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COLLECTED RAINFALL AS A WATER SOURCE IN DANISH HOUSEHOLDS – WHAT IS THE POTENTIAL AND WHAT ARE THE COSTS?

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ABSTRACT

The water resource, energy and economy aspects of rainwater collection are assessed to evaluate rainfall collection as an alternative option for sustainable water supply. A maximum of 229 million m^3/year of rainwater can be collected from Danish roofs, provided that all possible surfaces are used and all rain falling on the surfaces is collected. This is equivalent to 24% of the total present production of drinking water, which is mainly based on groundwater. From household roofs 64.5 million m^3/year can be collected if used for toilet flushing and washing of clothes. This is 68% of the actual demand for toilet flushing and washing of clothes in households and 22% of the total water consumption in households, but only 7% of the total present drinking water production in Denmark. From the society point of view there is neither an environmental nor an economic reason to systematically promote rainfall collection on a larger scale in Denmark. Thus it is important to see rainfall collection in a *local* context, and in each case to evaluate whether there are cheaper alternative water sources or options for minimising the water consumption. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Water consumption; rainfall collection; collection ratio; replacement ratio; energy; economy; sustainability.

INTRODUCTION

Water supply in Denmark

More than 98% of the Danish water supply is based on groundwater. However, groundwater depressions and leaking contaminants from agriculture and waste deposit sites are endangering the reservoirs. As a consequence, wells have been closed, and in areas close to big cities like Copenhagen the water supply uses more groundwater than is formed through natural infiltration of rain.

Denmark covers a total area of 43,000 km^2 and consists of four parts; the isles Zealand, Funen and Bornholm and the peninsula Jutland. The mean annual precipitation varies from 900 mm in the southwestern parts and 500 mm in the eastern parts, cf. Fig. 1 (left). The net annual precipitation is 30-50% of the mean annual precipitation and may either infiltrate to form groundwater or run off to form streams, rivers and lakes. Zealand, Funen and the northern and eastern parts of Jutland are covered with clayey and sandy moraine deposits whereas Bornholm situated south of Sweden consists of bedrock. In western Jutland the surface is sandy, and the groundwater formation is as large as 160 mm due to a large amount of precipitation and the favourable geological conditions. For comparison, it is only 41 mm in Zealand.

Sustainable use of groundwater

It is important to realise that water is not a finite resource. In principle, water can be abstracted from aquifers for an infinite number of years, provided that the groundwater abstraction is matched by an amount of

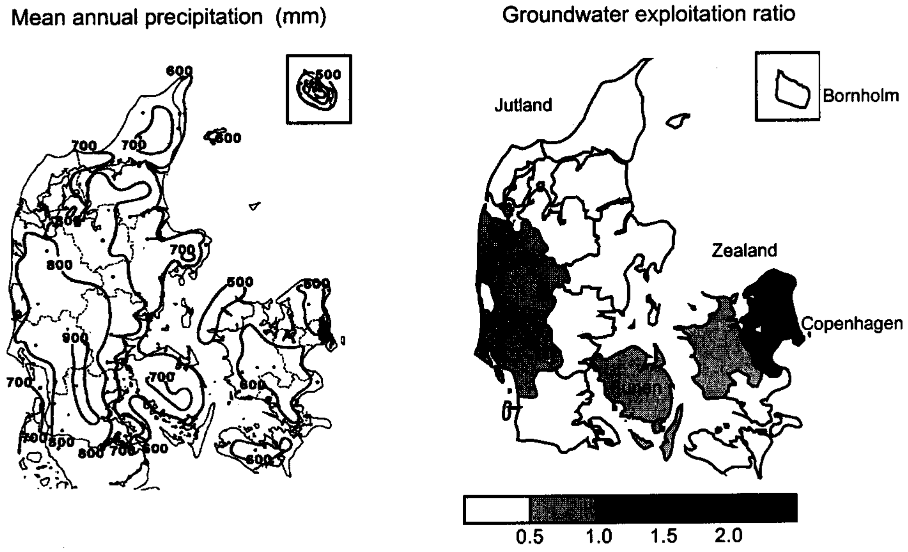
Table 1. Overview of the groundwater resource and current abstraction rate for the four Danish provinces Jutland, Funen, Zealand and Bornholm.

	Area	Mean ann.prec.[1]	Net ann. prec.[2]	Groundw. formation[3]	Sust. groundw. abstraction[2]		Current abstraction[4]	Expl. ratio
	(km^2)	(mm)	(mm)	(mm)	(mm)	(10^6 m^3/yr)	(10^6 m^3/yr)	(-)
Jutland	29,797	763	318	160	51	1,489	671	0.45
Funen	3,473	637	203	55	24	83	54	0.65
Zealand	9,358	606	186	41	28	253	212	0.84
Bornholm	588	566	270	-	31	18	6	0.33
Denmark	43,216	682	276	125	43	1,843	943	0.51

[1] Calculated from average values for the period 1961-90 (DMI, 1997). [2] Calculated from values published by a governmental consensus group (DEPA, 1992). [3] Calculated from values published by the counties in 1996. [4] Calculated from values published by the counties in 1995-96.

groundwater recharge that assures replenishment of the aquifer with rain. However, abstraction at any rate, be it small or large, will lead to physical effects in nature such as decreasing groundwater tables and drying out of local streams. Sometimes a decreasing groundwater quality is connected with these effects due to e.g. release of nickel and pyrite or intrusion of salt water. Sustainable use of groundwater implies that abstraction should occur at a rate that prevents such undesirable effects to occur. However, it is not an easy task to define the magnitude of a sustainable groundwater abstraction.

The Danish Environmental Protection Agency gave in 1992 an assessment of the sustainable groundwater abstraction in the country (DEPA, 1992). The work was based on estimating the net precipitation and judging based on experience the part of the groundwater recharge that can be abstracted without unacceptable physical changes to the hydrological system. It appears from Table 1 that the sustainable groundwater abstraction is only 4-8% of the mean annual precipitation, 12-16% of the net annual precipitation and 32-


Mean annual precipitation (mm)

Groundwater exploitation ratio

Fig. 1. Left: Geographical distribution of the mean annual rainfall in Denmark (DMI, 1994). Right: The groundwater exploitation ratio in the 14 Danish counties.

68% of the groundwater formation. The "true" sustainable groundwater abstraction may be even lower than these estimates since they do not account for future contamination of aquifers with e.g. nitrate and pesticides.

In principle, the exploitation ratio (current abstraction/sustainable abstraction) is below one for each of the four parts of Denmark (Table 1, last column). However, there are large geographical variations within each part of the country, and the exploitation ratio is well above one around the city of Copenhagen, cf. Fig. 1 (right). The same is the case in several smaller areas where local aquifers are over-exploited at the moment.

Possible options for the future

It is clear from the above that groundwater abstraction at the current rate is not sustainable in some parts of Denmark and hence, alternative water sources and options for minimising the water consumption are being explored. At the same time, Denmark is today oriented towards "green" solutions where urban planning is re-thought from an "urban ecology" perspective. This brings local solutions into focus as opposed to the conventional centralised water supply and distributions systems. Rainwater collection from roof areas is often proposed as a more sustainable water resource in urban areas, but it has not been made clear to what extent rainwater collection can actually replace the present consumption of drinking water. This study sets out to determine the collectable rainfall resource for the country as a whole, so that rainwater collection can be evaluated and compared with other alternative options. Focus is on the water resource aspects and we refer to Albrechtsen et al. (1998) for details regarding economy and energy aspects.

RAINFALL COLLECTION

Outline of a rainfall collection system

A typical rainfall collection system for Danish household conditions is outlined in Fig. 2 (left). Runoff water from the roof surface is captured by a pre-filter placed on the downpipe and flows to a tank where it is stored for later usage. The rainwater is pumped from the tank via a floating filter and used for toilet flushing and washing of clothes.

The water balance of the system is illustrated for an average year in Fig. 2 (right), using 75 m^2 of effective roof area and 3 inhabitants (40 l/cap/d for flushing and 10 l/cap/d for washing) as a basis for the calculations. The mean annual rainfall is 600 mm/year in the example but the rainfall is not uniformly distributed over the

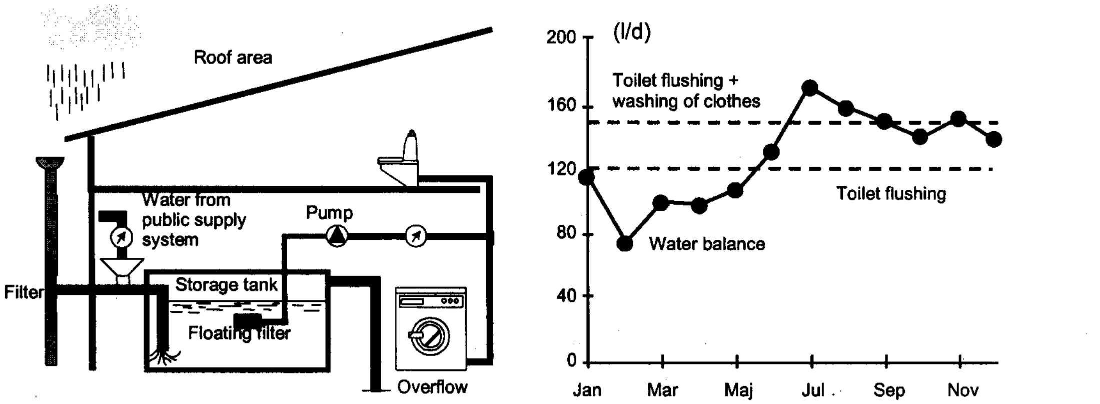


Fig. 2. A typical rainfall collection system where the storage tank is situated in the basement and the rainwater is used for toilet flushing and washing of clothes. Left: Outline of the system. Right: Illustration of the mass balance for the storage tank.

year. There is enough rain during 8 months (June-January) to satisfy the water demand for toilet flushing but the additional water demand for washing clothes can only be satisfied in 4 months (July-September and November). The rain water deficit during part of the year is balanced partly by the storage tank and partly by adding drinking water from the public water supply in the dry season.

As indicated in Fig 2. (left) the public water supply is not connected directly to the in-house water distribution system. An air gap is required where drinking water enters the storage tank to minimise the risk for contaminating the public water supply system. Thus, the pressure energy of normal tap water is lost and energy has to be added again via pumping to distribute the water.

Ideally, it is possible to utilise almost all the rainfall that runs off from the roof area but this would require an unrealistically large volume of the storage tank. For a realistic volume the tank will be filled up during heavy rain storms, resulting in excess water being spilled, e.g. to an infiltration pit or to the public sewer.

Hydrology of rainfall collection systems

When assessing rainfall collection systems detailed knowledge about the type and quality of roof materials, actual evaporation etc. will generally not be available. This justifies that simple models should be used when describing their hydrologic behaviour. The following relation may describe the rainfall-runoff process

$$V_{runoff} = v_{rain}\ \psi\ A = v_{rain}\ A_{eff} \tag{1}$$

V_{runoff} is the volume (in m^3) of runoff water resulting from rain with depth v_{rain} (in mm) over the area A. The runoff coefficient ψ reflects that only part of A will effectively contribute with runoff. Thus $A_{eff}=\psi A$ is denoted the *effective area*. ψ is different from the identical term used within urban storm drainage where extreme rainfalls are in focus and evaporation is limited. In relation with rainfall collection ψ reflects the average behaviour (e.g. over a year) of a runoff surface, including the effects of evaporation, snow gliding etc.

The mass balance of storage tanks can be evaluated by using a hydrological storage model and high-resolution rainfall time series as input to simulations. The results depend, of course, on the effective surface area (A_{eff}), the volume (V) of the tank and the consumption (Q) of water from the tank, whereas the flow time from the surface to the tank (a few minutes) can be neglected. However, using the effective area A_{eff} as a scaling factor only two important parameters remain, namely the specific storage volume (v) and the specific water consumption (q)

$$v = \frac{V}{A_{eff}} \quad ; \quad q = \frac{Q}{A_{eff}} \tag{2}$$

Fig. 3 (left) shows the collected rainfall on an average annual basis as a function of the specific water consumption. The curves correspond to different values of specific storage volume (v) and illustrate that a large storage tank or large water consumption will allow more rainwater to be collected. It appears that the gain from using tanks larger than 4 m^3/100 m^2 effective area is rather limited.

For large q, the curves in Fig. 3 (left) meet at a level of 78.1 m^3/100 m^2 effective area, which corresponds to the mean average rainfall (781 mm) of the historical rain series used as input to the simulations. A general set of curves was produced using the mean annual rainfall as scaling factor. The curves shown in Fig. 3 (right) give for a tank size of 4 m^3/100 m^2 effective area the collection ratio, c, of the mean annual rainfall (collected rain/fallen rain) as a function of the specific water consumption. The small differences between the curves illustrate that, naturally, for a given tank size more water is spilled in areas with high mean average precipitation than in drier areas.

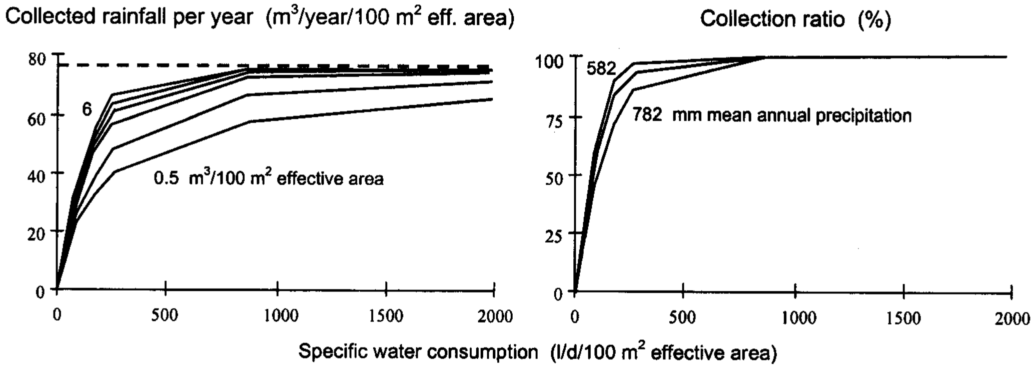


Fig. 3. Results from computer simulations of rainfall storage tanks. Left: Collected rainfall for different tank sizes (0.5, 1, 2, 3, 4 and 6 $m^3/100\ m^2$ effective area). Right: Normalised curves giving the collection ratio (in %) for different levels of the mean annual precipitation.

Estimating the collectable rainfall resource

Graphs as shown in Fig. 3 (right) are easily computed and may be used as a general tool to evaluate the performance of rainfall collection systems. However, it has to be considered that some roofs may not be usable due to either building preservation restrictions or specific roof materials resulting in too low water quality. This leads forward to the following general equation that can be used for estimating the collectable rainfall resource, R_c

$$R_c = MAP\ f\ \psi\ A\ c = MAP\ f\ A_{eff}\ c = R\ c \quad ; \qquad R = MAP\ f\ A_{eff} \tag{3}$$

MAP is the mean average precipitation, f expresses that only part of the total roof area is useable, $A_{eff}=\psi A$ is the effective surface area, and c is the collection ratio. R is the maximum rainfall resource (without deducting spilled water) and can be estimated without prior knowledge about the water consumption and c.

THE MAGNITUDE OF THE RAINFALL RESOURCE

Basic data

Data about roof materials and numbers, types and use of buildings were obtained from central databanks at the Ministry of Housing (MH, 1997). Further data about population density in different household categories was taken from the national statistical yearbook (DS, 1996). The total 478 km^2 of roof area in Denmark roughly covers households (182 km^2), industry and trade (212 km^2) and institutions (84 km^2) but much more detailed information is available in the database. The total area is distributed between the following roof material categories: Built-up asphalt and roofing felt (16.4%), fibrous cement (50.9%), concrete and tile (20.5%), metal (6.9%), thatched roof (1.4%), PVC and glass (0.2%) and other materials (3.7%).

Although part of the fibrous cement roofs contains asbestos, the total area covered with fibrous cement was included in the investigation since it is not very likely that eroded asbestos would enter the human respiratory system (Albrechtsen, 1998). Thatched roof was the only type of roof material that was systematically left out (due to coloured runoff water). In addition, roofs of theatres, museums and hospitals (part of the "institutions" group above) were left out because using runoff water from such surfaces was considered impractical or conflicting with building preservations regulations. In total, this lead to f-values in the range 95-98%, depending on the building category. A short literature study gave only very few documented references about the magnitude of ψ for different roof materials. Thus values from 70-75% were used based on information from manufacturers of rainfall collection systems and the author's judgement.

The maximum rainfall resource for the country as a whole

The maximum rainfall resource (*R*) was estimated to give a rough estimate of the potential replacement of drinking water (Table 2). A total of 229 million m^3/year of rainwater can be harvested from all surfaces, corresponding to 24% of the total water consumption. Hereof, 91 million m^3/year comes from household roof areas, covering 31% of the current water consumption in households.

Table 2. Calculation of the maximum rainfall resource for the country as a whole, based on the mean average rainfall (682 mm).

	Roof area[1]	Water consumption[2]	Rainfall resource			Replacement ratio
			MAP A	*MAP A f*	*R=MAP A f* ψ	
	(km^2)	(10^6 m^3/year)	(10^6 m^3/year)			(-)
Households	182	295	124	122	91	0.31
All buildings	478	943	326	309	229	0.24

The basic statistics are taken from [1]a central database at the Ministry of Housing (MH, 1997) and [2]calculated as in Table 4.

The collectable rainfall resource for households

The collection ratio (*c*) depends on the actual water consumption according to Fig. 2 (right) and thus, the collectable rainfall resource can only be estimated after specifying the rate at which rainwater is intended to be used. Obviously, there is a potential for collecting and using rain in some types of industries but only households were studied detailed. The daily water consumption in households is now down to about 160 l/cap/d in Copenhagen and other parts of Denmark where water savings have been promoted for some years. This includes the following consumption categories and approximate rates: Bath and hand washing (45 l/cap/d), toilet flushing (40 l/cap/d), washing of clothes (10 l/cap/d), dish washing and cleaning (25 l/cap/d), kitchen (20 l/cap/d) and other uses including leakage from the distribution system (20 l/cap/day). It is important to stress that rainwater is not considered as potable water in Denmark, due to public health considerations. This means that the only in-door consumption categories where rainwater can be used is toilet flushing and washing of clothes (Albrechtsen, 1998).

The specific water consumption (*q*) for "toilet flushing plus washing of clothes" is calculated in Table 3 based on average values of the number of occupants and the size of the roof area (ψ=0.75) of four different households categories. It appears that there is a big difference in corresponding collection ratios between the household categories. The collection ratio is high (94%) for apartment houses where the water consumption is high relative to the effective roof area. In contrast, it is low for farmhouses and detached houses in residential developments (55%) where the water consumption is low relative to the effective roof area.

Table 3. Collection ratios for four household categories when using rainfall for toilet flushing plus washing of clothes.

	Per household		Water consumption		Collection ratio
	Occupants[1]	Roof area[2]			
	(cap.)	(m^2)	(l/d)	(l/d/100 m^2 eff. area)	(-)
Farmhouses	2.75	130	138	141	0.66
Detached houses	2.65	130	133	136	0.65
Row houses	2.13	76	107	187	0.82
Apartments	1.70	26	85	436	0.94

The basic statistics are taken from [1]Danmarks Statistik (1996) and [2]a central database at the Ministry of Housing (MH, 1997).

Table 4. Maximum and collectable rainfall resource, and water consumption and replacement ratio for each of the four household categories when using rainfall for toilet flushing and washing of clothes.

	Roof area	Rainfall resource		Water consumption		Replacement ratio	
		R	R_c	Toilet+clothes	Total	Toilet+clothes	Total
	(km^2)	(10^6 m^3 $year^{-1}$)		(10^6 m^3 $year^{-1}$)		(-)	
Farmhouses	19.3	9.3	6.1	7.2	22.6	0.85	0.27
Detached houses	117.2	58.6	38.1	47.0	146.6	0.81	0.26
Row houses	22.2	11.2	9.2	11.6	36.3	0.79	0.25
Apartments	23.2	11.8	11.1	28.4	88.8	0.39	0.13
Households	181.9	90.9	64.5	94.2	294.6	0.68	0.22

Based on the collection ratios from Table 3 the collectable rainfall resource (R_c) constitutes a total of 64.5 million m^3/year rainwater (Table 4), which is about 30% less than the estimated maximum rainfall resource. The water consumption for toilet flushing and washing of clothes was calculated from the total number of each type of household, the average number of persons occupying each household and a water demand per capita of 50 l/d. When comparing with the water consumption for toilet flushing and washing of clothes the replacement ratio is low (39%) for apartments due to the little available roof area, but it is high (79-85%) for other household categories where more roof area is available. This illustrates again the big difference between household categories. Compared with the total consumption in households the replacement ratio is only 13-27%.

DISCUSSION

A maximum of 229 million m^3/year of rainwater can be collected from Danish roofs, provided that all possible surfaces are used and all rain falling on the surfaces is collected. This is equivalent to 24% of the total present production of drinking water, which is primarily based on abstracted groundwater. From household roofs 64.5 million m^3/year can be collected if used for toilet flushing and washing of clothes. This is 68% of the actual demand for toilet flushing and washing of clothes in households and 22% of the total water consumption in households, but only 7% of the total present drinking water production in Denmark.

Experiences from pilot collection systems indicate that the energy consumption related with pumping rain-water from the storage tank is in the range 0.3-0.5 kWh/m^3. This is not alarming compared with the 0.39 kWh/m^3 used for production and distribution of water in the public supply network. However, due to the required air-gap between the public water supply system and the storage tank, added drinking water consumes energy twice. This highlights an antagonism; if focusing solely on the water resource aspect, e.g. on saving drinking water, rainfall collection should be implemented primarily in apartment houses (with big energy expenditure) because in this case there will be minimum spill to the sewer system (the collection ratio is high). However, if focusing on energy consumption, rainfall collection should be implemented primarily in detached houses where the replacement ratio is high, but where the collection ratio is low.

The production costs for drinking water in Denmark is DKK 1-10/m^3, depending on the location. However, the full costs of water today include a number of taxes to cover e.g. wastewater treatment and environmental protection. This results in full water costs up to DKK 35/m^3 in some areas. For comparison, experience from pilot systems in apartment buildings indicates the present value (including both construction and maintenance costs) of collected rainfall to be in the range DKK 26-83/m^3. Costs down to DKK 10/m^3 can be found for detached houses if the collection system is home made. This underlines that rainfall collection is not economically attractive from a private economy perspective unless exemption from taxes are granted.

Rainfall collection can only cover a (minor) part of the Danish water demand and it will not in general replace the present centralised water distribution systems. The present production capacity will have to be maintained to ensure water supply under draught conditions and society's loss of income due to exemption from taxes will have to be balanced in some way, probably by increasing the water price. Moreover, rainfall collection on a larger scale will be costly, even though lower wastewater and stormwater flows will probably reduce the societal costs somewhat. As an example, there are almost 1 million detached houses in residential areas across Denmark. Using today's commercial prices (DKK 15.000 per installation) it would take an investment of DKK 15 billion to collect rainfall from all these properties, replacing only 4% of the total Danish water demand. There is reason to believe that the water consumption could be decreased or the groundwater recharge increased with a similar amount of water in a much less costly manner.

The large groundwater exploitation ratio in the Copenhagen area which is caused by the large population density and the low groundwater formation consists a problem that will have to be solved in the future. Part of the problem may be solved by continuing efforts to decrease the water consumption and even by introducing rainfall collection when it is economically feasible, However, other options like groundwater production through artificial recharge or treatment of surface water should also be investigated. In the end, import of drinking water via pipelines from other regions with abundant groundwater resources may turn out to be less costly and more practical than local solutions like rainfall collection.

CONCLUSIONS

From the society point of view there is neither an environmental nor an economic reason to systematically promote rainfall collection on a larger scale in Denmark. Thus it is important to see rainfall collection in the right context, based on local circumstances and local problems, and in each case to evaluate whether there are cheaper and more practical alternatives. There may be an environmental point in promoting rainfall collection in and around Copenhagen and in other areas with too heavy exploitation of the groundwater. On the other hand, it seems pointless to promote rainfall collection e.g. in western Jutland, because there is no water shortage at the moment.

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