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# Floodplain roughness parameterization using airborne laser scanning and spectral remote sensing

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**Abstract**

Floodplain roughness parameterization is one of the key elements of hydrodynamic modeling of river flow, which is directly linked to exceedance levels of the embankments of lowland fluvial areas. The present way of roughness mapping is based on manually delineated floodplain vegetation types, schematized as cylindrical elements of which the height (m) and the vertical density (the projected plant area in the direction of the flow per unit volume, $m^{-1}$) have to be assigned using a lookup table. This paper presents a novel method of automated roughness parameterization. It delivers a spatially distributed roughness parameterization in an entire floodplain by fusion of CASI multispectral data with airborne laser scanning (ALS) data. The method consists of three stages: (1) pre-processing of the raw data, (2) image segmentation of the fused data set and classification into the dominant land cover classes (KHAT=0.78), (3) determination of hydrodynamic roughness characteristics for each land cover class separately. In stage three, a lookup table provides numerical values that enable roughness calculation for the classes water, sand, paved area, meadows and built-up area. For forest and herbaceous vegetation, ALS data enable spatially detailed analysis of vegetation height and density. The hydrodynamic vegetation density of forest is mapped using a calibrated regression model. Herbaceous vegetation cover is further subdivided in single trees and non-woody vegetation. Single trees were delineated using a novel iterative cluster merging method, and their height is predicted ($R^2$=0.41, rse=0.84 m). The vegetation density of single trees was determined in an identical way as for forest. Vegetation height and density of non-woody herbaceous vegetation were also determined using calibrated regression models. A 2D hydrodynamic model was applied with the results of this novel method, and compared with a traditional roughness parameterization approach. The modeling results showed that the new method is well able to provide accurate output data. The new method provides a faster, repeatable, and more accurate way of obtaining floodplain roughness, which enables regular updating of river flow models.


*Keywords:* Data fusion; Multispectral data; ALS data; Object-oriented classification; Tree detection; Floodplain vegetation; Hydrodynamic modeling

## 1. Introduction

Over the last decade, flooding has become a large environmental hazard with significant economic damage and human suffering. Examples of flooding catastrophes are the Mississippi flood in 1993, the Oder flood in 1997 and the Elbe and Danube flood in August 2002 and April 2006. Understanding flood events and predicting flood prone areas and potential damage have become important issues in river management. In this context, hydrodynamic modeling is a tool, not only to compute water levels for unprecedented discharges to assess the design levels for embankments, but also to assess the possible effects of future climate change and ecological river restoration measures on flood water levels. Therefore, considerable effort has been undertaken in recent years in the development of 2D and 3D hydrodynamic models that accurately simulate overbank flow patterns and predict extreme flood water levels in rivers and floodplains (Baptist et al., 2005; Bates et al., 1992; Nicholas & McLelland, 2004; Stoesser et al., 2003). In addition to surface topography (Marks & Bates, 2000), hydrodynamic roughness of

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the floodplain surface is the key input parameter of these models. It is common practice to calibrate hydrodynamic models by tuning the hydraulic roughness until model predictions fit observations. This method is suspect, as shortcomings in the model scheme, computation method or model input can be compensated using roughness values that are physically not representative. Therefore, accurate estimates of roughness input parameters help to constrain the range of input parameters that should be allowed during calibration of such models. This is especially important as these models are routinely used to compute water levels for the design of embankments with discharges far exceeding the range of observed data.

Hydrodynamic roughness of the non-vegetated river bed is a function of grain size and bed form (Van Rijn, 1994). Vegetation roughness is dependent on vegetation structural characteristics like vegetation height and density, rigidity of the stems and the presence of leaves (Dawson & Charlton, 1988; Kouwen & Li, 1980). Seasonal variation and dynamic management of floodplains lead to a high spatiotemporal variation of vegetation structural characteristics and inherent roughness patterns (Baptist et al., 2004; Jesse, 2004; Van Stokkom et al., 2005). To provide hydrodynamic modelers with reliable input, the spatial and temporal distribution of surface characteristics is needed. This asks for accurate and fast monitoring methods that can cover large floodplain areas.

Despite the fact that vegetation roughness models generally use a range of vegetation structural parameters as input, 2D hydrodynamic flow models are often run with a uniform floodplain roughness. (e.g. Bates et al., 2006; Horritt & Bates, 2002). However, taking the spatial roughness distribution into account has an important effect on the modelled flow velocities and water elevations (Mason et al., 2003). Considerable progress has been reported on mapping of natural vegetation using multispectral and hyperspectral remote sensing data (Mertes, 2002; Ringrose et al., 1988; Schmidt & Skidmore, 2003; Thompson et al., 1998; Van der Sande et al., 2003). In several studies, spectral information has been combined with height information in vegetation classification schemes (e.g. Dowling & Accad, 2003; Ehlers et al., 2003; Hill et al., 2002; Rosso et al., 2006). In the Netherlands, floodplain vegetation units are distinguished based on visual interpretation and manual classification of false-color aerial photographs (Jansen & Backx, 1998), a time consuming and unrepeatable method. All of these classification methods can be used to assign spatially distributed roughness values using a lookup table. The spatial resolution and the level of detail of the classification may vary with the type of remote sensing data. The use of a lookup table, however, leads to undesirable loss of within-class variation. Airborne Laser Scanning (ALS), has proven its ability to quantitatively map vegetation structural characteristics such as forest vegetation height, biomass, basal area, and leaf area index (Lefsky et al., 2002; Lim et al., 2003) and vegetation density (Straatsma, in press). Successful applications have also been reported in mapping of vegetation height of low vegetation in summer (Cobby et al., 2001; Davenport et al., 2000; Hopkinson et al., 2004) and vegetation height and density in winter (Straatsma & Middelkoop, 2007). A recent study has parameterized floodplain roughness using vegetation height derived from ALS data (Mason et al., 2003). Due to the noise level of ALS data, which is around 4 cm (Davenport et al., 2000; Hopkinson et al., 2004), these relations can not be applied to all floodplain land cover classes. The extraction of surface properties of, for example, sandy surfaces or meadows will still be inaccurate if based on ALS data.

In this paper, we present a standardized and repeatable method for parameterizing the floodplain roughness based on a combination of spectral and ALS remote sensing data. The method comprises (1) image segmentation and object-based classification into the main hydrodynamically relevant land cover types, and (2) determination of roughness characteristics of various land cover types using direct analysis of vegetation structure using ALS and a lookup table. The results of this method are compared to the current method of roughness parameterization in The Netherlands based on manual interpretation of aerial photographs and a lookup table, the 'ecotope' approach. The effects on 2D flow patterns and water levels within a river and floodplain segment are assessed using the Delft3D hydrodynamic model (Gerritsen & Verboom, 1994; Kernkamp et al., 2005; Postma et al., 2000).

## 2. Roughness formulations

Roughness determines the friction of the water flow exerted by the underlying surface. In practice, roughness is a model parameter that is calibrated to account for any loss of momentum of the water flow, which can be due to bed friction, vegetation friction, discrepancies in elevation data, the exchange of mass or momentum between the main channel and the floodplains, the presence of obstacles in the flow, or any other momentum loss (Baptist et al., 2005). Since the presence of vegetation adds considerably to the bulk floodplain roughness, we here focus on the description of vegetation roughness.

One of the ways to express roughness is by the Chézy coefficient. This coefficient ($C$ in $\mathrm{m}^{1/2}\ \mathrm{s}^{-1}$) relates depth averaged flow velocity ($u$ in m $\mathrm{s}^{-1}$) to the hydraulic radius of a water course ($R$ in m), and the energy gradient, or slope, ($i$ in $\mathrm{m \cdot m^{-1}}$) by:

$$u = C\sqrt{Ri} \tag{1}$$

Note that the higher the Chézy value, the lower the roughness, or resistance to flow is. There is general agreement that the roughness of subaqueous non-vegetated areas depends on the grain size and the size and shape of the bed forms, although the scatter of the derived relations is large (Van Rijn, 1994). Chézy values for sandy beds can then be calculated based on the Nikuradse equivalent grain roughness ($k$ in m) as defined by the Colebrook–White formula (Keulegan, 1938):

$$C = 18\log\frac{12R}{k} \tag{2}$$

For vegetated areas we use the vegetation height and vertical density for roughness parameterization, which builds on the early work of Einstein and Banks (1950), Kouwen et al. (1969),