

# Locating suitable sites for the construction of subsurface dams using GIS

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**Abstract** Subsurface dams constitute an affordable and effective method for the sustainable development and management of groundwater resources when constructed on suitable sites. Such dams have rarely been constructed in crystalline rock areas and to best of our knowledge, geographic information system (GIS) has never been used in any methodology for locating suitable sites for constructing these dams. This paper presents a new methodology to locate suitable sites for the construction of subsurface dams using GIS software supported by groundwater balance modelling in a study area Boda-Kalvsvik, Sweden. Groundwater resources were calculated based on digitized geological data and assumptions regarding stratigraphic layering taken from well archive data and geological maps. These estimates were then compared with future extractions for domestic water supply using a temporally dynamic water balance model. Suitability analyses for subsurface dams were based on calculated topographic wetness index (TWI) values and geological data, including stratigraphic information. Groundwater balance calculations indicated that many of the most populated areas were susceptible to frequent water supply shortages. Of the 34 sub-catchments within the study area: ten were over-extracted, nine did not have any water supply demand at all, one was self-sufficient and the remaining 14 were able to meet the water supply demand with surplus storage capacity. Six suitable sites for the construction of subsurface dams were suggested in the vicinity of the over-extracted sites based on suitability

analysis and groundwater balance estimates. The new methodology shows encouraging results for regions with humid climate but having limited natural water storage capacities. The developed methodology can be used as a preliminary planning step for subsurface dam construction, establishing a base for more detailed field investigations.

**Keywords** Subsurface dam · GIS · Groundwater balance · Wetness index · Water supply

## Introduction

Water is an essential resource for life, and due to potential climate changes and current consumption trends, it is feared that water crises will be ubiquitous across the globe by the middle of this century (Danilenko et al. 2010). One of the ways to cope with the emerging trends of population growth and climatic severity is to store water in unconventional ways such as rain water harvesting (RWH) (Ngigi 2003) and artificial recharge (Bouwer 2002). RWH can be defined as a water conservation technique generally comprising accumulating, storing and collecting the rain-water for public and agricultural demands (Rockström 2000). In addition to constructed storages at surface, RWH can also be used for groundwater recharge by raising groundwater levels (Helmreich and Horn 2009; WaterAid 2011). Recharge to groundwater can be natural (through percolation from surface water) and artificial (through civil structures) (WaterAid 2011).

Groundwater resource management using artificial storage of water can either be done with an open sand-filled dam or directly using existing aquifers for storage as with subsurface dams. Such constructed dams constitute an effective and economical way to augment the aquifers and

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have been in practice since decades (Foster and Tuinhof 2004; Raju et al. 2006). Petersen (2010) concludes that subsurface dams have had better success rates over the sand storage dams since many sand storage dams have failed because of changes in river courses, tilting of dams during floods, and other physical phenomena. Subsurface dams are generally preferable due to their higher functionality, lower cost of construction, lessened risk for contamination, lower evaporation losses and possibility of utilizing land over the dam (Foster 1998; Jha et al. 2009; Nilsson 1988).

Subsurface dams create reservoirs which are filled during periods of increased flow from upper parts of the catchment as the runoff passes through the valleys and a portion of the water infiltrates into the aquifer (Stevanovic and Lurkiewicz 2009). Ishida et al. (2011) report the existence of subsurface dams in a wide range of countries, i.e. Japan, Korea, China, India, Ethiopia, Burkina Faso, Brazil, Kenya and USA. Huge constructed subsurface dams with individual storage capacities exceeding 10 million cubic meters have been reported from Japan (Ishida et al. 2003).

Subsurface storage for water supply and/or prevention of seawater intrusion shows great potential as it generally has few social and environmental impacts (Archwichai et al. 2005; Baurne 1984; Onder and Yilmaz 2005). Ishida et al. (2006) studied the fluctuation of  $\text{NO}_3\text{-N}$  concentration and concluded that groundwater quality did not deteriorate due to construction of subsurface dam. However, Ishida et al. (2011) and Yoshimoto et al. (2011) stated that subsurface dams can change the groundwater levels and groundwater flow upstream and downstream, which occasionally can detrimentally affect the quality of the water.

Recharge to an aquifer is generally dependent on the climate, topography, geology, soil moisture and vegetation of the landscape (Abu-Taleb 1999; Alley et al. 2002; Frot and Wesemael 2009; Winnaar et al. 2007; Ziadat et al. 2006). Nilsson (1988) describes three physical factors which govern the selection of a suitable site for the construction of subsurface dams: climate, topography and hydrogeology. Landscapes in which the variability in the hydrologic conditions is high are characterized by water flow towards valleys, which also are settings for permeable soils suitable for the construction of subsurface dams. Moreover, the physical features of the surface and subsurface, such as lithology, geological structures, stratigraphy and thickness of the soil layers play important roles in the groundwater storage and groundwater flow (Al-Adamat et al. 2010; Ghayoumian et al. 2007; Onder and Yilmaz 2005; Winnaar et al. 2007), and thus need to be identified to locate suitable sites for such dams. Furthermore, the site selection of a subsurface dam is also governed by social factors such as water demand and population development. Under international collaboration with the United Nations

convention to combat desertification (UNCCD), the ministry of environment of Japan constructed a subsurface dam as a model project in Burkina Faso in 1997–1998 (Ministry of the Environment Japan 2004; United Nations 1994). To select a suitable site for the subsurface dam, satellite images and aerial photographs were used to examine the physical conditions and electrical resistivity sounding techniques and magnetic measurements were carried out in order to detect underground structures.

Locating suitable sites for construction of subsurface dams requires integration of multiple parameters. Geographic information systems (GIS) and remote sensing (RS) afford the possibility to simultaneously display multiple parameters; reducing the time and expenditure required for complex cartographic information processing, and thus enable quick decision-making and efficient water resources management through identifying specific areas which could be used as potential sites for a specific purpose (Chowdhury et al. 2010; Drobne and Lisec 2009; Huang et al. 2010; Kumar et al. 2008; Malczewski 2004; Narendra and Rao 2006; Pandey et al. 2011; Stamatis et al. 2011). Topography, soil characteristics and weather data are often used in GIS with methodologies such as Thornthwaite-Mather's (TM) (Jasrotia et al. 2009; Singh et al. 2009) and weighted linear combination (WLC) (Al-Adamat et al. 2010) to locate suitable sites for constructing rainwater harvesting structures. However, methods to identify artificial groundwater storage zones have also been tested using GIS and RS (Anbazhagan et al. 2005; Chenini and Mamou 2010; Ghayoumian et al. 2005; Kallali et al. 2007).

GIS and RS tools, to best of our knowledge, have never been used for identifying suitable sites for construction of subsurface dams. Most of the existing subsurface dams are constructed in coarse soils in semi-arid climatic regions with strongly seasonally varying precipitation, whereas very few are reported from humid areas. Despite a humid climate, geological conditions are sometimes unfavourable for natural storage of groundwater, which may lead to water shortage during dry periods. The methodologies thus far presented are therefore not appropriate for small catchments and glaciated terrains with limited storage capacities.

The aim of this study was to develop and test a methodology to locate suitable sites for construction of subsurface dams in areas consisting of small and diversified watersheds with small storage capacities by using suitability analysis in GIS along with groundwater balance modelling. With the methodology developed the total storage capacity of the aquifers within the study area was assessed, vulnerability zones facing water shortage were identified and suitable sites for the construction of subsurface dams were located. Furthermore, through groundwater balance calculations sites with surplus water storage

capacity were identified which could help to plan future expansion in the area. The developed methodology can be used as a preliminary planning step for subsurface dam construction, establishing a base for more detailed field investigations.

## Methods

### Study area

The study was conducted in Boda-Kalvsvik, which has a total area of about 6 km<sup>2</sup> and is located on an island 20 km east of Stockholm at 60°01'N and 17°13'E (Fig. 1). The Boda-Kalvsvik has a maximum altitude of about 36 m above sea level. Northern European regions such as this study area were under an ice sheet (more than 2 km thick) which retreated about 10,000 years ago. Glacial transport caused the deposition of unsorted debris called “till” directly on the bedrock surface. Till is generally composed of different sizes of particles, ranging from clay-sized to boulders. During melting of the ice sheet, glacial rivers formed large esker systems composed of sand, gravel and cobbles, which are potentially important for water supply. Glacial clay was deposited at the receding edge of glaciers in the sea and lakes. On top of the clay, organic soils (gyttja and peat) were formed (Andersen and Borns 1997; Flint 1971). In hard crystalline rock terrain, which is prevalent in many parts of Sweden, extractable volumes of water only exist in rock fractures occupying a very small part of the bedrock, usually <0.05 % (Olofsson 1991). The fracture orientation in rock is often complex and the kinematic porosity is usually low due to limited flow connection between the fractures (Olofsson and Rönkä 2007). In such terrains subsurface dams can be constructed in the soil layers covering the less-permeable bedrock. The area has a mild climate, where the mean temperature during winter ranges between −7 and 2 °C and during summer typically ranges between 16 and 22 °C (SMHI 2010a). Like other parts of Sweden, precipitation often takes the form of snow between November and March. The average annual rainfall is 650 mm in this area where the highest precipitation amounts are observed in July, August and September. The average annual runoff is reported to about 200 mm in the study area (Engqvist and Fogdestam 1984). In Sweden, direct surface runoff is not common and a large part of runoff usually infiltrates and finds its way into the ground. A small portion of infiltrated water recharges the bedrock, but most of it flows through the soil layers towards the discharge areas (Olofsson et al. 2001). However, during the wet summer period the potential evapotranspiration is much higher than the precipitation leading to a very small net precipitation and groundwater recharge (Fig. 2). Long-

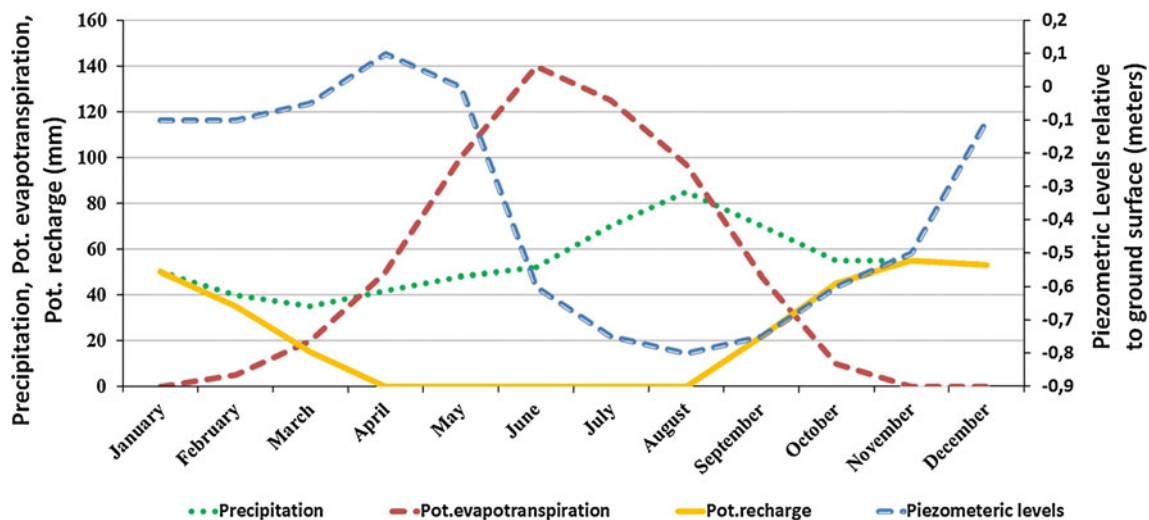
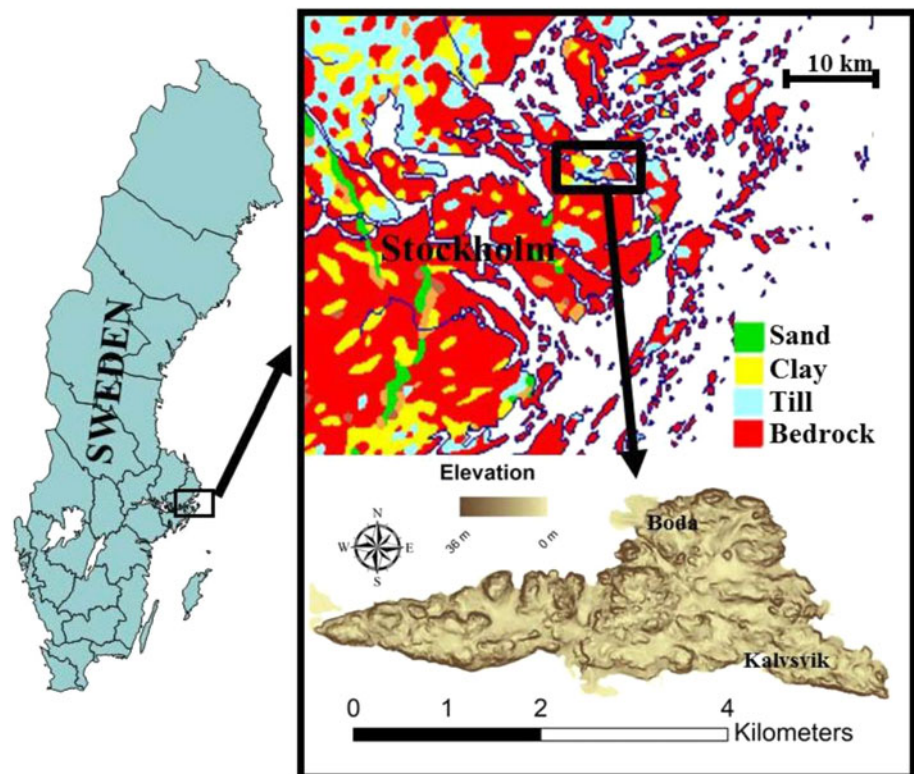
term measurements of the piezometric levels in this region show that during the summer period natural groundwater levels are often lowered on average by 1 m in till deposits between May and September (Fig. 2). During this period the natural outflow of groundwater is therefore significantly higher than the possible recharge and extraction for water supply has to rely on the groundwater storage capacities. A water balance model after introduction of a subsurface dam, which is based on the assumption that the dam will block the natural discharge of water and periodically raise the groundwater levels by 1 m in till and lead to an increase of the fill by 40 % in a normal year and by 18 % in a dry year (Fig 3). Boda-Kalvsvik is expected to develop in the coming years with an increased construction of houses as well as conversion of existing summer cottages into permanent residences, which will likely result in increased groundwater extraction. The domestic water supply, which is completely based on private and often drilled wells, is already stressed and if appropriate water conservation techniques are not identified and implemented water quantity and quality problems are predicted to arise (Värmdö municipality 2012). Subsurface dams in this case can be efficiently used to increase the groundwater storage by stopping the outflow of water which otherwise would be lost.

The data for this study were retrieved from different sources and in different formats (Table 1). The methodology involved a series of steps in GIS supported by the groundwater balance model (Fig. 4).

### Modelling

The GIS software *ArcGIS* (ESRI 2006) with the *ArcHydro* extension was used for processing topographical and geological data. For the groundwater balance model, a software package called *GWBal* was used which was developed by Olofsson (2002). From the available elevation contour map, a digital elevation model (DEM) of 5 m resolution was constructed from which a slope map was generated. The slope map was then reclassified to create a map indicating areas with suitable slopes. The geology of the area primarily consisted of bedrock, till, clay, sandy sediments and peat. Bedrock has limited groundwater storage capacity, which depends on complex fracture patterns and often has low kinematic porosity values (<0.05 %) (Olofsson and Rönkä 2007). Bedrock is of course not perfectly impermeable and the stored water is to some extent expected to flow through the underlying bedrock fractures. Groundwater flow entering the fractures will recharge the bedrock, mitigate seawater intrusion and increase the extraction capacities of wells, which are usually constructed as drilled wells in bedrock in this terrain type (SGU 1996). Therefore, the bedrock surface was assumed to act as the semi-hydraulic boundary for

**Fig. 1** Location of the study area

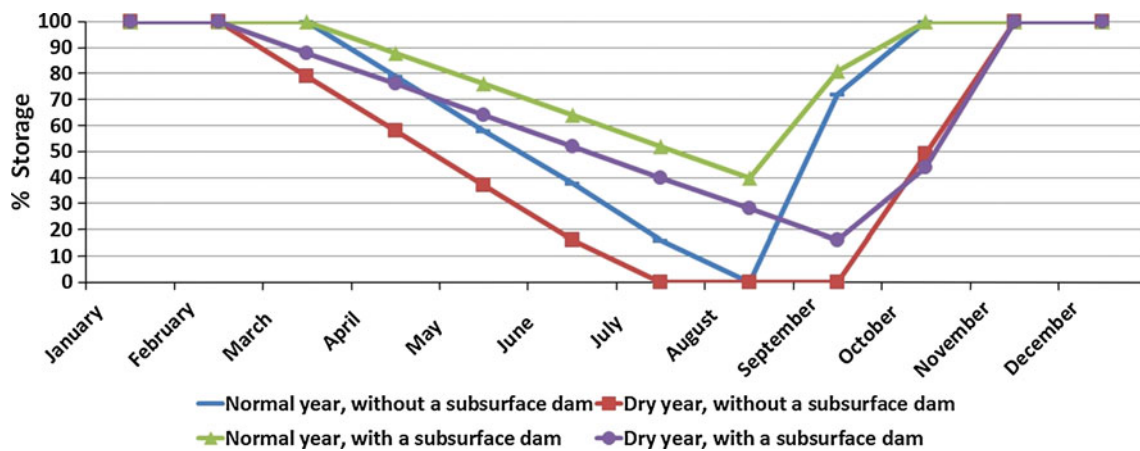


**Fig. 2** Monthly variation of precipitation, potential evapotranspiration and recharge at precipitation station Stockholm 9821, 1931–1960 average values (Engqvist and Fogdestam 1984; SMHI 2010b, c)

compared to 30 years monthly average values of groundwater levels at site 5501 in glacial till, Bogesundslandet, Vaxholm received from SGU (1996)

construction of subsurface dams. Sandy sediments and till were considered suitable geological formations for the groundwater storage for subsurface dams. The prevailing sandy till is not commonly counted as an aquifer but its kinematic porosity, amounting to 3–5 % (Grip and Rodhe 1988), is 100 times higher than that of bedrock and thus can be considered appropriate for single household water

storage. Rainwater may infiltrate into the bottom till layers through either permeable top soils or as runoff from outcrops entering the till and flowing along the bedrock surfaces. Clay is usually a less-permeable soil with limited infiltration capacity. However, geological maps and well data from this area show that clay formations often cover coarser sediments such as glacial till (Lindén 2001).



**Fig. 3** Example of storage fill scenarios with and without a subsurface dam. The results are obtained by performing a groundwater balance using the GWbal software (representing catchment 2),

where a normal year refers to normal precipitation and a dry year refers to 30 % reduction in precipitation

**Table 1** Data used for GIS modelling

Type of data	Format
Height contours <sup>a</sup>	Vector file
Land cover <sup>a</sup>	Vector file
Hydrography <sup>a</sup>	Vector file
Watershed <sup>b</sup>	Vector file
Weather data <sup>b</sup>	Charts
Soil data <sup>c</sup>	Vector file
Well data <sup>c</sup>	Excel sheet

<sup>a</sup> National Land Survey of Sweden (2010) (grant I 2008/1818)  
<sup>b</sup> SMHI (Swedish Meteorological and Hydrological Institute) (2010c)  
<sup>c</sup> SGU (Geological Survey of Sweden) (1996)

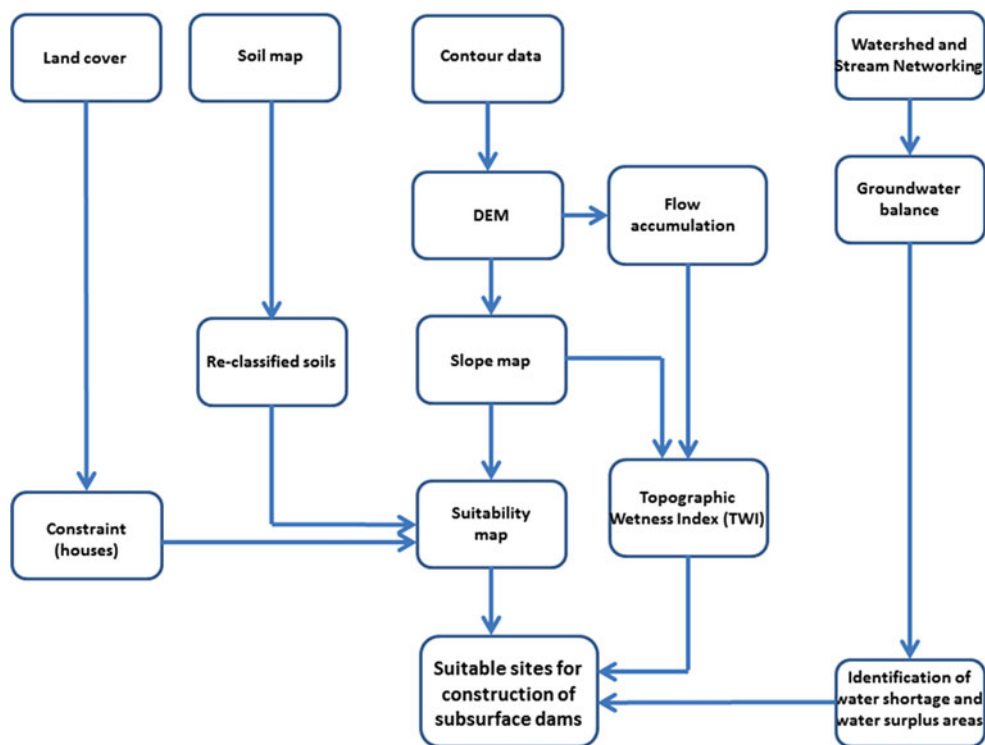
However, subsurface dams constructed in clay will slow down the downstream flows and may cause hazards such as water logging and flooding. To encounter such problems, drainage tubes on top section of the dam are recommended which act like sluice gates by allowing water to flow downstream in case of excessive pressure. Clay layers on top of the dam could also be replaced with coarse materials such as sand and gravel to make downstream flows faster. Therefore, within this study, the suitable stratigraphy according to the geological map consisted of areas which have top soil layers of till, clay or sandy sediments in areas where the soils were assumed to be saturated during most periods of the year. The combination of geological and slope suitability maps produced a boolean map showing suitable geological stratigraphy on suitable slopes. The geology-slope suitability map was also combined with a land cover map, where suitable geology and suitable slopes were determined only viable if 50 m or further away from houses due to the risk for groundwater pollution.

Watersheds and stream networks were outlined in *Arc-Hydro*, a process which involved various steps including: (A) Calculation of flow direction where numerical values within the model cells of the flow direction grid showed the direction of the steepest drop between those cells. (B) Generation of a flow accumulation grid which determines the accumulated number of cells upstream from any single cell, where, in the model a higher pixel value of the flow accumulation in a certain area implies more water accumulation in these areas, or vice versa (Czekanski and McKinney 2006). (C) Preparation of a stream grid from which stream segmentation could be performed. Although these streams might not be meaningful and truly representative of the existing streams, they were useful in expediting further delineation. (D) Delineation of a catchment grid in which each cell was assigned a specific code relative to which catchment it belonged. Essentially, this function was used to divide the entire catchment into sub-catchments based on flow direction and flow accumulation. However, a limit was needed regarding the number of sub-catchments used by the model, and the model used 1 % of the maximum flow accumulation of entire study area in this paper. (E) Calculation of the drainage line, which converted the inputs (stream segmentation and flow direction) into a drainage line feature class, with each line in the feature class being assigned an identifier relative to the sub-catchment in which it was located (Czekanski and McKinney 2006). Thus, drainage line processing created small streams which were used to represent the watersheds of the area based on the flow directions of the basin.

Groundwater balance

Sustainable aquifer exploitation is important, which implies that discharges from the system must always be

**Fig. 4** Methodology used to locate suitable sites for construction of subsurface dams



less than or equal to the recharge of the system (Loaiciga and Leipnik 2001) and that the accumulated discharge should not exceed the storage capacity during periods of lowest groundwater recharge. Therefore, groundwater balance calculations were performed for the study area. Olofsson (2002) noted that groundwater balance methods applied in Sweden often have been based on a simple recharge–discharge approach, essentially comparing the infiltrated precipitation to the extraction from the groundwater (Eq. 1).

$$P \cdot C \cdot A = Q \cdot n \pm r \quad (1)$$

where,  $P$  = precipitation (m),  $C$  = coefficient of infiltration (–),  $A$  = area ( $\text{m}^2$ ),  $Q$  = specific withdrawal ( $\text{m}^3/\text{person, year}$ ),  $n$  = number of persons and  $r$  = rest term.

However, this approach assumes that the entire net precipitation can be stored in the soil and rock, and neglects losses due to natural groundwater flow out of the system. In the prevailing type of terrain at Boda-Kalvsvik, the storage capacity of the subsurface strata is usually the limiting factor for the groundwater extraction as opposed to infiltrated volumes (Olofsson 2002). The aquifer properties should therefore be incorporated when performing groundwater balance modelling.

Olofsson (2002) developed a temporally dynamic numerical groundwater balance model, *GWbal*, taking into account recharge, extraction and storage properties, and tested this model in various municipalities around Stockholm, Sweden (Eqs. 2–5).

$$\sum_{i=1}^{365} \left( \sum_{g=1}^m N_i \cdot \phi_g \cdot A_g \cdot \tau_g = Q_i \cdot n_i \pm \sum_{g=1}^m \Delta S_{g,i} \right) \quad (2)$$

$$N_i = P_i - ET_i + R_i \text{ (if } N_i < 0 \text{ then } N_i = 0) \quad (3)$$

$$S_g = \sum_{j=1}^h \phi_j \cdot d_j \text{ (between } w_g \text{ and } D_g) \quad (4)$$

where,  $P$  = precipitation (mm),  $ET$  = evapotranspiration (mm),  $N$  = net infiltration (mm),  $R$  = artificial recharge (mm),  $\phi$  = infiltration factor (%),  $A$  = area ( $\text{m}^2$ ),  $\tau$  = homogeneity factor (%),  $Q$  = specific withdrawal ( $\text{m}^3$ ),  $n$  = number of users,  $\Delta S$  = storage, change in storage ( $\text{m}^3$ ),  $\phi$  = kinematic porosity (%),  $d$  = thickness of the soil and rock layers (m),  $w$  = depth to groundwater level (m),  $D$  = total depth of the aquifers (m),  $j = 1, 2, \dots, h$  are various soil and rock types at depth and  $g = 1, 2, \dots, m$  are various soil and rock types at the ground surface.

Withdrawal of groundwater is given as:

$$Q \cdot n = Q_p \cdot n_p + Q_s \cdot n_s \quad (5)$$

where  $Q_p$ ,  $n_p$  = permanent housing  $Q_s$ ,  $n_s$  = summer housing

These Eqs. (2–5) have two parts which are set in *GWbal* model as inputs

- The temporally dynamic water storage, which is based on parameters such as  $P$ ,  $ET$ ,  $N$ ,  $R$ ,  $\phi$ ,  $A$ ,  $\tau$ ,  $\Delta S$ ,  $\phi$ ,  $D$  and  $w$  for which climatic data are collected from Engqvist and Fogdestam (1984) and SMHI (2010c) and

literature values are used for some parameters. The maximum water storage capacity of each sub-catchment was based on the area of the sub-catchment (taken from Table 2), the distribution of geological formations within the sub-catchment (taken from Table 2) and their hydraulic properties, the stratigraphy (used from Fig. 5) and the minimum depth to the groundwater level [data received from the SGU (1996)]. The maximum storage capacity refers to total

pore space available or the size of the aquifers and not necessarily saturated.

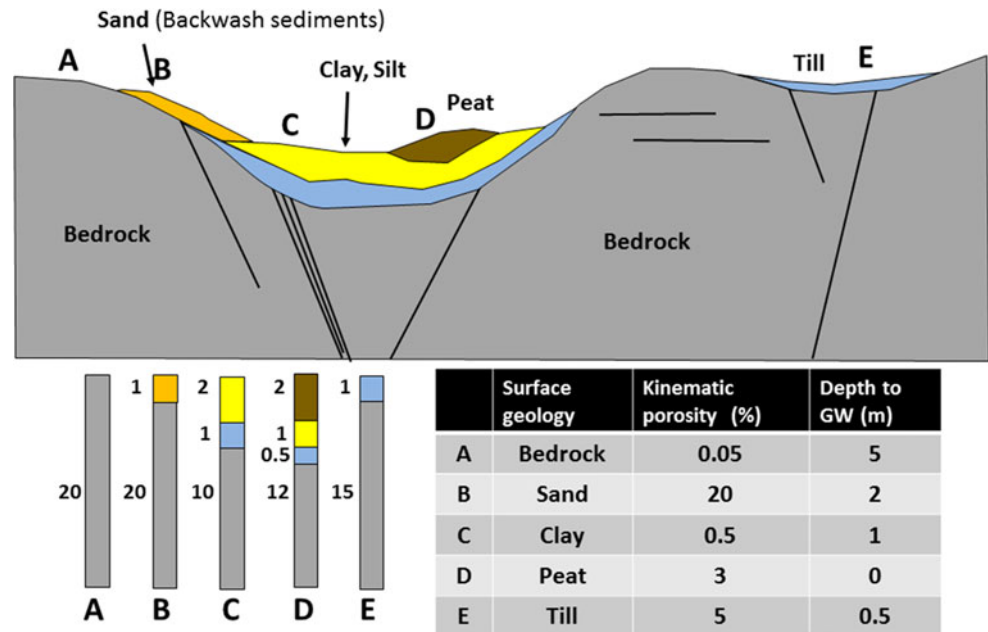
- ii) The water extraction, which is calculated on basis of parameters such as  $n$ ,  $Q$ . Equation 5 shows the extraction scenarios and in this case permanent housing is considered.

To estimate the total water supply demand in the different sub-catchments, it was assumed that each residence

**Table 2** Groundwater balance modelling data

Sub-catchment no.	Total area (1,000 m <sup>2</sup> )	Distribution of geological formations (%)					Maximum storage capacity (m <sup>3</sup> )	Number of houses
		Rock	Till	Clay	Sand	Peat		
1	114	59	18	23			2,613	0
2	176	59	8	33			4,601	64
3	174	37	38	25			4,667	2
4	147	58	14	28			3,660	32
5	76	61	31	8			1,204	19
6	84	46	32	22			2,039	11
7	226	51	29	20			5,159	21
8	60	59	38	3			888	10
9	65	50	15	35			1,858	0
10	106	32	48	20			2,686	0
11	68	56	20	24			1,602	0
12								
13	97	45	38	3	14		1,468	20
14	69	18	19	63			3,018	0
15	88	39	20	41			2,898	10
16	172	30	2	66	2		7,567	10
17	66	35	45	0	20		833	15
18	73	62	29	9			2,363	15
19	73	30	40	30			2,195	0
20	60	34	37	29			1,743	0
21	97	36	35	29			2,540	1
22	463	45	35	20			10,992	17
23	151	37	15	48			4,547	5
24								
25	92	23	20	57			3,846	1
26	114	29	17	40	14		3,609	4
27	259	45	24	20		11	12,168	11
28	112	39	39	16	6		2,410	22
29	204	53	9	38			5,940	35
30	129	47	21	32			3,614	65
31	71	24	62	9		5	2,358	0
32	55	34	0	66			2,390	1
33	88	37	57	6			1,687	13
34	93	23	34	29	14		2,686	7
35	56	13	0	87			3,105	0
36	196	40	27	24	8	1	5,214	41

**Fig. 5** Generalized typical stratigraphies and data used in the water balance modelling. Thicknesses of geological formations are exaggerated and given in meters. Values of kinematic porosity (%) are compiled from literature (Norton and Knapp 1977; Grip and Rodhe 1988). Depth to groundwater (minimum depth of water table below ground surface) and thickness of geological formations as well as the typical stratigraphies are generalized from the well archive data (SGU 1996), from previous geotechnical soundings and from local geological maps (Lindén 2001)



had three inhabitants. Today, some of the estates are used for summer housing but the degree of permanent residency in the area is steadily increasing until it reaches 100 % permanent housing, which is assumed to be a “worst case” scenario. For permanent households, the groundwater demand in the model was assumed to be 170 litre/capita/day, which was a reasonable estimate of the water demand as this region has a rather high sanitary standard. Output from GWbal model is a plot showing number of houses that could be supplied with given inputs. The model also accounts for specific dry years (extreme years with 30 % reduction in precipitation) in order to represent drought conditions with a reoccurrence frequency of approximately 20 years based on data from SMHI (2010c). Groundwater balance modelling performed by Olofsson (2002) using the GWbal model within some areas of Stockholm archipelago produced reasonable results of recharge and discharge volumes. Sazvar (2010), who attempted to compare the results of the GWbal model with several other water balance models in an adjacent area in eastern Stockholm, found that the former gave the most realistic results.

The possible water storage capacity of the aquifers is an important factor in the GWbal model, which needed to be estimated. Therefore, it was necessary to evaluate the stratigraphy of the area. Since no field survey was conducted to investigate the subsurface characteristics of the study area, total thickness of the geological formations and the stratigraphy used were based on geological maps (Lindén 2001) and the well archive data from the area (SGU 1996) (Fig. 5).

Periodically covered by salt or brackish water after the last period of glaciation, saline groundwater is still

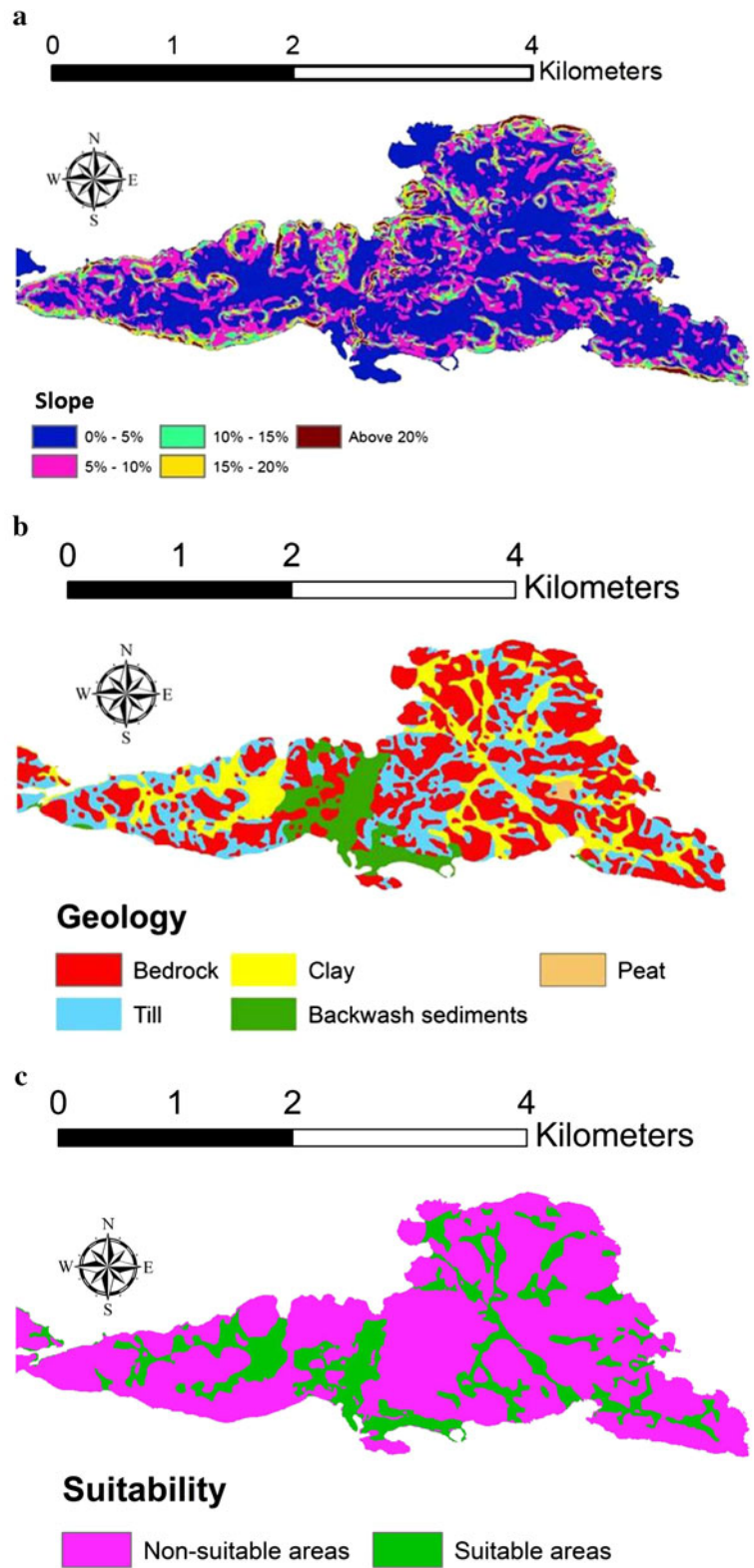
preserved at deeper levels within the region and more than 25 % of the drilled wells exhibit increased salinity concentrations 5–1,000 times greater than natural salinity concentrations due to precipitation (Olofsson 1996). Bleppony (2012) concludes that salinity of groundwater wells increases with the increase in well depth in Stockholm County. In order to minimize the risk for seawater intrusion and increased salinity due to fossil seawater, the total thickness of the groundwater storages in the model had to be limited and not allowed to extend far below the sea level. For geological formations commonly found at high topographical positions, the total storage stratigraphy was assumed to be thicker than the ones at lower positions. Estimated aquifer storage volumes were therefore calculated based on the land elevation above sea level (calculated directly from DEM in ArcGIS), the surface geology (Table 2), the stratigraphy and the maximum thickness of the storage (Fig 5). This gives a conservative value based on previous experiences regarding the probability of seawater intrusion in the region (Olofsson and Rönkä 2007). The average land elevation in the Boda-Kalvsvik area is about 15 m above mean sea level. The well archive data and geological maps of this area lead to the conclusion that the stratigraphy varies depending upon what type of geological formations that occur in the top layer (Fig. 5). Five typical stratigraphies were formulated based on the well archive data and previous geotechnical soundings in this type of terrain. If bedrock outcroppings occur at the surface at high topographical locations then the storage thickness was estimated to be maximum 20 m of crystalline rock. If the uppermost layer was clay, then its thickness was assumed to be 2 m covering 1 m of sandy-silty till and



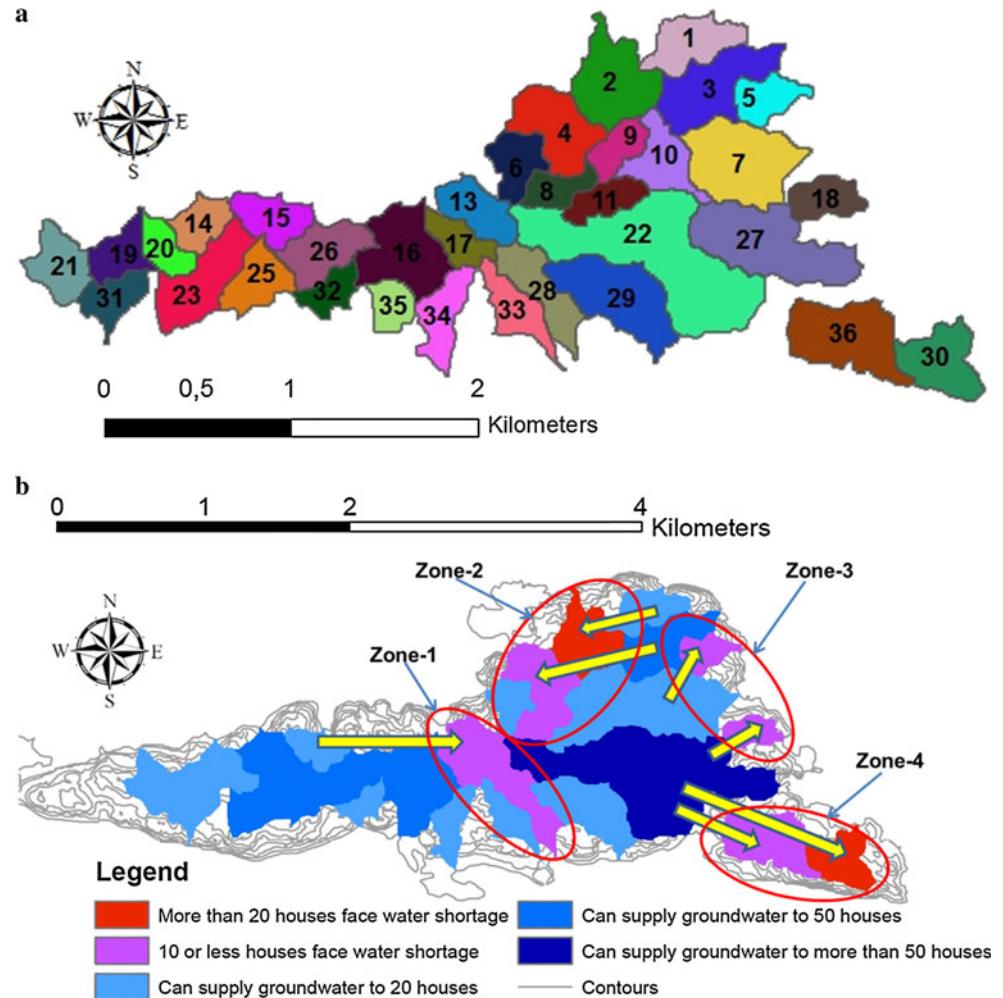
underlain by 10 m of bedrock. For till areas, the stratigraphy was defined as 1 m of till covering 15 m of bedrock. The stratigraphy of the peat was set to 2 m of peat covering 1 m of silt and 0.5 m of sandy-silty till on top of 12 m of

bedrock. If backwash sandy sediment was at the surface, then its thickness was assumed to be 1 m covering 20 m of the bedrock. Sand and gravel deposits can locally be much thicker but the values used here were set on a conservative

**Fig. 6** **a** Slope map, **b** geological formations, reclassified from digital data taken from SGU (1996), **c** suitability map



**Fig. 7** **a** Sub-catchments (catchments no. 12 and 24 are not seen here as they are too small in size and were not considered for calculations), **b** groundwater balance results. The yellow arrows show the possible additional supply to the areas facing water shortage from neighbouring sub-catchments with surplus water storage



basis due to lack of information. Full saturation was assumed beneath the groundwater levels, which were defined as a mean value for each geological formation (Fig. 5).

The hydrological response of the study area in the form of a topographic wetness index (TWI) was calculated in *ArcGIS* by dividing flow accumulation by slope (in radians). TWI is commonly used to quantify topographic control on hydrological processes and was first presented by Beven and Kirkby (1979) and the index is based on a digital elevation model (Eq. 5).

$$\ln(\alpha / \tan \beta) \quad (5)$$

where  $\alpha$  = the cumulative upslope area draining through a point (per unit contour length) and  $\tan \beta$  = the slope angle at that point.

The index communicates the water accumulation in the catchment in terms of the slope of the terrain (i.e.  $\alpha$ ) and the movement of the water down the slope in terms of the hydraulic gradient (i.e.  $\tan \beta$ ). TWI can quantify the effect of topography on runoff generation and serves as a

physically based index for approximating zones of surface saturation and the spatial distribution of soil water (Quinn et al. 1995).

## Results and discussion

It is estimated that about 70 % of the area of Boda-Kalvsvik comprises land surface with a 0–10 % slope (Fig. 6a). Therefore, the area in general could be classified to have gentle land slopes in most areas, with some more steeply sloping areas near the coast. It is important that subsurface dams should be placed on valleys with gentle slopes to be able to utilize maximum storage capacity behind the dam and to prevent rapid subsurface flows out of the system. Topographically, a gradient between 0.2 and 4 % has been considered adequate, but slopes of up to 15 % have been used for construction of subsurface dams (Nilsson 1988). Since most parts of the area fall on slopes from 0 to 10 %, slopes of up to 10 % were considered suitable for constructing subsurface dams, which were

**Table 3** Groundwater balance results

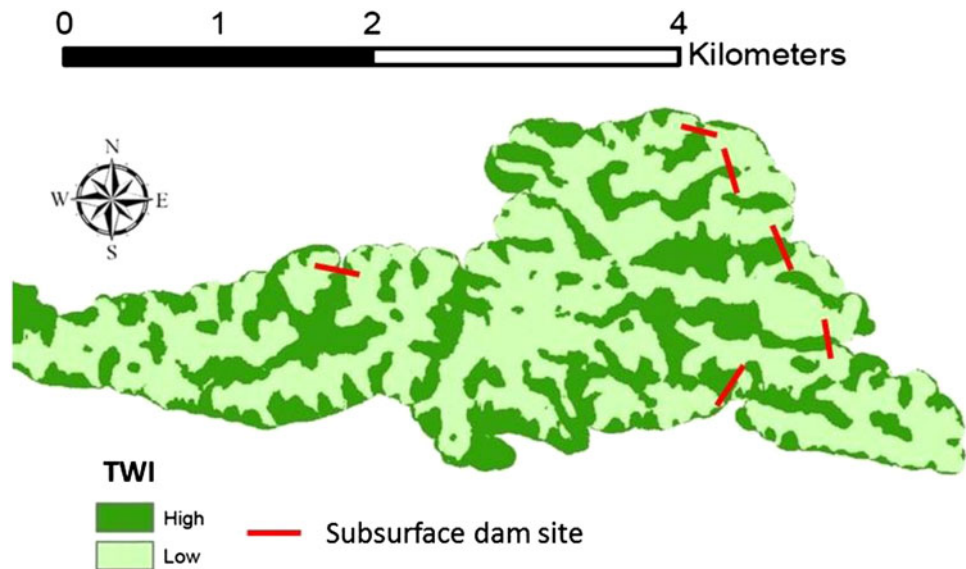
Catchment no.	Area (1,000 m <sup>2</sup> )	No. of houses currently need to be supplied	Max. no. of houses that could be supplied	Net balance (houses)
1	114	0	20	20
2	176	64	34	−30
3	174	2	35	33
4	147	32	27	−5
5	76	19	9	−10
6	84	11	15	4
7	226	21	38	17
8	60	10	7	−3
9	65	0	14	14
10	106	0	20	20
11	68	0	12	12
12				
13	97	20	11	−9
14	69	0	23	23
15	88	10	22	12
16	172	10	56	46
17	66	15	7	−8
18	73	15	9	−6
19	73	0	17	17
20	60	0	13	13
21	97	1	19	18
22	463	17	81	64
23	151	5	34	29
24				
25	92	1	29	28
26	114	4	27	23
27	259	11	90	79
28	112	22	18	−4
29	204	35	44	9
30	129	65	27	−38
31	71	0	18	18
32	55	1	18	17
33	88	13	13	0
34	93	7	20	13
35	56	0	23	23
36	196	41	39	−2

outlined on the slope suitability map. Outcropping bedrock covered roughly 50 % of the study area. Till and clay covered about 20 and 15 % of the land area, respectively. The remaining area consisted of sandy sediments and some isolated peat zones, which covered approximately 1 % of the land area (Fig. 6b). Originally the geological map had 11 geological classes, which were reclassified based on hydrogeological properties, such as combination of glacial and postglacial clay. The reclassified geological map and the slope map were combined into a geology-slope suitability map showing areas suitable for the construction of

subsurface dams, which were estimated to comprise about 20 % of the total area of Boda-Kalvsvik (Fig. 6c).

In total 36 sub-catchments were produced in *ArcGIS* with the *ArcHydro* extension, out of which two (sub-catchments 12 and 24) were too small, far less than the threshold set in the *ArcHydro* model, which was 1 % of the maximum flow accumulation of the study area and therefore were not included in the study (Fig. 7a). Furthermore, areas which consist solely of flat terrain were also excluded by the model. In this process an “island” was formed near sub-catchment 36 (Fig. 7a). Most of the omitted areas were

**Fig. 8** Topographic wetness index (TWI) map showing suitable sites for construction of subsurface dams



located close to the shoreline, within a distance of 200 m, which affords an additional benefit as the risk of the sea water intrusion into the storage aquifers was minimized.

Groundwater balance calculations of the area showed that some of the sub-catchments lacked sufficient recharge, while others had no water supply or only responded the required demand. Out of the 34 sub-catchments on which the groundwater balance was performed, ten were over-extracted, nine did not have any demand at all, one was self-sufficient and the remaining 14 were able to meet the demand and still had surplus water storage capacity. The most vulnerable sub-catchments which faced water shortages were number 2 and 30 (Fig. 6b). These sub-catchments were situated in the most populated areas of Boda-Kalvsvik. Sub-catchment 2 had an area of about 175,000 m<sup>2</sup> with water supply demand of 64 residences. The water storage capacity (total volume of the water that could be stored in existing stratigraphic situation) of sub-catchment 2 was approximately 4,600 m<sup>3</sup> and soil composition consisted of 59 % of bedrock, 33 % clay and 8 % till (Tables 2, 3).

Despite a relatively large area, the unsuitable soil composition made it impossible to store sufficient amounts of water, which resulted in an imbalance. The area of sub-catchment 30, which also faced water shortage, was about 129,000 m<sup>2</sup> and was supposed to supply 65 residences. Outcropping bedrock was predominant in this sub-catchment and occupied 47 % of the total surface area, whereas till and clay comprised 21 and 32 % of the surface area, respectively. The water storage capacity of sub-catchment 30 was 3,614 m<sup>3</sup>; however, it was still not capable of responding to the demand of 38 residences during dry periods (Tables 2, 3). From the groundwater balance results, four vulnerability zones were identified, which

should be supplemented with an additional supply from the neighbouring areas (Fig. 7b). Vulnerability Zone 1 consisted of three sub-catchments: 13, 17 and 28. The cumulative shortfall of this zone equated to the amount needed to supply 21 residences (10.7 m<sup>3</sup>). The neighbouring sub-catchments, i.e. 15, 23, 25 and 26 had surplus capacity to supply 92 residences (47 m<sup>3</sup>) (Fig. 7a, b; Table 3). TWI results showed the hydrological response of the sub-catchments. A higher value of TWI implied more upslope drainage area through a point (Fig. 8), similarly, a lower value implied a smaller drainage area through a particular point. The TWI map showed a high wetness index through the sub-catchment 15 (Figs. 7a, 8), which also fell within the suitable areas in the suitability map (Fig. 6c). Since the topographic and geological criteria for constructing subsurface dams were also fulfilled, sub-catchment 15 could potentially be a suitable site for a subsurface dam in Vulnerability Zone 1. Vulnerability Zone 2 comprised three sub-catchments: 2, 4 and 8, with an estimated cumulative supply deficit of 38 residences (19.3 m<sup>3</sup>). Adjacent to Vulnerability Zone 2 were sub-catchments 1 and 3, which could potentially supply 53 residences (27 m<sup>3</sup>) (Fig. 7a, 6b; Table 3). The suitability and TWI maps confirmed that both sub-catchments (1 and 3) could be potentially suitable sites for constructing subsurface dams (Fig. 6c, 8). Sub-catchments 5 and 18 together combine to form Vulnerability Zone 3, with an estimated supply deficit of 16 residences (9 m<sup>3</sup>) (Fig. 7a, b; Table 3). The neighbouring sub-catchments 7 and 27 could be individually dammed, which would increase the capacity to supply 96 residences (49 m<sup>3</sup>). Vulnerability Zone 4 was near Kalvsvik region, and comprised sub-catchments 30 and 36 (Fig. 7a, b). Zone 4 was estimated to have a supply deficit of 40 residences (20.4 m<sup>3</sup>), but could be supported by sub-catchment 22,

which was located adjacent to this zone. Sub-catchment 22 had the largest surface area of those in the study area, and had an estimated groundwater supply surplus of 64 residences (32.6 m<sup>3</sup>) (Fig. 7a; Table 3). The suitability map and TWI map confirmed that sub-catchment 22 could be dammed on the South-Eastern side (Figs. 6c; 8).

Sub-catchments with surplus water storage capacity can also supply more houses than what exist today and can therefore be important for future expansion planning. For instance, sub-catchment 22 and 27 (Fig. 7a, b) have huge groundwater storage capacities and can accommodate more houses in future.

## Conclusion

The developed methodology of using a combination of suitability analysis in GIS and water balance calculations, employing *GWbal* software to locate suitable sites for construction of subsurface dams is a new approach to evaluate and mitigate groundwater supply problems. Such dams have rarely been constructed in crystalline rock areas where the groundwater storage capacity is the limiting water supply factor. Geographic Information System (GIS) software has strong tools which can be used as a basis for decision-making through suitability analysis and groundwater balance model produced reasonable results with generalized data inputs. Out of the 34 sub-catchments of the study area, on which the groundwater balance was performed, ten were over-extracted, nine did not have any demand at all, one was self-sufficient and the remaining 14 were able to meet the demand and still had surplus storage capacity. Based on the suitability analysis and the topographic wetness index (TWI) results combined with results from the groundwater balance model, six suitable sites for construction of subsurface dams were located in the vicinity of the vulnerable sub-catchments. With the applied methodology it was demonstrated that the island of Boda-Kalvsvik likely experiences water supply stress in the most populated areas. Municipal authorities therefore either somehow discourage increases in permanent habitation in these areas or adopt new strategies in order to meet water supply demands in a sustainable way. The former case may not be practically viable to implement, and so for the latter case with rainwater harvesting (RWH) through subsurface dam construction and use seems to be a possible solution. The sub-catchments with surplus water storage capacity can also supply more houses and thus be important for future municipal planning. The new methodology showed encouraging results for regions with humid climate but having limited natural water storage capacities. The developed methodology can be used as a preliminary planning step for subsurface dam construction, establishing a base for more detailed field investigations.

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