into the groundwater extraction well [26,34].

An available 3D variable-density groundwater flow model coupled with a salt transport model [34] was used to provide the necessary data on hydraulic conductivities [35] and the groundwater salinity distribution expressed as mg Cl^- up to a depth of ~140 m below mean sea-level (MSL) [26,34]. The 100 × 100 m resolution model uses the MODFLOW [36] based computer code MOCDENS3D [65,66] and consists of 40 model layers to reproduce the movement of groundwater salinity in the vertical direction. Stresses in the model on the groundwater system includes six different surface water types (sea and estuarine waters, lakes, canals, (small) rivers, water courses up to ditches), seasonal natural groundwater recharge from the National Hydrological Instrument [37], a shallow drainage system, and existing groundwater extraction wells. The surface water and drainage systems (seasonal water level, and with a certain resistance to the groundwater system) are inserted into the model using an accurate Digital Elevation Model ('Actueel Hoogtebestand Nederland' (AHN [38]), resolution 5 × 5 m); boundary conditions (in the sea and at the hinterland) complete the model [34]. To obtain an estimate of fresh groundwater availability, the depth of the fresh-saline groundwater 1500 mg Cl^-/l interface was determined for the study area. The resulting interface served as an initial estimate of the potential availability of fresh groundwater locations. As the movement of groundwater is a dynamic process, sustainability constraints need to be placed on extraction rates. Determining the extraction locations and associated rates was done in two steps: (1) obtaining an initial selection of extraction coordinates based on the hydraulic properties of the subsoil [35] in combination with an analytical formula which estimates the maximum extraction without upconing of the fresh-saline groundwater 1500 mg Cl^-/l interface into the extraction well [39], and (2) calculating the phreatic groundwater level drawdown for given extraction rates based on the super-positional effect of the extraction well clusters. The drawdown is based on hydrogeological parameters of a semi-confined groundwater system and the extraction rates (calculated with the so-called Formula of De Glee) of the wells [40].

Upconing of saline groundwater can be approximated using analytical methods such as discussed in Refs. [39,41,42], where a *critical rise* of the interface can be calculated. The maximum sustainable extraction rate for the case study is set to the rate before saline groundwater will experience an abrupt rise towards the well screen. This rise is given by the model of Bear and Dagan [41], and was calculated using fresh-saline groundwater interface depths, resulting in maximum extraction rates (*Qmax*) in m^3 day^{-1} per grid cell (see Annex 1). Cells with extractions that are too small ($Qmax < 500$ m^3 day^{-1}) were removed. The remaining locations were extracted as points and finally grouped into clusters with extraction wells 100 m apart. This step serves as an initial selection but does not yet consider the summed (superposed) effect of clustered extraction wells on the overall drawdown of the phreatic groundwater level.

Saline groundwater upconing is related to drawdown, therefore the latter was also quantified using an analytical method. Pumping rates were optimized for minimal summed drawdown and maximum extraction rates considering interference, the summed effect, of neighboring extraction wells. The outcome allows the user to quantify the fresh groundwater extractable in m^3 $year^{-1}$ for a given maximum drawdown.

The relationship between the maximum accepted drawdown and the maximum extraction rate is linear; reducing the maximum accepted drawdown by half yields half the extraction rate (see Annex 1). Through this property the effect of altering the accepted drawdown, as a possible sustainability criteria, on the optimal WSN can be explored. This analytical approach provides a first estimate of the sustainable yield at a specified groundwater drawdown. The presented approach can be expanded with additional criteria to ensure overall sustainability of the groundwater system [43–45].

Demand sites: the spatial location (coordinates) of the demand site(s) and their demand (m^3 $year^{-1}$) for a specified quality of water. For the case study in Zeeland a single industrial user is used as the demand location. The demand quality is set to a maximum of 1500 mg Cl^-/l. The model was built to accept multiple demand sites.

Landscape types: The type of landscape and land use influence the costs of placing pipeline infrastructure [46,47]. We use a landscape type map of the study area to find the pipeline routes with the lowest costs (Fig. 2). The landscape types used in this work correspond to publicly available data for the Netherlands [48].

Landscape weights: To determine the pipeline routes with the lowest costs, the different landscape types were weighted to reflect the costs of placing pipeline infrastructure within them. The weights assigned to the landscape types reflect the relative differences in costs between the landscape types. For example, the costs associated with placing pipeline infrastructure in a built-up area are high relative to an agricultural area. The list of included landscape types can be expanded based on data availability and importance of specific landscape types in a region (e.g. industrial areas or groundwater extraction areas).

3.2. Cost of passage surface

The lowest costs for a pipeline between two locations do not necessarily correspond to a straight line [46]. Feldman et al. [46] showed that the use of spatial data in the form of a cost of passage surface based on land use can reduce pipeline construction costs by 14%; even when the total length of pipeline increases by 21% as a consequence.

A cost of passage surface is a raster in which each cell value represents the costs of traversing that cell and can be based on any type of costs. For the case study the costs refer to the placement of pipeline infrastructure. In this paper the weights assigned to each of the landscape types (Fig. 2) were combined and overlaid using GIS software to create the general cost of passage surface for pipeline infrastructure in the area. The cost of passage surface is the input data to determine the least cost path, the route with the lowest total costs to connect two locations, in this case with pipeline infrastructure [49–51].

3.3. Least cost paths

Based on the general cost of passage surface the lowest costs route for a pipeline between two locations was calculated (Fig. 3). The least cost path between two locations is the shortest route between two locations according to the metric used in the cost of passage surface [52]. Least cost path methods have been widely used for infrastructure routing [49,50,53]. To create the least cost paths the cost of passage surface was converted into an accumulated cost surface for each location. The accumulated cost surfaces were then used to trace the lowest cost route between the departure and destination locations [51]. The weighting procedure (section 3.1) allows users to consider criteria with different metrics (e.g. construction costs, slope, distance to protected areas) and to have all criteria be reflected in the final least cost path [54].

The steps shown in Fig. 3 describe the procedure to determine the least cost path between a set of two locations. To generate the WSN with the lowest costs, all the possible connections between all the demand and supply locations are needed. For each demand or supply location the least cost paths to all other locations were calculated. The resulting least cost paths, for all possible combinations of

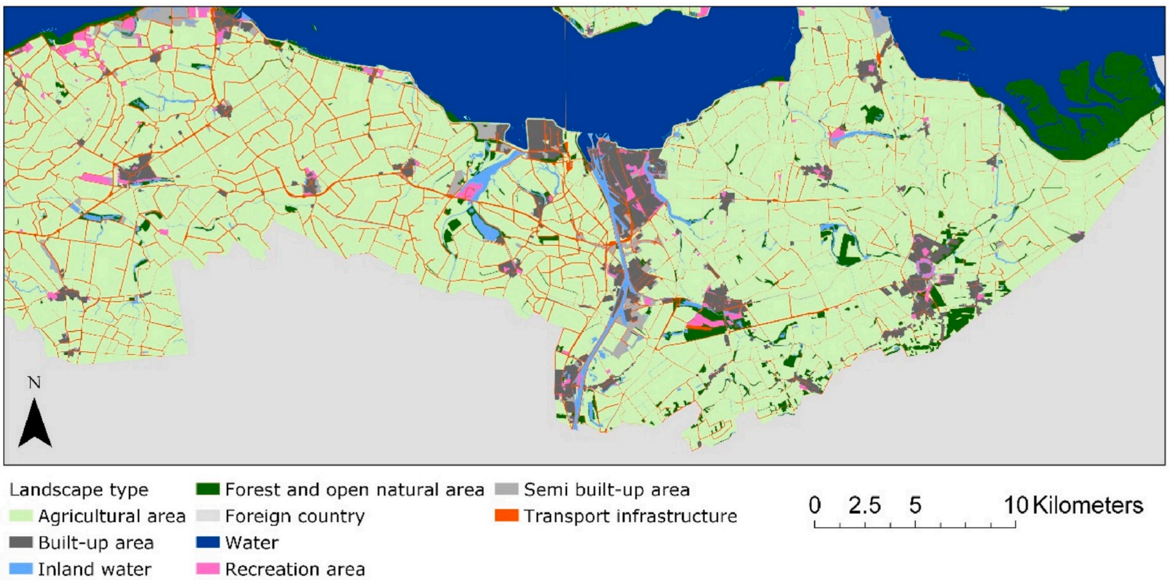

Fig. 2. Landscape types in Zeeuws-Vlaanderen affecting pipeline construction costs used in the model.

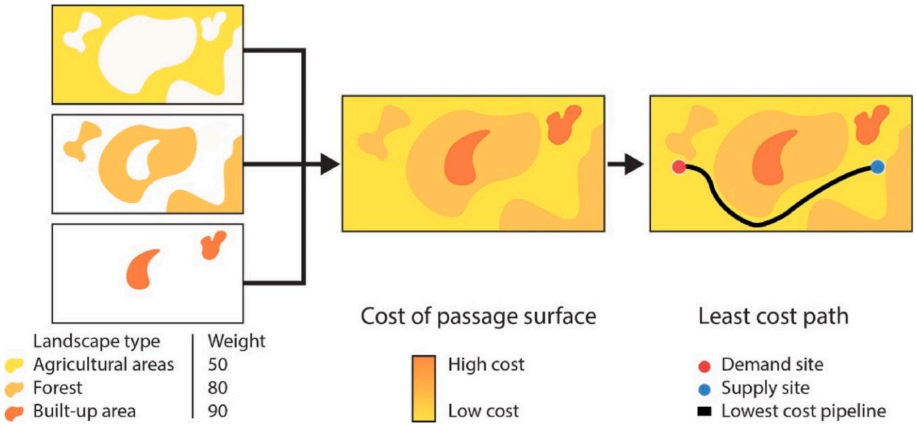

Fig. 3. Procedure showing the combination of landscape types into a cost of passage surface and into the least cost path between the water supply and demand location. Due to the different costs to place pipeline infrastructure in each landscape type, the least costs pipeline is not a straight line, but avoids the forest and built-up areas.

locations, were overlaid and combined into a single least cost network.

When creating the network a node was added at each location where pipelines intersect. The added nodes serve as transport hubs where flows can merge, but do not affect the overall water balance in the network. The model considers the merging of flows by calculating the required pipeline capacity, and associated costs, before and after the transport hubs. Hubs are represented by their location (coordinates) but have a demand and supply of zero.

The above procedure results in a $|V|\ x\ |V|$ (where V is the set of all locations or nodes) adjacency matrix as shown in Step 3 of Fig. 1. The values in the matrix represent the length (kilometers) of the lowest cost pipeline route between each starting location (i) and destination location (j). The diagonal zeros represent the fact that the distance from each location to itself is zero.

3.4. *Water supply network selection*

The mathematical representation of the optimization problem in this work is a variation of the *fixed charge network flow problem*, which is used to model many practical problems in the areas of transportation and distribution [55]. The problem is characterized by the set-up costs, a fixed charge, that is incurred when an activity is performed [56,57]. For pipeline construction the fixed charges are the costs that need to be made irrespective of the size of the pipe being placed. We used a mixed integer quadratic programming (MIQP) method to solve the optimization problem and to generate the optimal WSN [56]. The system is represented by a graph $G(V,E)$ with nodes V and edges E. The supply and demand locations are the nodes and the possible transport pipelines the edges. The set of edges E is the result of Section 3.3. Each edge (i,j) in E, where i is the source and j is the destination, is described according to the following parameters:

- Flow ($x_{i,j}$): the amount of water being transported over the edge.
- Maximum capacity ($u_{i,j}$): the maximum amount of water which can be transported over an edge. Since the WSN is not yet built, the maximum capacity is not yet defined. This parameter makes it possible to generate WSNs incorporating (parts) of existing pipeline infrastructure.
- Fixed costs ($f_{i,j}$): the fixed costs which will be incurred to place the pipeline, irrespective of the amount of water transported.
- Costs per unit flow ($c_{i,j}$): the costs to increase the capacity of a pipeline according to the amount of water which needs to be transported.
- On/off ($y_{i,j}$): binary variable with value 1 if the pipeline connection is used, or 0 the pipeline connection is not used.
- Water demand/supply (s_i): the water demand (negative value) or supplied (positive value) to the network at each node. Transport hubs have a demand/supply of zero.

Each node has an associated water supply or water demand s_i in the network. For locations that supply water $s_i > 0$, for transport hubs that do not provide or consume water $s_i = 0$, and for water users that extract water from the network $s_i < 0$.

The costs per unit flow ($c_{i,j}$) are based on the length of the pipeline section (i,j), the result of the least cost path analysis, and the pipeline diameter required to achieve a suitable flow speed. The suitable range for flow speed, while considering a 1.5 factor for peak demands, was set between 0.5 m s^{-1} and 1.5 m s^{-1}. The fixed costs ($f_{i,j}$) are also based on the length of the associated pipeline section but are not dependent on the water flow. The capacity dependent pipeline placement costs used in the model were 0.5 euro mm^{-1} diameter m^{-1}. The relation between accepted flow velocity and available pipeline diameters, generally available in increments of 100 mm, yield a stepwise behavior in terms of costs against flow (Annex 2). We approximate the stepwise behavior with a quadratic function from which the constants serve to establish the objective function for the network selection procedure according to

$$\text{minimize } TPPC = \sum_{(i,j)\in E} c_{\alpha,ij}\cdot x_{ij}^2 + \sum_{(i,j)\in E} c_{\beta,ij}\cdot x_{ij} + \sum_{(i,j)\in E} f_{ij}\cdot y_{ij} \quad (1)$$

$$\text{where } c_{\alpha,ij} = \alpha \cdot L_{ij} \quad (2)$$

$$\text{where } c_{\beta,ij} = \beta \cdot L_{ij} \quad (3)$$

$$\text{where } f_{ij} = \varepsilon \cdot L_{ij} \quad (4)$$

where *TPPC* is the total pipeline placement costs for the WSN based on the adequate diameter to accommodate the required flow over each edge and L is the length of the pipeline (km) between nodes i,j generated through the least cost path analysis. The coefficients α, β and ε are the constants derived from the quadratic relationship between flow and pipeline placement costs (Annex 2). The optimization problem can be characterized as a Mixed Integer Quadratic Program due to the quadratic term in the objective function. The left and middle terms represent the sum of the costs per unit flow over each edge. The right term is the sum of the fixed costs for all the edges used. If an edge is not used there are no costs, fixed or per unit flow, associated with that edge.

The constraints of the optimization model are given by Equations (5)–(7). The first constraint ensures that the sum of the flows out of any node (left term) is smaller or equal to the sum of the flows entering the node (middle term) and the supply (right term) at the node, Equation (2) applies to every node i in the set of nodes V

$$\text{subject to } \sum_{(i,j)\in E} x_{ij} - \sum_{(j,i)\in E} x_{ji} \le s_i \quad \forall i \in V \quad (5)$$

The second constraint ensures that if an edge is used, the flow should be larger or equal to zero, while at the same time it should be smaller or equal to the maximum capacity of the edge (Equation (6)). Existing pipeline infrastructure has a maximum capacity which can be incorporated in the model through parameter $u_{i,j}$. The model returns the flow over each pipeline, and therefore the capacity which needs to be installed. This constraint only applies to edges in use but is evaluated for every edge i, j in the set of edges E

$$0 \le x_{ij} \le u_{ij}\cdot y_{ij} \quad \forall (i,j) \in E \quad (6)$$

The variable y_{ij} denotes whether an edge is used or not and can take the value 0 (not in use) or 1 (in use) (Equation (7)). If the edge is used the fixed costs to place the pipeline are incurred. This variable is also evaluated for every edge i, j in the set of edges E

$$y_{ij} \in \{0, 1\} \quad \forall (i,j) \in E \quad (7)$$

The output of the optimization yields the edgelist of the lowest cost WSN, the amount of water to be transported over each edge, and the capacity at which the supply locations should be operated.

The (MIQP) was implemented in Python and solved with the Gurobi Optimization solver.

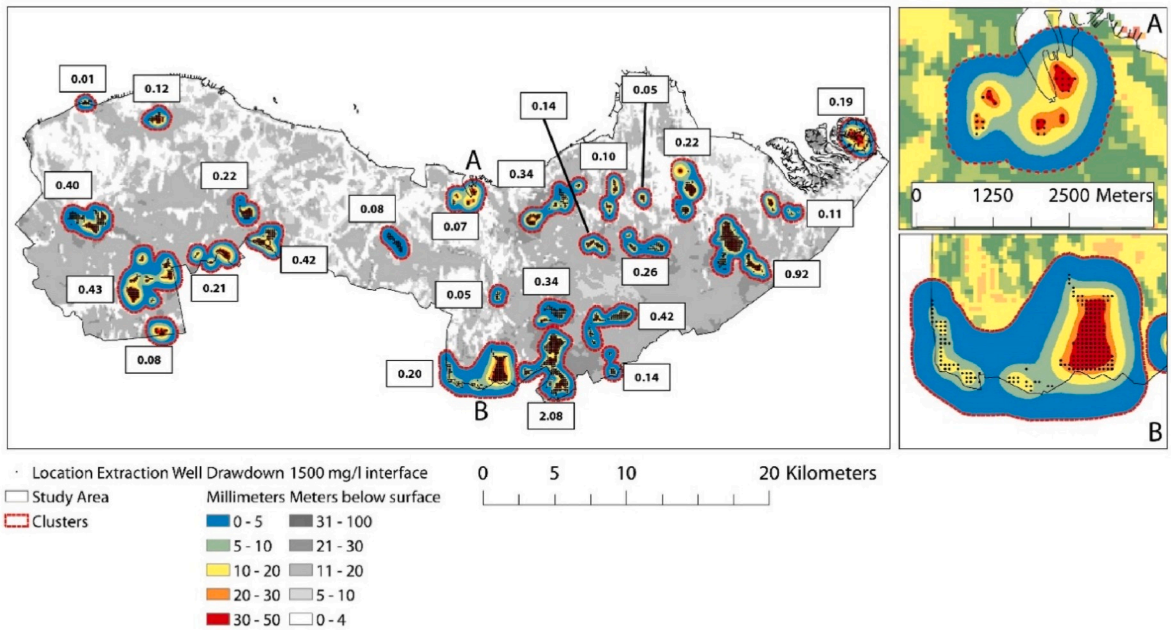

Fig. 4. Supply locations and available water supply (million m^3 year^{-1}) at optimized extraction rates when constraining maximum head drawdown to 50 mm.

4. Results: Zeeuws-Vlaanderen case

4.1. Regional water supply: fresh groundwater sources

The extraction location selection procedure yielded about 2000 extraction well locations from which fresh groundwater could be extracted. The possible extraction wells were grouped into 25 clusters in which individual extraction wells are at least 100 m apart. Clusters close to the coastlines are dune type geological formations capturing and storing fresh rainwater. The optimized clusters including the individual extraction wells are shown in Fig. 4.

The total amount of water which can be extracted from the 25 clusters, when limiting head drawdown to 50 mm, is 7.6 million m^3 $year^{-1}$. The spatial center of each cluster is used to generate the WSN.

4.2. Least cost pipeline network

The construction of pipeline infrastructure is preferred in areas where the construction costs are the lowest. Table 1 shows the weighted costs for pipeline infrastructure construction used in this work. The weights assigned to the different categories were determined in consultation with water supply experts. A distinction was made between crossing a road or waterway as opposed to building parallel to these landscape types. The zones parallel to transport infrastructure are relatively suitable to place pipeline infrastructure because other uses for these areas are limited. Crossing transport infrastructure should be avoided to reduce costs. In this work, we reduced the costs of pipeline infrastructure parallel to transport infrastructure by 70% compared to the original landscape type traversed.

Fig. 5A shows the combined cost of passage surface based on the landscape cost weights to place pipeline infrastructure. The areas with the lowest costs are agricultural areas along existing transport infrastructure. The original weighted cost for agricultural areas was 50 (Table 1), which is reduced by 70% in the zones parallel to existing infrastructure to yield the lowest final weighted cost of 15.

Generation of the least cost paths for all possible connections between the water supply and demand locations yielded a preliminary network with 408 edges (Fig. 5B). The preliminary number of edges did not yet account for the possibility to transport water in both directions. To include the possibility to transport water in both directions the original edges were copied and the start and end points were inverted. The result is an adjacency matrix (not shown) with 816 (2×408) values. The total number of nodes in the network is 269, of which 25 are the supply locations (Fig. 5B), 1 is the demand location, and 243 are transport hubs. The complete network has a total length of 1796 km: 21% passes agricultural area, 1% built-up, and 1% forest and open natural area. The remainder (76%) falls within the parallel zone alongside existing transport infrastructure or waterways. The length of pipeline traversing each landscape type is a reflection of the weights assigned to each type (Table 1). Assigning equal weights to each landscape type would result in (unrealistic) straight lines between nodes.

4.3. Lowest cost water supply network

The model creates the lowest cost WSN specific to the demand of the user and the available water supply (Fig. 6). Pipeline diameter and flow velocity are shown in Annex 3 and Annex 4.

We discuss the WSNs I-VII of Fig. 6 in order of increasing demand below:

I. The optimal WSN to supply the starting demand of 0.5 million m^3 $year^{-1}$ uses three supply locations and is 25.1 km long.
II. The WSN configuration changes considerably because the supply locations of I, while being closer, cannot cover the demand of 0.6 million m^3 $year^{-1}$. The optimal WSN uses the most southern supply location as the single supply source.
III. Demand reaches 2.1 million m^3 $year^{-1}$, exceeding the 2.08 million m^3 $year^{-1}$ available at the most southern location. A small supply location close to the existing route is added to the WSN to cover the demand. The inclusion of the small supply location reduces the capacity at which the southern supply locations is operated, and reduces the diameter of the pipeline up to the point where the pipelines merge.
IV. The optimal WSN shifts to the east to include a supply location with more water to cover the demand. The inclusion of this new location reduces the capacity at which the southern well is operated from 2.05 (in III) to 1.8 million m^3 $year^{-1}$.

Table 1
Relative cost weights for pipeline construction.

Landscape feature	Cost weight 1-100
Agricultural areas	50
Built-up area	90
Inland water (crossing)	90
Forest and open natural area	80
Foreign country	100
Water (crossing)	90
Recreation area	60
Semi built-up area	80
Transport infrastructure (crossing)	75

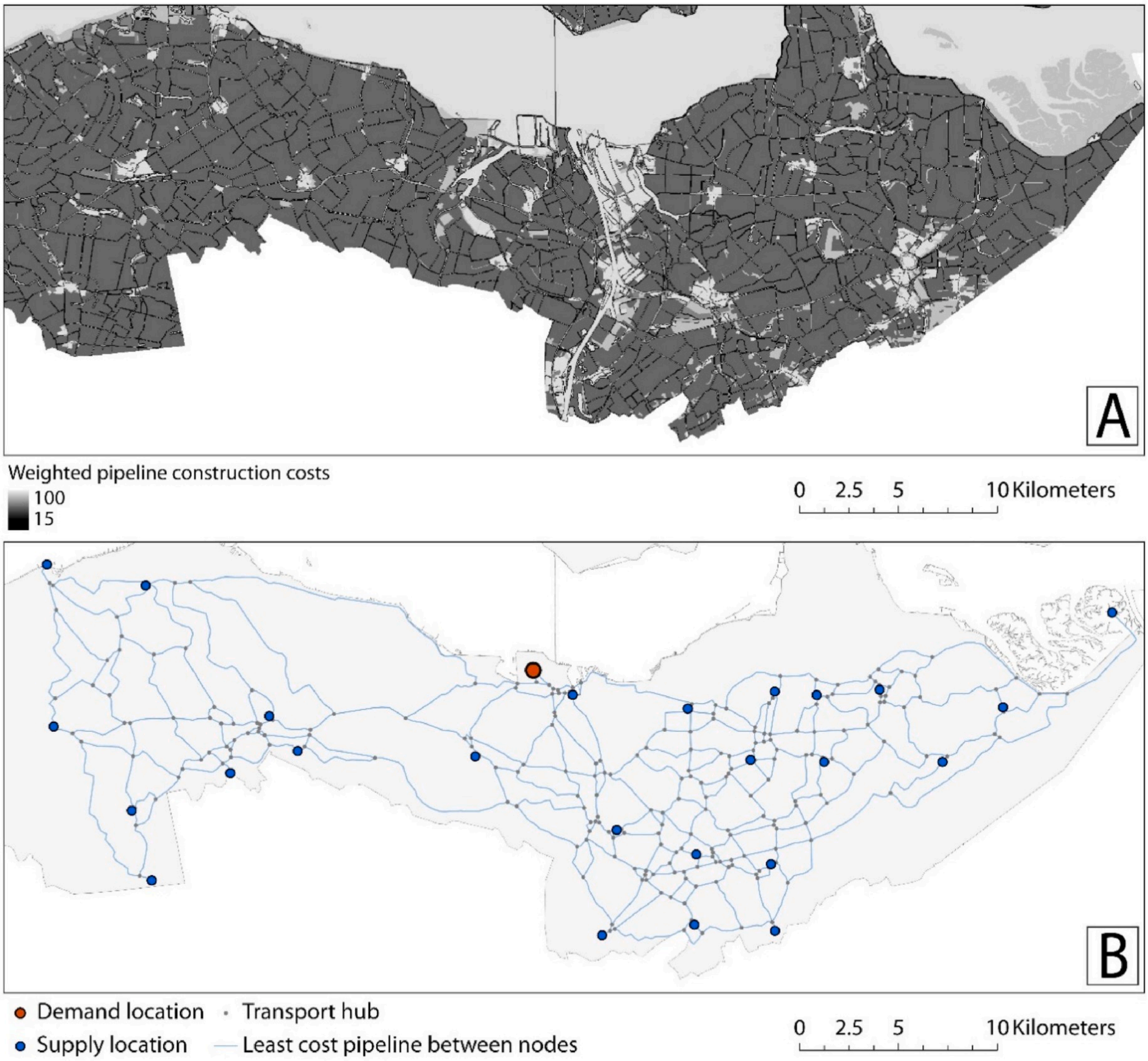

Fig. 5. Cost of passage surface with weighted costs to place pipeline infrastructure (A), lowest cost pipeline network connecting all possible pairs of supply and demand locations (B).

V. The optimal WSN still includes the most southern supply location but now also includes the second largest supply location in the area with a supply of 0.92 million m^3 year^{-1}. The second largest supply location is operated at 98% capacity (0.90 million m^3 year^{-1}) because demand is still below the maximum water availability.
VI. The optimal WSN is rearranged to include the southern supply source with 0.14 million m^3 year^{-1}. The capacity at which the most eastern supply location is operated is lowered to 93% (0.86 million m^3 year^{-1}).
VII. The optimal WSN has a different configuration compared to VI to supply the maximum investigated demand of 5.5 million m^3 year^{-1}. The most eastern supply site with a supply 0.92 million m^3 year^{-1} is approached with a new branch of the network directly going east, instead of expanding the branch from the south-east as in V and VI.

In general, the optimal WSN configuration results from operating the supply location furthest from the demand location at the lowest possible capacity. This can reduce the amount of water supplied by a specific well when demand increases and new supply locations are added to the WSN (an example of this occurs in the transition from III to IV). By reducing the operating capacity of the furthermost supply location, the pipeline diameter which needs to be installed over the complete network is minimized, leading to reduced costs.

As the demand increases the costs of the optimal WSN increase with steps to reflect the shifts in WSN configuration (Fig. 7). In Fig. 7 the costs of the WSNs I-VII of Fig. 6 are annotated, and the optimal WSN costs for a drawdown of 75 mm are shown for comparison. The steps in costs arise from the need to add new supply locations to the WSN each time demand exceeds the maximum capacity of a set of supply locations. At each step increasing the diameter (capacity) of pipelines is no longer sufficient to cover the demand and additional

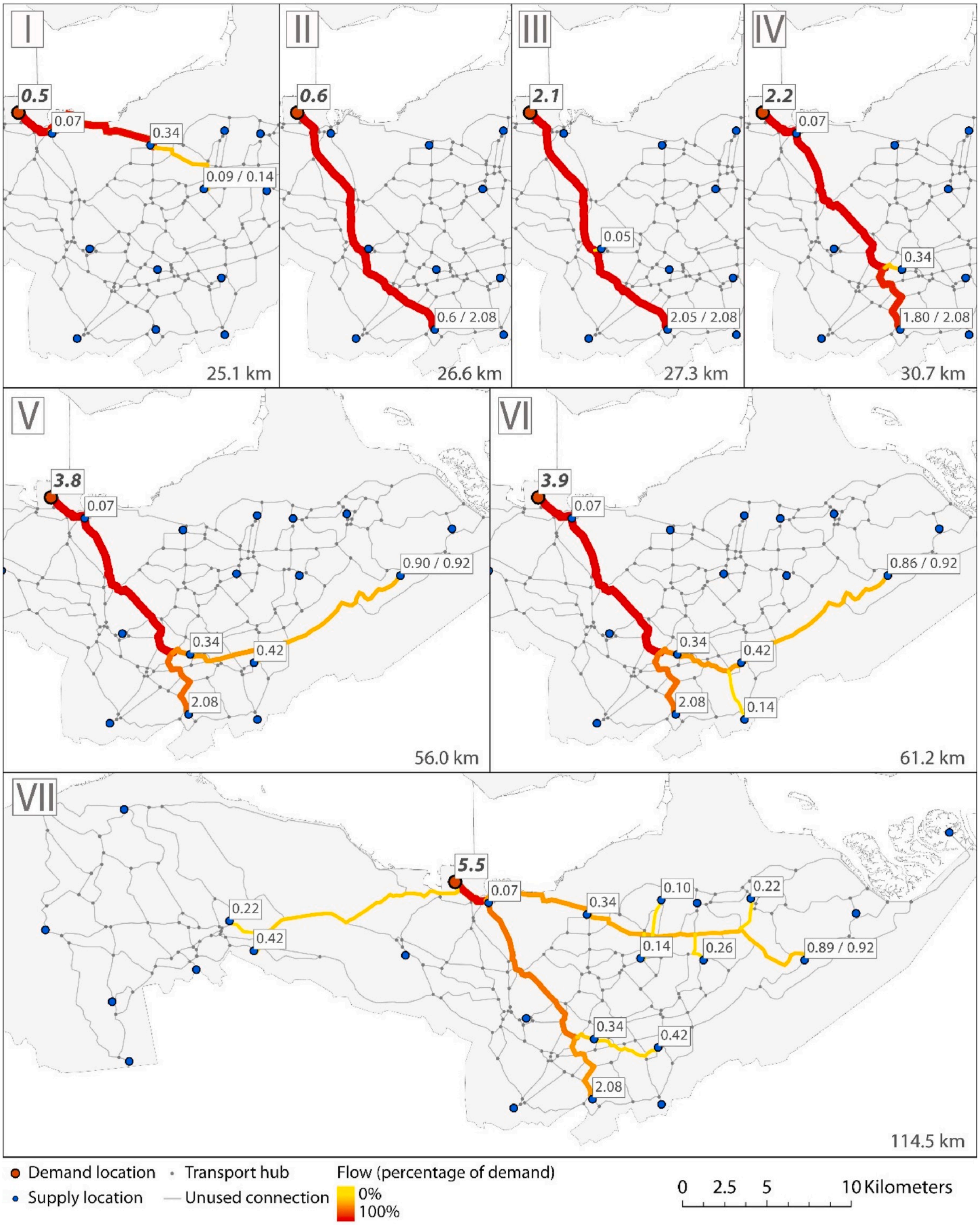

Fig. 6. Optimal WSN for a demand of 0.5 (I) 0.7 (II), 2.1 (III), 2.2 (IV), 3.8 (V), 3.9 (VI), and 5.5 (VII) million m^3 $year^{-1}$ and a maximum accepted drawdown of 0.05 m in the phreatic groundwater level at each supply location. The labels show the amount of water supplied by each well. Labels with two values indicate that a well is operated below maximum capacity (water supplied/maximum capacity). Labels in **bold** indicate the demand location. The value in the bottom right corner of each frame indicates the total pipeline length for the WSN.

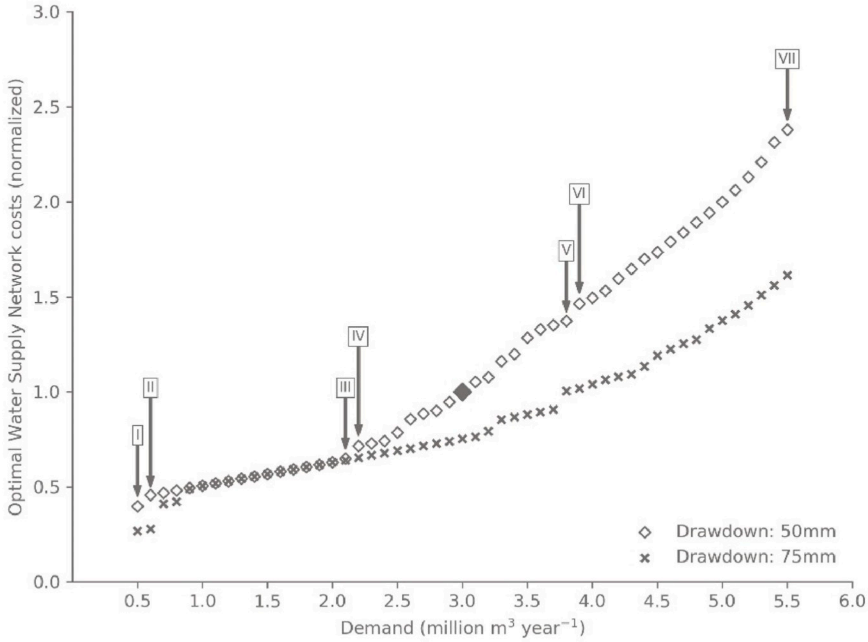

Fig. 7. Optimal water supply network costs in relation to demand of the water user. Costs are normalized based on the WSN costs for a demand of 3.0 million m^3 $year^{-1}$ and a drawdown of 50 mm (indicated with the filled square). Normalization was done according to: $\textit{NormalizedWSNcost}(D) = \textit{WSNcost}(D)/\textit{WSNcost}\left(3.0 \text{ million m}^3 \text{ year}^{-1},\ 50\text{mm drawdown}\right)$ where D is the demand.

pipelines to new supply locations are needed. The addition of a new pipeline connection incurs the fixed costs, which causes the steps in costs. In the lower demand range, up to VI, the steps in costs for adding supply locations are more pronounced. At higher demand ranges the cost steps become less pronounced because the total number of supply locations required to cover the demand is larger. When many supply location are needed subtle changes in the network are possible to minimize costs, making the steps less pronounced. A linear increase in costs, as occurs between a demand of 0.7 (II) and 2.0 million m^3 $year^{-1}$ (at 50 mm drawdown), indicates that the only added costs occur from adding additional capacity (increasing pipeline diameter) to the network.

5. Discussion

5.1. Modelling approach

Over the last decades water resources management has increasingly relied on computer models [58]. The model in this study adds to the existing modelling toolbox by offering the possibility to generate and evaluate decentralized water supply networks. These networks are based on local fresh (and in the future saline) water resources as a base for enhancing regional water self-sufficiency. The model accepts any supply location if the spatial location and the available amount of water are provided. This allows the evaluation of water supply networks in which surface water, rainwater, wastewater, brackish or saline water are used as decentralized supply sources. The complexity of the optimization problem, in terms of the number of network configurations which can cover the demand, increases exponentially as the number of supply locations increases. The presented model is therefore particularly suited to assist in the design process for decentralized water supply networks with many smaller supply locations adhering to maximum sustainable yields.

Reducing the overall water demand of a user is directly related to a reduction in the amount of water which needs to be transported. The stepwise behavior of the WSN costs reveals tipping points where reductions in demand can significantly influence the WSN configuration and costs. The model can be used to compare the costs of transport with the costs for demand reduction through the implementation of water saving technologies, or through an increase of water re-use. Depending on the local landscape and water supply sources either option may be favorable. For example: the costs for desalination have been decreasing over the years [59] which can make water supply networks based on small scale local brackish sources preferable over long distance transport of high quality water.

The costs of pipeline infrastructure depend on many factors [60], and can vary with a factor of 25 based on the methods and materials used [61]. As long as the same cost function for placing pipeline infrastructure is applicable to the complete case study area the model will generate the lowest cost WSN. The WSN can also be optimized based on other criteria than monetary costs. A cost function in terms of carbon dioxide emissions or energy use will yield the optimal WSN in terms of the respective cost function metric.

5.2. Sustainable water use

Self-sufficiency and sustainability can be enhanced by harvesting alternative local renewable resources [62,63]. The model we present generates the optimal network to connect supply and demand within the boundaries of sustainably available water resources on any scale. Considering sustainable water availability over all relevant scales is needed to ensure overall long-term sustainability [64,65]. Long-term sustainability of the decentralized WSN requires adherence to the catchment's water budget [66] and ensuring that the cumulative effect of local extractions do not negatively alter the entire drainage basin [8].

In the case study the maximum phreatic water level drawdown was set to a single value for all well clusters. Determining and applying specific drawdown values for each location, based on criteria applicable to the local context, is suggested for future research. Prevention of land subsidence as a consequence of draining peatlands [67] is such an additional criteria for specific low-lying areas in the Netherlands. In other areas the maximum phreatic water level drawdown should be sensible with the presence of water intensive crop areas. Drawdown values and subsequent extraction rates can be matched with these local conditions at a very high spatial resolution. For this study it was decided that the analytical methods to determine water extraction rates are sufficient to identify possible supply locations and to show the functionality of the modelling approach. Validating the extraction rates through a 3D numerical groundwater flow model [34,68,69] with an adequate resolution is suggested as a future step.

5.3. Context specific application

The case study presents a single set of weights for the landscape types in the region based on contact with water transport infrastructure experts. Involving local stakeholders to determine the weights makes the model results more context specific. Methodologies such as multi-criteria evaluations can be applied to spatial data to determine which areas are more or less suited for a certain purpose [70]. Each set of favored criteria will yield a specific cost of passage surface, which will in turn yield a specific WSN configuration. By defining and assigning the cost weights for each landscape type in consultation with local stakeholders the model generates water supply networks tailored to the local context.

Publicly available spatial data on landscape types limited to the Netherlands was used to demonstrate the workings of the model. Spatial data from other countries, Belgium for this case study, can be incorporated to assist with the transboundary nature of integrated water resources management [71]. Consultation with local stakeholders can increase the number of landscape types included in the model because the categories of the national dataset are limited. The manual addition of no-go areas (such as Natura 2000 areas [72], or local heritage sites) makes results more site specific, and complements the generic spatial data relevant for pipeline construction costs.

6. Conclusion

This study presents a modelling approach to generate decentralized water supply networks based on the local landscape characteristics and water availability of a region. We add a novel approach to the modelling toolbox for regional water planners by incorporating spatial data and the effect of landscape types on the costs to place pipeline infrastructure, in combination with an optimization procedure based on a water balance between supply and demand. Water supply networks optimized to the local context can be generated by incorporating these spatial aspects. Representing the water network as nodes and edges makes it possible solve the complex optimization problem with mixed integer quadratic programming. The model was used for a case study in Zeeuws-Vlaanderen, in the south of the Netherlands, to supply an industrial zone with regional fresh groundwater as an alternative to importing fresh water from outside the region. The model generates: (1) the pipeline configuration for the lowest cost water supply network, (2) the amount of water flowing over each pipeline in the network, (3) the capacity at which the supply locations should be operated. The model can be extended with other conventional and alternative water sources such as brackish water resources and wastewater treatment plant effluents. In that case treatment costs to achieve adequate quality and related costs need to be included. Decision makers can use the model to evaluate scenarios with varying supply and demand settings, and to identify the points at which sudden increases in transport network costs occur.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

CRediT authorship contribution statement

Joeri Willet: Project administration, Conceptualization, Methodology, Data curation, Visualization, Writing - original draft. **Jude King:** Data curation, Methodology, Visualization, Writing - original draft. **Koen Wetser:** Conceptualization, Supervision, Visualization, Writing - review & editing. **Jouke E. Dykstra:** Conceptualization, Supervision, Visualization, Writing - review & editing. **Gualbert H.P. Oude Essink:** Methodology, Data curation, Visualization, Writing - review & editing. **Huub H.M. Rijnaarts:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wri.2020.100131.

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