Royal Netherlands
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# Brief review of wind and drag transformations in WBI2017

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**Abstract**

To determine the hydraulic boundary conditions for the design of coastal defence structures, hydraulic (wave, water level) models are forced by observation-based winds. Winds observed at land stations are first transformed to open-water winds and then into stress to drive the respective model. The translation to stress is done using a drag coefficient that is parametrised as a function of wind speed. At first sight all production runs have to be repeated if new research suggests a new drag parameterization to be used. A recent memorandum describes a method to avoid repeating these runs. We here evaluate that method, and at the same time assess the method to translate the land wind to open-water wind.

# Contents

## Samenvatting

Hydrologische modellen (golven, wateropzet) worden gewoonlijk aangedreven door winden. Deze worden binnen het model omgezet in stress (windschuifspanning), waarbij gebruik wordt gemaakt van een parameterisatie van de dragcoëfficiënt. In een recente memo (Van Vledder, 2017) wordt een methode beschreven om de resultaten van bestaande productieruns te kunnen hergebruiken als de dragparameterisatie ten gevolge van nieuwe inzichten verandert. Uit een evaluatie blijkt dat deze methode baseert op het idee dat de stress, en niet de wind, de relevante variabele voor het beschrijven van de lucht-zee wisselwerking is. Het gebruik van deze methode introduceert geen nieuwe onzekerheid in de analyse van de productieruns.

Los van de correctiemethode beschrijft Van Vledder (2017) ook de bestaande procedure om de op landstations waargenomen wind tot de wind op de aangrenzende wateroppervlakken (open-water wind) te komen. Deze methode maakt gebruik van het concept van potentiële wind, waarbij aangenomen wordt dat er een blending height bestaat waar de windsnelheid onafhankelijk is van de lokale ruwheidslengte. De geldigheid van deze aanname kan betwist worden. Het wordt daarom aanbevolen om een alternatief voor deze methode te zoeken. Dit advies sluit aan bij de aanbevelingen van Caires et al. (2012) en het recente advies van Wichers Schreur (2017). In beide gevallen wordt voorgesteld om numerieke modellen voor de aandrijving van de hydrologische modellen te gebruiken. Inconsistenties en onzekerheden bij de omzetting van waargenomen wind naar open-water wind worden op die manier voorkomen.



## Executive Summary

Hydraulic (waves, water level) models are usually forced by winds, which are translated into stress within the model. The translation involves a parameterization of the drag coefficient. In a recent memorandum (Van Vledder, 2017) a method is devised to re-use existing production runs if the drag parameterization has to be changed. An evaluation finds that the method is based on the idea that the stress, and not the wind speed, is the relevant variable in air-sea coupling. Its use does not introduce new uncertainty into the analysis of the existing runs.

Although independent of the correction method, Van Vledder (2017) also describes the current procedure to derive an open water wind from wind measured at land stations. This method involves a transformation using the potential wind, assuming the existence of a blending height at which the wind speed is independent of the local roughness length. The validity of this assumption can be challenged. It is therefore recommended to find an alternative for this method. This recommendation is in line with that of Caires et al. (2012) and a recent advice of Wichers Schreur (2017). Both recommend to use numerical models to force the hydraulic models. This eliminates inconsistencies and uncertainties associated with the transformation of observed winds over land to open-water winds.

# 1 Introduction

In his memo, Van Vledder (2017) devises a method to transform existing potential wind speeds into an equivalent wind speed that can be used with a new drag formulation. We here review its derivation. The transformation involves the application of the logarithmic wind profile.

# 2 Theoretical background

## 2.1 Logarithmic wind profile

The wind profile of a turbulent flow above a rough surface is logarithmic (e.g., Tennekes, 1973):

$$U(z) = \frac{u_*}{\kappa} \ln(\frac{z}{z_0}), \tag{1}$$

where $u_* = \sqrt{\tau/\rho_a}$ is the friction velocity, $\kappa = 0.41$ the von Kármán constant[1] and $z_0$ the roughness length. The roughness length is a characteristic of the conditions at the measurement site. $\tau$ and $\rho_a$ are respectively the wind stress and the air density. Applying (1) at two different heights $z_1$ and $z_2$ yields

$$U(z_1) = U(z_2) \frac{\ln(\frac{z_1}{z_0})}{\ln(\frac{z_2}{z_0})}. \tag{2}$$

## 2.2 Drag coefficient

The stress $\tau$ exerted by the wind on the ocean is usually parameterized as

$$\tau = \rho_a u_*^2 = \rho_a \, C_{D,z} \, U(z)^2, \tag{3}$$

where $C_{D,z}$ is the drag coefficient for height $z$. Usually, $z = 10$ m is used as the reference height, and $C_{D,10}$ is abbreviated as $C_D$. Combining the logarithmic profile (1) with the definition of the drag coefficient (3) and putting $U(10) = U_{10}$ results in

$$C_D = \left(\frac{u_*}{U_{10}}\right)^2 = \frac{\kappa^2}{\ln^2\left(\frac{10}{z_0}\right)}. \tag{4}$$

## 2.3 Potential wind

Wind measurements are usually done over land. Each measurement location has its own characteristic surface roughness. Measured winds are therefore not representative for a wider area. To make measured winds comparable between locations, they are transformed to *potential wind* (Wieringa, 1986). This $U_{\text{pot}}$ is the 10 m wind that would have been measured if the local roughness had been that of flat grassland. The corresponding roughness length $z_{0,\text{ref}} = 0.03$ m is used as the *reference roughness* (see Figure 1). A more thorough description of the concept, together with a discussion of its shortcomings and problems, can be found in Caires et al. (2012).

The potential wind is determined by first using (2) to transform the observed 10 m wind $U_{10}$ to $U(60) = U_{\text{blend}}$, the wind at the *blending height* of 60 m, where the wind speed (*meso wind*) is assumed to be independent of the local surface roughness. In this transformation the actual roughness $z_{0,\text{act}}$ at the measurement site is used. In a second step, $U_{\text{blend}}$ is transformed

[1] Note that some authors use $\kappa = 0.4$. Use of different values of $\kappa$ in different parts of the modelling chain can potentially lead to inconsistencies.

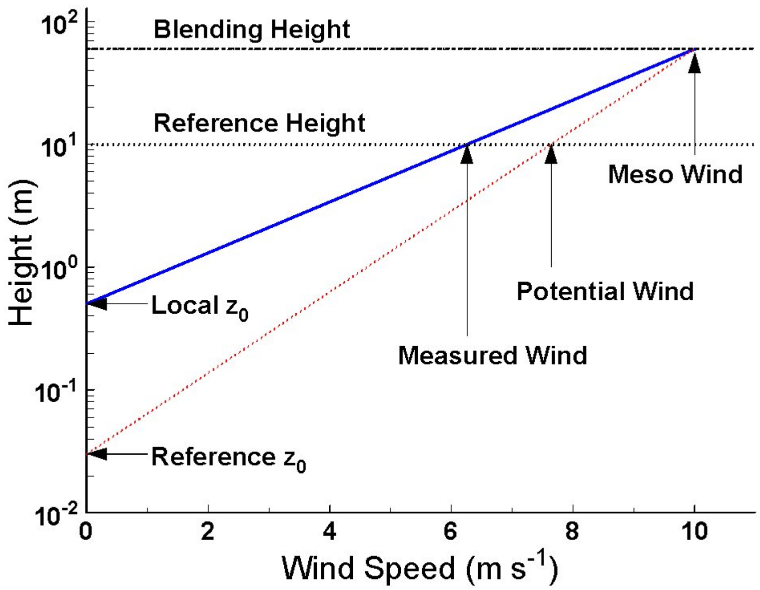


**Figure 1:** Potential wind speed: From the measured wind speed and the local roughness length, the wind speed at the blending height is computed. This *meso wind* speed is translated downwards to the potential wind speed at standard height and with standard roughness length. In this plot the measuring height and the standard height are both 10 m, the blending height is 60 m, the local roughness length is 0.5 m, and the standard roughness length is 0.03 m. The height transformations are done using the logarithmic wind speed profile. (Copied from `https://projects.knmi.nl/hydra/faq/upot.htm`.)

back to 10 m. Again (2) is used, but with the reference roughness $z_{0,\mathrm{ref}}$,

$$U_{\mathrm{blend}} = U(60) = U_{10}\,\frac{\ln(\frac{60}{z_{0,\mathrm{act}}})}{\ln(\frac{10}{z_{0,\mathrm{act}}})}, \tag{5}$$

$$U_{\mathrm{pot}} = U_{\mathrm{blend}}\,\frac{\ln(\frac{10}{z_{0,\mathrm{ref}}})}{\ln(\frac{60}{z_{0,\mathrm{ref}}})} \tag{6}$$

$$= U_{10}\,\frac{\ln(\frac{60}{z_{0,\mathrm{act}}})}{\ln(\frac{10}{z_{0,\mathrm{act}}})}\cdot\frac{\ln(\frac{10}{z_{0,\mathrm{ref}}})}{\ln(\frac{60}{z_{0,\mathrm{ref}}})}. \tag{7}$$

# 3 Production runs at RWS

## 3.1 Open water wind

To drive their hydraulic models, RWS use statistical distributions of $U_{\mathrm{pot}}$ that are derived from measurements at nearby KNMI land stations. These production runs form the basis for their assessment of coastal defence structures.

The potential wind is representative for open grass land. The corresponding roughness length $z_{0,\mathrm{ref}} = 0.03$ m is much larger than that of water, which additionally is not constant but depends on wind speed (see recent review of Sterl, 2017). To derive an open water wind $U_{\mathrm{ow}}$ that accounts for the wind speed dependence of the roughness, the potential wind is transformed back to the blending height using the reference roughness $z_{0,\text{ref}}$, and then again down to 10 m using the roughness $z_{0,\text{ow}}$ of open water. Applying (2) twice as in section 2.3 yields

$$U_{\text{ow}} = U_{\text{pot}} \, \frac{\ln(\frac{60}{z_{0,\text{ref}}})}{\ln(\frac{10}{z_{0,\text{ref}}})} \cdot \frac{\ln(\frac{10}{z_{0,\text{ow}}})}{\ln(\frac{60}{z_{0,\text{ow}}})}. \tag{8}$$

Inserting (7) yields

$$U_{\text{ow}} = U_{10} \, \frac{\ln(\frac{60}{z_{0,\text{act}}})}{\ln(\frac{10}{z_{0,\text{act}}})} \cdot \frac{\ln(\frac{10}{z_{0,\text{ow}}})}{\ln(\frac{60}{z_{0,\text{ow}}})}, \tag{9}$$

showing that this is equivalent to skipping the calculation of the potential wind and directly transform the observed wind $U_{10}$ to the open water wind using the open water roughness $z_{0,\text{ow}}$. Note, however, that the concept of blending height is still used.

The open water roughness length is calculated from (4) as

$$z_{0,\text{ow}} = 10 \, e^{-\kappa/\sqrt{C_D}}, \tag{10}$$

where the drag coefficient is assumed to increase linearly with $U_{10} = U_{\text{ow}}$ according to Wu (1982). Therefore the roughness length depends on wind speed, and (9) is an implicit equation for $U_{\text{ow}}$ that needs to be solved iteratively. Note that this procedure not only produces the open water wind, but at the same time the drag coefficient and thus the stress.

### 3.2 Re-use of production runs according to Van Vledder (2017)

Recent research has shown that the Wu (1982) parameterization of the drag coefficient yields too high values for wind speeds $\gtrsim$ 30 m/s (see review of Sterl, 2017). The drag coefficient stops growing for higher wind speeds. Consequently, a parameterization where the Wu (1982) parameterization is held constant for wind speeds above 30 m/s is more appropriate ("capped Wu" parameterization in the following).

At first sight it seems that to properly account for the new drag parameterization, all production runs performed at RWS need to be redone. To avoid this, Van Vledder (2017) suggests a method to re-use the vast amount of existing production runs, which are based on the original Wu (1982) parameterization. He determines the *pseudo wind* (see Van Nieuwkoop et al. (2015) for an explanation of the concept), which is the wind speed that gives the same stress if the old (Wu) parameterization is used, as the real wind gives for the new (capped Wu) parameterization.

The concept is schematically depicted in Figure 2. The right part shows the relation between wind speed $U$ and wind stress $\tau$. If $U$ is the open water wind, the relation is given by a simple analytic function and can easily be evaluated. If $U$ is the potential wind, the relation between $U$ and $\tau$ is a bit more complex, involving the implicit calculation of the open water wind according to (9) and (10). The left part depicts the relation between wind stress $\tau$ and the hydraulic variable $H$ of interest (usually wave height or water level). This relation is not known analytically but follows from the integration of a numerical model. The aim of the method suggested by Van Vledder (2017) is to avoid the repetition of these (costly) integrations.

Under the old parameterization, a given wind speed $U_1$ results in a certain stress $\tau_{\text{old}}$, which translates into a wave height (water level) $H_{\text{old}}$. Under the new parameterization, the same wind $U_1$ leads to $\tau_{\text{new}}$ and $H_{\text{new}}$. The same values of $\tau_{\text{new}}$ and $H_{\text{new}}$ are generated by $U_2$ under the old parameterization. $U_2$ is the pseudo wind speed corresponding to the real wind speed $U_1$. The recipe suggested by Van Vledder (2017) to re-use old calculations can be described as "If you want to know the effect (wave height or water level) of wind speed $U_1$ under the new parameterization, determine the corresponding pseudo wind speed $U_2$ and take the result you

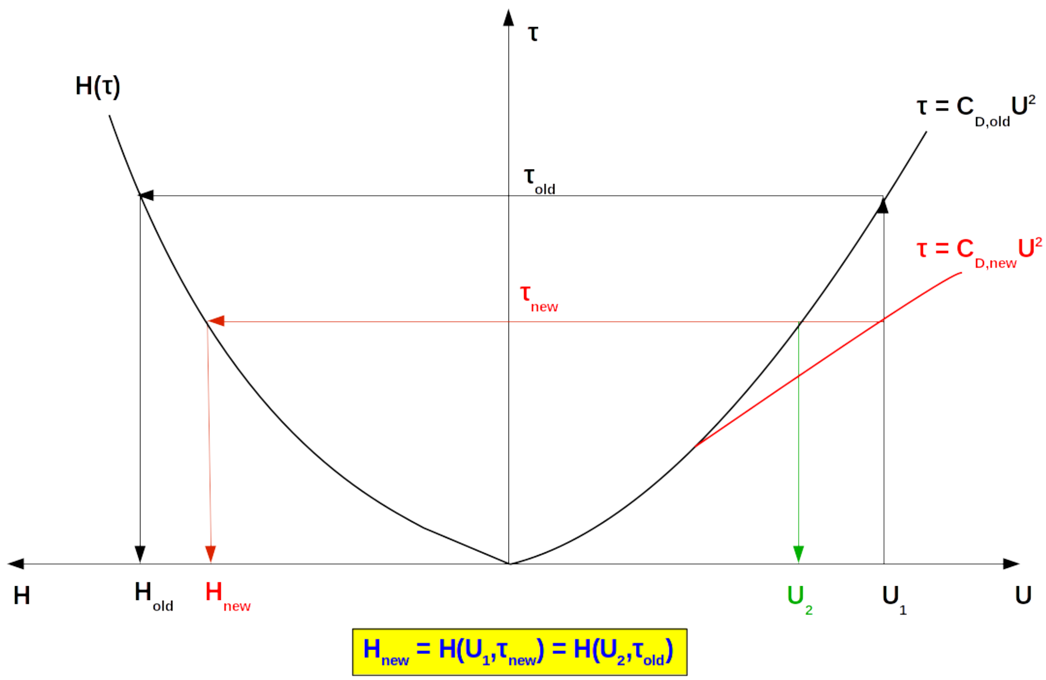


**Figure 2:** Graphical representation of the correction method of Van Vledder (2017). The right part shows the relation between wind speed ($U$; x-axis) and wind stress ($\tau$; y-axis), and the left part the relation between stress ($\tau$; y-axis) and a hydraulic variable ($H$; x-axis with $x$ positive to the left). The hydraulic variable $H$ can be wave height or water level. Using the original Wu (1982) parameterization ($C_{\mathrm{D,old}}$), a given wind speed $U_1$ results in a certain stress $\tau_{\mathrm{old}}$, which causes a corresponding wave height (or water level) $H_{\mathrm{old}}$. Under the new parameterization ($C_{\mathrm{D,new}}$), the same wind leads to a different (lower) stress $\tau_{\mathrm{new}}$, and a different wave height (or water level) $H_{\mathrm{new}}$. The same $H_{\mathrm{new}}$ would have been caused by $U_2$ using the old parameterization. The method is illustrated here for a constant wind field. It is easily generalized to time or spatially varying fields.

obtained for that wind speed in your earlier calculations with the old parameterization". So instead of repeating the production run, the result of an old one can be used.

For a given $U_1$ the stress $\tau_{\mathrm{new}}$ is easily determined as $\rho_a\, C_{\mathrm{D,new}}(U_1)\, U_1^2$. To find the associated pseudo wind $U_2$, the equation

$$u_*^2 = \tau_{\mathrm{new}}/\rho_a = C_{\mathrm{D,old}}(U_2) \cdot U_2^2 \tag{11}$$

has to be solved. As $C_{\mathrm{D,old}}$ is linear in $U$ (Wu, 1982), (11) is a third-order polynomial that can easily be solved iteratively.

Although the method has been described above for a constant wind field $U_1$, it can easily be generalized to fields varying in space and time by determining a value for $U_2$ for each value of $U_1$. This ensures meeting the crucial requirement that the stress field $\tau$ is the same for both drag parameterizations.

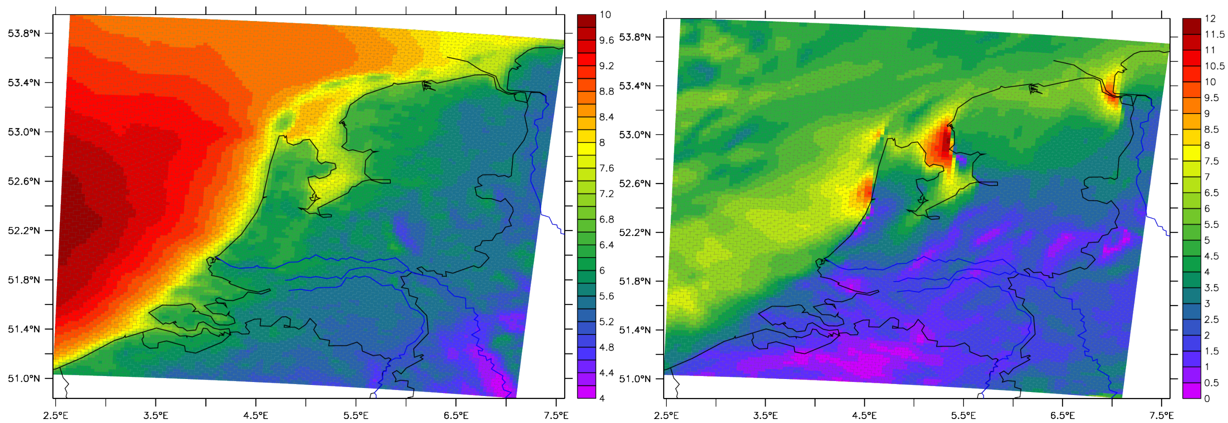


**Figure 3:** 60-m wind from a run using the high-resolution (2.5 km) Harmonie model for May 2012. Left: monthly average, right: May 16, 11.00 hours. Note the different scales in both plots.

### 3.3 Summary of Van Vledder (2017)

At first sight the method proposed by Van Vledder (2017) to re-use old production runs is a four-step process:

1. for a given potential wind, determine the open water wind, using the new $C_D$ parameterization,
2. determine the corresponding wind stress,
3. determine the corresponding pseudo wind,
4. use the result from the production run in which this pseudo wind was used as the forcing wind.

However, the underlying argument is much more straightforward:

> For a given potential wind, determine the corresponding wind stress using the new $C_D$ parameterization and use the production run that applied this wind stress.

This view is based on the idea that not the wind, but the stress is the driving variable. What Van Vledder (2017) does is just changing the relation between wind (either potential or open water) and stress. A given wind corresponds to a different stress and thus a different result (wave height or water level) of the production runs. No pseudo-wind is necessary.

# 4 A critical note on the method to determine the open water wind

Van Vledder (2017) determines the open water wind according to (9). As shown, this involves the assumption that the wind speed $U_{\text{blend}}$ at the blending height is independent of the local surface roughness, or that it is the same above the measurement location and the adjacent water. While this assumption may be true in the vicinity of the land-water transition or for small water bodies, the open water wind determined in this way is not representative for a larger water body like a lake or a wide river arm.

To illustrate this, Figure 3 shows the wind speed at 60 m height from a run with the high-resolution (2.5 km) atmosphere model Harmonie. In the monthly-mean picture (left) land-water contrasts clearly show up, even those that are not included in the coastline definition of the plotting program. For instance, the Wadden Islands are clearly visible, as are different open water bodies in the Rhine/Meuse delta. In the plot of an instantaneous wind field (right) the distinction between land and water is less clear but still visible. Especially the IJsselmeer (Lake IJssel) is clearly visible. The 60 m wind over the water is clearly higher than over the adjacent land, in clear contrast to the assumption behind the open water wind according to (9).

Even at 100 m height the wind speed over land is distinctly different from that over adjacent water (not shown). Thus the concept of a blending height at which wind speed is independent of surface roughness is invalid, yet the existence of such a blending height is the basic assumption behind the method to determine the open water wind. The current practice to transform wind over land to wind over adjacent water (see section 3) may thus be flawed, and the consequences of this inadequacy for the modelling work at RWS need to be investigated in more detail.

The problem signalled here is closely related to the *curvature problem* which is discussed at great length by Caires et al. (2012). Although they identify a lot of factors unaccounted for in the application of the potential wind concept, they conclude that incorporation of all these factors into the concept is not feasible [2]. Based on Caires et al. (2012) and other research, KNMI recently advised RWS to switch to a model-based approach to determine forcing wind fields for WBI2023 (Wichers Schreur, 2017). Figure 3 clearly supports that advice.

## 5 Summary and conclusion

The results of this note can be summarized as follows:

- The method devised by Van Vledder (2017) to re-use existing production runs if the $C_D(U_{10})$ relation is changed, is based on the view that the stress, and not the wind speed, is the relevant variable in air-sea coupling. Its use does not introduce new uncertainties into the analysis.

- Although independent of the correction method, Van Vledder (2017) also describes the current procedure to derive an *open water wind* from wind measured at land stations. This method involves a transformation using the potential wind. It assumes the existence of a *blending height*, at which the wind speed is independent of the local roughness length. This assumption may *not* be valid and needs further evaluation.

- This adds additional weight to the earlier advice to use numerical models to derive the hydraulic boundary conditions necessary to design coastal defence structures.

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[2]Note that Caires et al. (2012) implement the full two-layer-model of Wieringa (1986), which distinguishes between a local roughness and a mesoscale roughness, which is representative for a large (5 km × 5 km) upstream area, while Van Vledder (2017) use a reduced version with only one roughness. The latter is equivalent to assuming a constant wind at the (fixed) blending height, while the full implementation of the two-layer model assumes a constant wind at the (variable) top of the atmospheric boundary layer. Even the correct implementation of the two-layer model in Caires et al. (2012) produces land-water-differences which are not in accordance with measurements (M. Bottema, pers. comm., 2017).

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