# Evaporation in 2$^{nd}$ Generation Willow-Based, Zero-Discharge Wastewater Treatment Facilities

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**Quick Appraisal**

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# Preface

This quick appraisal of the water relations in 2[nd] generation willow-based wastewater treatment facilities (2GWTF) was commissioned by SalixGreenTech A/S in April 2021. The objective was to evaluate the compatibility of 2GWTF with the current regulations for zero-discharge, planted basin willow wastewater treatment facilities in Denmark.

Lenglern, April 2021

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# Content

# Summary

A desk study was performed to assess the compatibility of a new willow-based wastewater treatment facility (2GWTF) concept with the Danish regulations. The new design uses considerably less area compared to the first generation willow-based wastewater treatment facilities (1GWTF) and can be customised for operation in a range of different climatic conditions. These traits together with reduced maintenance costs make 2GWTF an attractive solution for decentralised wastewater treatment for individual households or small communities in rural areas. The focus of the study was on the water balance, especially the prospects for the facility to fully evaporate the waste and rainwater inflow on the long-term and to be able to safely buffer the seasonal fluctuations of the water storage as affected by weather variability.
For comparison with the Danish regulations, the so-called crop coefficient, a core parameter of the simple evaporation model, was set to the suggested reference value of 2.5. Using ten years averaged monthly weather data across Denmark, the minimum facility length and the minimum wastewater storage capacity that enable zero-discharge operation were determined. The estimated values fell well within the ranges of the flexible facility design. While the estimated requirements for the facility length were close to the default values, the default storage capacity needs likely to be enlarged. Optimal adaptation to the Danish climatic conditions requires larger flexibility in the storage volume of the facility per unit facility length.
The study concludes that given the assumptions and parameters used in the simulations, the new facility design is equally compatible with the Danish regulations as the larger 1GWTF. As the reference parameters and boundary conditions suggested by the Danish guidelines have not yet been scientifically investigated, effective monitoring of the facilities is recommended. Simple procedures to intervene where necessary exist that reduce the risk of pollution in case of unexpected malfunctioning of the new facility design. The results from this study suggest that the risk of pollution of the environment for the new facility design is not higher compared to the first generation.

# 1. Introduction

Wastewater treatment with willow offers an attractive option to digest the organic fraction in wastewater and remove water by transpiration. Zero-discharge, willow-based wastewater treatment facilities (WTF) are of particular advantage in areas remote from centralised wastewater treatment plants with high availability of land. WTF can be scaled from household to community level and can replace the obsolete cesspool technology.
Using wastewater treatment facilities in Denmark is regulated by the Ministry of Environment of Denmark (MST), which publishes the legal requirements and guidelines for the establishment of first generation (1G) zero-discharge, planted wastewater facilities on their web-sites (Gregersen et al., 2003b).
One critical factor on zero-discharge facilities is to maintain a dynamic steady state water balance, i.e. that the inputs into the system equate on average the outputs and that seasonal fluctuations of the water storage are smaller than the storage capacity.
The water balance equation is

$$0 = F_{ww} + P - R - E_t + \Delta_S \quad (1)$$

with $F_{ww}$ as wastewater input flux, $P$ precipitation, $R$ run-off, $E_t$ as total evapotranspiration comprising evaporation from soil ($E$), transpiration from plants ($T$) and evaporation of intercepted rain water ($I$), and $\Delta_S$ as rate of change of water storage in the system, all of which related to a relevant reference frame. This frame must consider the correct combination of area and facility based water flux rates, which is not trivial for such facilities.

Apart from $F_{ww}$, all water fluxes fluctuate seasonally. The design of the facility must assure a capacity to buffer these fluctuations especially the $\Delta_S$ within safe margins in both ways, i. e. avoiding overflow of wastewater into the environment and avoiding drought stress for willow trees in dry periods. The design of such facility requires data on the climate, foremost the seasonal variability of precipitation, but as well factors that affect evaporation and plant growth, plant physiological parameters and the wastewater generation rate.
In a background report, Gregersen et al. (2003a) collected the then existing data from 1GWTF in Denmark. A key component is the estimation of evaporation, which they based on a Food and Agriculture Organisation (FAO) concept:

$$E_t = K_C E_0 \quad (2)$$

with $K_c$ as the crop coefficient and $E_0$ the potential evaporation.
From the then existing 1GWFT data, the average $K_c$ for willow was estimated to reach a value of 2.5 times the reference potential evaporation ($E_0$), enabling an evaporation of, e.g., 1500 mm or more per year, i. e. about 2/3 of that wastewater and the rest being precipitation. In these calculations, it was assumed that no wastewater has ever left the systems other than by evaporation and transpiration. Such rates are about one to two times higher than the total evaporation measured at the short rotation willow biomass plantation field research infrastructure at the DTU-Risø campus (Wang et al., 2019; Wang et al., 2018) with highest daily evaporation rates reaching up to 5 mm $d^{-1}$.
New technological development of a second generation (2G) WTF aims at reducing the area requirements and costs per unit processed wastewater within the same or even an improved environmental safety margin. The 1GWTF were 8 to 10 m wide and several 10s of m long

sealed basins, filled with soil and planted with willow. The willow trees are maintained as short rotation coppice which is watered with wastewater and rain. The new design builds a new plant inhabited structure with a dedicated volume to store and buffer wastewater flows. Compared to the 1GWTF, the new design decreases the area of occupied land used per unit wastewater treatment capacity, by increasing the plant available water storage capacity per unit area, by increasing the evaporation rate per unit area and by reducing the water uptake from rain. All these novel traits mutually support each other, e.g., the higher evaporation rate decreases area and storage capacity requirements. Increased storage capacity per unit area enables buffering fluctuations more effectively and supplies the willow trees with water in dry periods with high evaporative demand. Microbial processes digest the organic waste components and mobilise nutrients that support intensive willow growth, which in turn establishes high leaf area per unit area ground (leaf area index, LAI) and thus evaporative potential for two reasons: Up to a certain LAI value, the transpiration increases with LAI. The interception evaporation (evaporation of liquid water on the canopy surfaces, i.e. leaves) increases over the whole possible range with LAI if rain intensities are high enough.
The increased transpiration rate is supposed to be accomplished by a continuously sufficient water supply, high leaf area and additionally supported by the strip-type canopy structure of two rows of densely planted willow, 4 m wide, arranged perpendicular to the main wind direction. This windbreak like canopy design is known to increase the coupling of the canopy with the atmosphere, maintaining high leaf to air water vapour pressure gradients and thus transpiration (Jarvis and McNaughton, 1986). Knowledge on this kind of vegetation is sparse. Windbreaks are normally not irrigated. Growth of windbreaks is thus usually rather hampered and evaporation limited by soil water availability.

# 2. High evaporation rates in willow challenge the theoretical upper limits for evapotranspiration

The FAO (Allen, 1998) has adopted an approach to describe the effect of the canopy structure on the crop coefficient (Fig. 1). The relationship is limited to a maximum $K_c$ value of 2.5 (Fig. 1b), when trees are surrounded by dry surfaces, heating up the boundary layer and increasing potential evaporation. For trees surrounded by well-watered vegetation, this $K_c$ threshold value reaches only up to 1.4. Usually, $K_c$ values rarely exceed 1.3, a level well supported by our measurements in a willow short rotation coppice at Risø. However, based on the high evaporation rates found in Danish 1GWTF, Gregersen et al. (2003a) recommended using a $K_c$ value equal to 2.5 as reference for WTF.

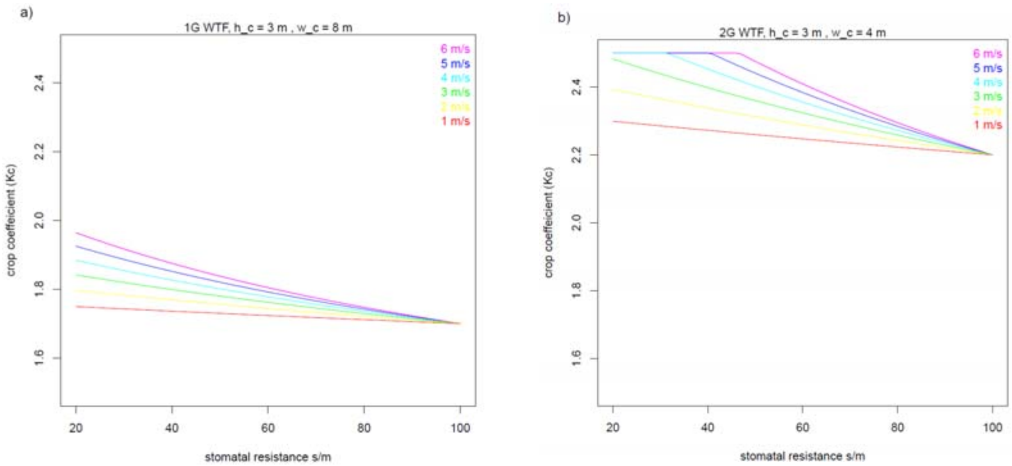


Fig. 1: Dependency for the crop coefficient for a) a 1GWTF and b) 2GWTF from stomatal resistance and wind speed (Allen, 1998), with h_c and w_c as canopy height and width, respectively.

The results show the extremely high evaporation potential of well-watered willow plantations. But according to theory, halving the width of the canopy stripe will even increase the $K_c$ value and it would be much higher, if the function would not limit $K_c$ to maximum 2.5.
The data observed in Danish 1GWTF are three-year averages. As over large parts of the year the willow trees do not have leaves, the evaporation must be much higher than the average during summer months, thus challenging the upper $K_c$ threshold value in the maximum growing season. These findings and considerations suggest that the limitation of $K_c$ that works apparently well in extended crop plantations might need to be revised to adequately describe evaporation in stripes of dense willow plantations. Initially, the new 20 m long design of the 2GWTF assumed a required $K_c$ value of 3.3, a value higher than the maximum value that the FAO approach suggest, exceeding the reference value for 1GWTF. But the next will show that actual $K_c$ value for 2GFTP can be lower than that.
As mentioned above, the reference frame for the water fluxes must be chosen with care. The potential evaporation is calculated in mm per unit time. All flows of the water balance equation, eq. (1), are estimated in $m^3$ water per unit time and facility. For the above estimations of the required $K_c$ value = 3.3 to establish steady state in the 2GWTF, the planted area and thus the physical extension of the built facility in its original concept of 75 $m^2$ ($A_{fac}$), while the willow canopy occupies 111 $m^2$, taking overhanging branches of at minimum 0.725 m beyond the margins of the facility base ($A_{can}$) into account. The $A_{can}$ is thus ~1.5 of $A_{fac}$. This means that the required $K_c$ assumed on the basis of $A_{fac}$, i.e. 3.3, can be relaxed to a value of 2.2 (i.e. $= 3.3\, A_{\text{fac}}/A_{\text{can}}$), i.e. even a bit smaller compared to reference value for 1GWTF.

Consequently there are no higher requirements on $K_c$ for the 2GWTF compared to the regulations but there are a couple of reasons to expect higher transpiration rates in the new, slimmer facilities.

# 3. Dimensioning of 2nd generation willow based wastewater treatment facilities for Denmark

The design concept of the 2GWTF allows for some flexibility. The facility length per unit expected wastewater inflow can be adapted to the local climate. Contrary to the 1GWFT the wastewater storage capacity per unit facility length can be adapted to the local conditions, by adjusting the cross-section of the storage volume. In order to show the viability of the 2GWTF design with respect to the water balance, the minimum facility length and minimum water storage capacity were calculated covering the climates of Denmark.
The minimum facility length ($l_{min}$) is defined as the length of the 2GWTF that enables a steady state water balance, i. e. the fulfilment of eq. (1) in the long-term over several years. If the actual facility length is larger than this value, one condition for zero-discharge WTFs is fulfilled.
The minimum water storage capacity ($\kappa_{min}$) is defined here as the average maximum difference in the net cumulative water loadings across different months, which is addressing the seasonality of the terms of the water balance equation. As for this quick appraisal, like with the background study for eth 1GWTF, only average climate data was available, the actual differences can exceed this simulated ranges. To fulfil the other condition for zero-discharge WTFs the realized $\kappa$ should thus be larger than $\kappa_{min}$ to also cover extreme climatic events.
The terms of the water balance equation, eq. (1), were estimated for averaged weather data (2001 - 2010) that was provided by the Danish Meteorological Institute on a 20 x 20 km grid (Wang, 2013). The facility parameters were used as listed in Table 1. To stay comparable with the Danish Guidelines, a $K_c$ value of 2.5 was adopted. The reference potential evaporation was calculated based on the area covered by the canopy. Run-off from the slanted soil surface at the outer margin of the facility and possible active rainfall exclusion was neglected, both of which would relax the demand for high $K_c$ and $\kappa$ values.

Tab. 1: Parameters for estimating the water balance of 2DWTF in Denmark in default design.

| Parameter | description | value | unit |
|---|---|---|---|
| $w$ | width of the facility base | 3.75 | m |
| $l_d$ | default length of the facility base | 20 | m |
| $A_{fac}$ | default area of the facility base | 75 | $m^2$ |
| $A_{can}$ | minimum default ground area of willow canopy (0.725 m overhanging branches at each edge) | 111.5 | $m^2$ |
| $V_{p,n}$ | normalised pore volume, as defined as pore volume per unit facility length | 2.48 | $m^2$ |
| $\kappa_d$ | default water storage capacity of the facility ($V_{p,n}$ $l_d$) | 49.5 | $m^3$ |
| $K_c$ | crop coefficient | 2.5 | |
| $F_{ww}$ | five person units' wastewater generation, assumed uniform across a year (10 $m^3$ month$^3$). | 120 | $m^3$ $yr^{-1}$ |
| $C_{Eo}$ | conversion factor for potential evaporation from mm to $m^3$ per facility (E0 $A_{can}$/1000). | 0.11154 | $m^3$ $mm^{-1}$ |
| $C_P$ | conversion factor for precipitation from mm to $m^3$ per facility ($A_{fac}$/1000) in the absence of run-off and active rain fall exclusion. | 0.075 | $m^3$ $mm^{-1}$ |

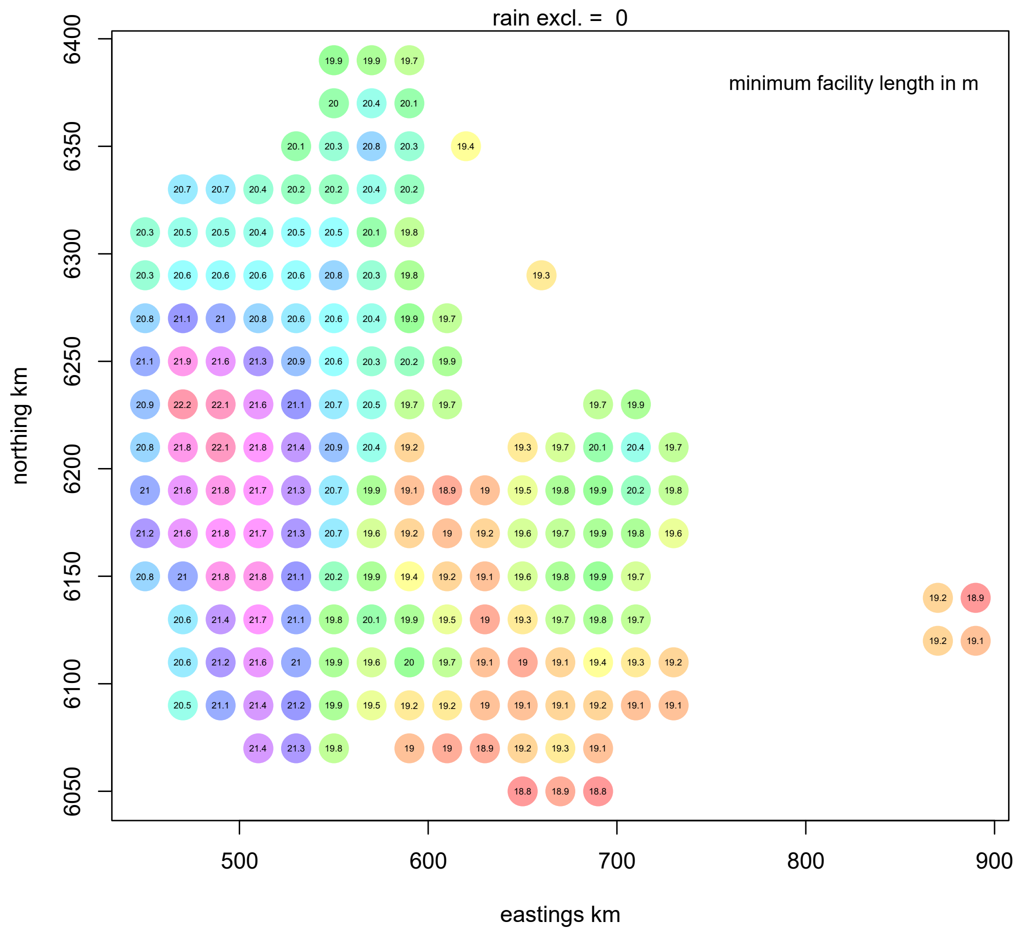


Fig. 2: Minimum facility length of the 2GWTF in different locations of Denmark with no rain exclusion.

The geographical distribution of $l_{min}$ (Fig. 1) reflects the relationship between averaged monthly potential evaporation and precipitation, with highest values in regions with the highest annual precipitation and lowest potential evaporation, i. e. Central Jutland. The average $l_{min}$ is 20.2 ± 0.9 m (uncertainty of the mean are given as standard deviation). In the Western parts of Denmark, $l_{min}$ tends to be larger than $l_d$, in the Eastern parts the default 2GWTF design is sufficient ($l_d \approx l_{min}$).

Interestingly the distribution of the demand for storage capacity (Fig. 3) is inversely related to that of the minimum facility length. The spatial distribution reflects the increasing amplitude of climatic factors with the more continental climate in SE Denmark. The average value of the minimum storage capacity ($\kappa_{min}$) over all locations is ca. 20% larger (59 ± 3 $m^3$) than the default storage capacity ($\kappa_d$ in Tab. 1). The true demand for storage capacity will be higher and should be estimated with monthly data rather than with averaged monthly data.

The strong dependency of $\kappa_{min}$ from $l_{min}$ (Fig. 3) caused by the spatial variability of the Danish climatic conditions, requires a flexible value of the normalised pore volume, which on average should exceed the value of the default design (Fig. 5). The average value of $V_{pn}$ for all locations is 2.9 ±0.2 $m^2$.

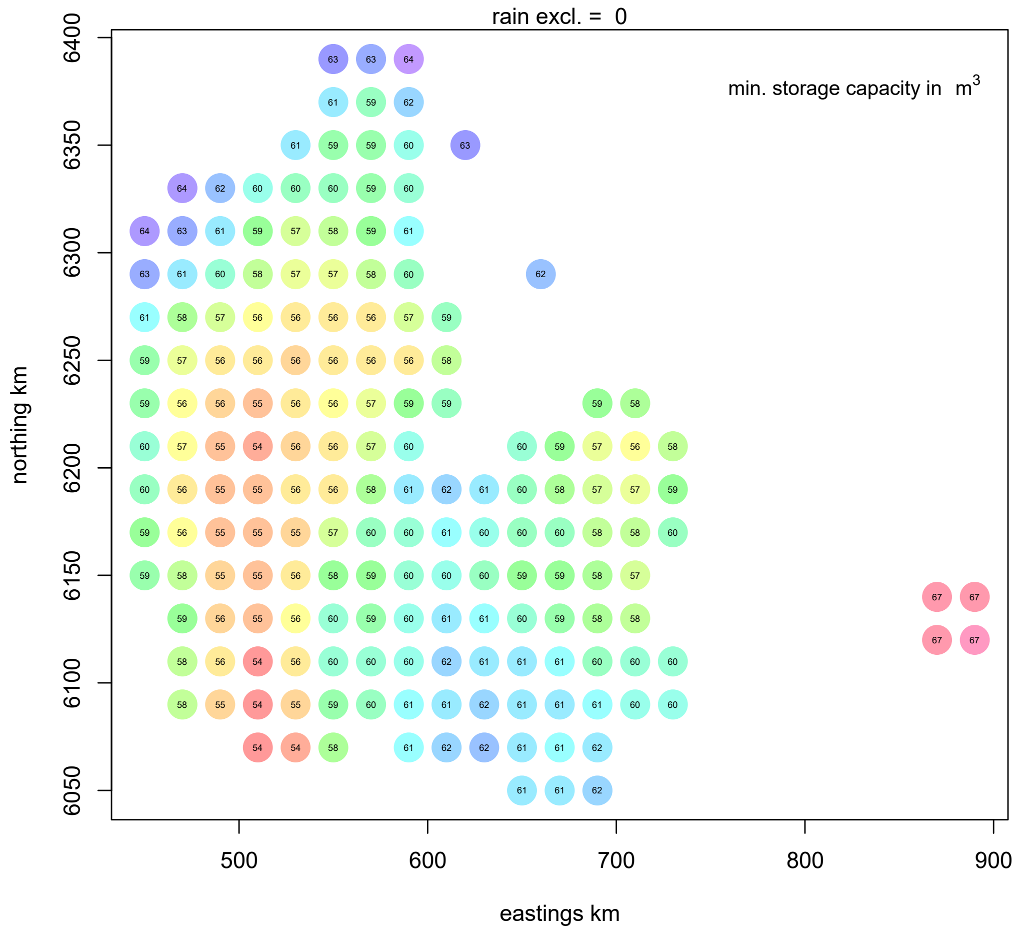


Fig. 3: Minimum storage capacity the 2GWTF in different locations of Denmark with no rain exclusion for facilities with minimum length as in Fig. 2.

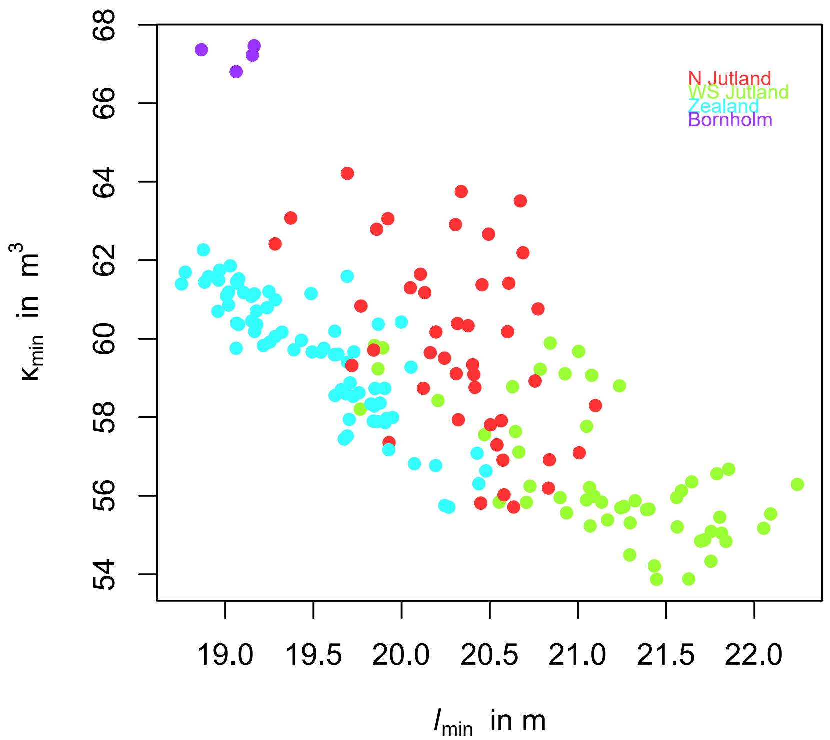


Fig. 4: Relationship between the minimum storage capacity ($\kappa_{min}$) and minimum facility length ($l_{min}$) for Danish regions.

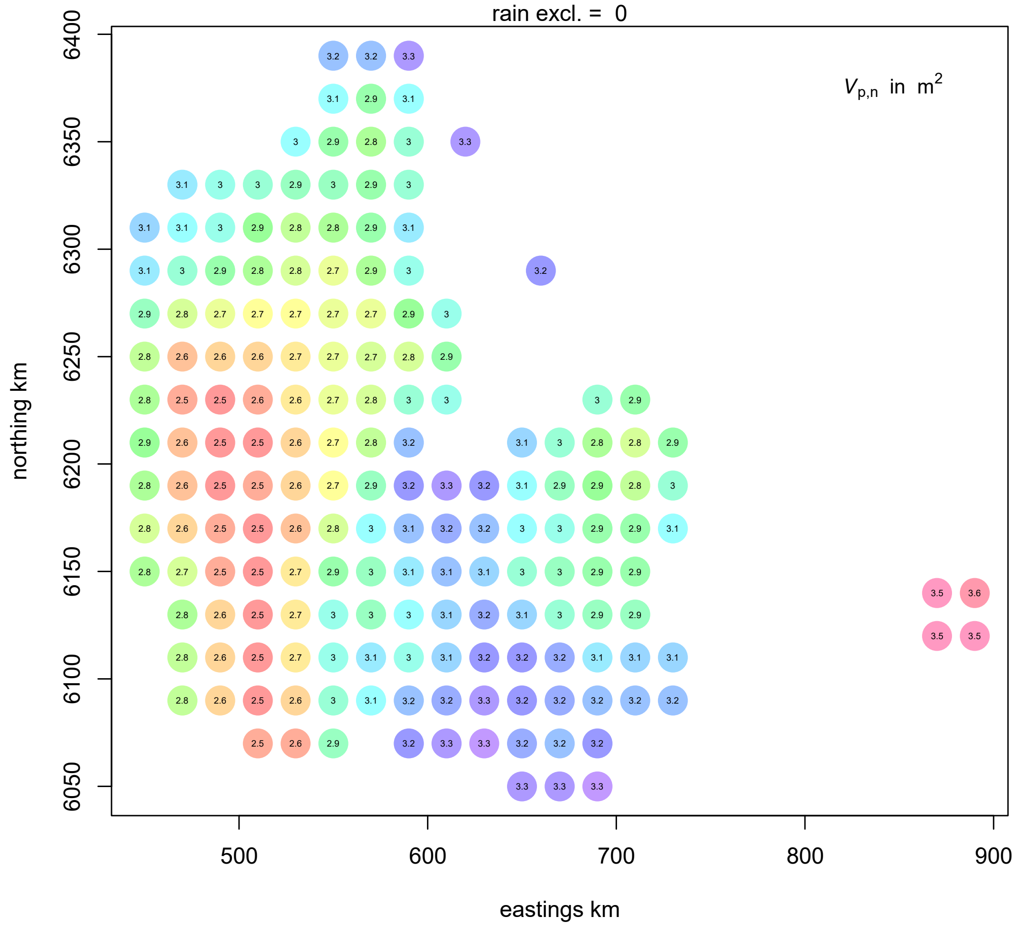


Fig. 5: Minimum normalised pore volume (m³ pore volume per unit facility length) the 2GWTF in different locations of Denmark with no rain exclusion for facilities based on minimum length as in Fig. 2.

## 3.1 Expected risks with first 2nd generation willow wastewater treatment facilities

Both types of WTF are vulnerable to disturbance of the willow canopy. This can be caused by animals foraging on the willow, insect infection (aphids) or due to water shortage, should the wastewater generation cease in summer. While fenced facilities reduce the risk from grazing, some of the other factors are more critical. In normal willow plantations the risk of damage from insect calamities is moderate, but the vulnerability of the strongly growing plantations might be different.

If the evaporation is for whatever reason not able to prevent the water level from rising and the capacity to store more water is reached, the facility must be emptied by the traditional method to avoid pollution of the environment with untreated wastewater. Continuous monitoring of the water level is recommended. The options for automated monitoring of the functioning of the facility are ample and some low-cost solutions are already being tested.

# 4. Conclusions

Technological progress comes with some risk of failure. Economic constraints during the innovation process give tight margins to test and consolidate the concepts and their realizations. The step from the 1G  to the 2G willow-based wastewater treatment facility (WTF) has introduced some new environmentally and economically attractive features, forming an ecosystem between a household and a small forest like structure. However to be sure to manage the system in a sustainable way, it has to be tested and scientifically examined. This quick appraisal was mainly concerned with the water balance and relied on existing information for other systems and theory. From theoretical considerations and empirical data from the 1GWTF, this new design seems promising, because it arranges the system components in a more effective way with the key innovation of an increased evaporation rate and a reduced area use. These rates are exceeding the hence known usual thresholds for actual evaporation, likewise as the 1GWTF already did, when the average $K_c$ value was set to its maximum possible value of 2.5. Theoretical considerations support this approach and indicate even higher transpiration rates in 2GWTF compared to 1G. Practice must show whether this potential realizes also in extreme weather conditions and under environmental change and human error. Effective observation and mindful maintenance in close exchange with scientific experts will help to manage risks of failure and even exploitation of hence unidentified potentials.

Based on best available knowledge and the theory underlying under the Danish regulations for will-based wastewater treatment facilities, the flexible 2GWTF design can comply with the regulations regarding the steady state water balance for many regions in Denmark provided the default design is adapted to the local climatic conditions. While the default facility length of 20 m is very close to the requirements, the wastewater storage capacity needs to be increased. The results suggest establishing the respective normalised pore volume together with the minimum length for a given climate.

Because the presented simulations are based on assumptions and averaged climatic data, a precautionary approach is advised. Continuous monitoring of the facility and intervention, when necessary, are recommended. Methods exist to monitor and counteract malfunctioning of the facility and thus to manage the potential risks of pollution of the environment with wastewater. Regarding the zero-discharge requirements, this investigation did not find any indication for any larger risk from the use of the adaptive 2GWTF design compared to the 1GWTF.

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