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Assessment of the hydraulic roughness of river flood plains using laser altimetry

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Abstract Airborne laser altimetry is a promising new technique for rapid and detailed mapping of land surface topography and vegetation cover. The availability of laser scan data is expected to yield a great improvement in mapping and quantification of hydraulic roughness, which is needed for two-dimensional modelling of overbank flow. In this study, hydraulic roughness of flood plain vegetation was estimated using airborne laser scan data. Distributions of vegetation height and density were derived from the laser altimetry measurements using geo-statistical techniques. Raster maps of vegetation types and associated hydraulic roughness were obtained by combining the laser scan data with hydraulic characteristics of different vegetation types reported in the literature. The results were in good agreement with hydraulic roughness maps based on field observations of vegetation density and height.

Key words airborne laser altimetry; vegetation; flood plains; hydraulic roughness; River Rhine; The Netherlands

INTRODUCTION

Laser altimetry is a promising new technique that provides rapid and detailed assessments of land surface topography (e.g. Ritchie *et al.*, 1993; Kraus & Pfeifer, 1998) and vegetation cover (e.g. Menenti & Ritchie, 1994; Weltz *et al.*, 1994; Næsset, 1997; Blair *et al.*, 1999). In March 1997, an airborne laser altimeter was used to obtain elevation measurements of the flood plain along the River IJssel in The Netherlands (Fig. 1). The availability of these laser data provides the means to explore the suitability of laser altimetry for the monitoring of vegetation and associated hydraulic roughness of flood plains, which are essential inputs for modelling of fluvial systems to estimate water levels during peak discharges.

The hydraulic roughness of flood plains in The Netherlands is presently derived from vegetation and ecotope maps, which requires extensive field surveys. There is a need to develop a method that enables accurate, spatially differentiated, and rapid assessment of the hydraulic roughness of flood plains. The aim of the present study was therefore to evaluate the feasibility of using airborne laser scan data combined with blockage data reported in the literature for the estimation of the hydraulic roughness of flood plain vegetation along the lower Rhine distributaries in The Netherlands.

The results were compared with those obtained from vegetation heights and blockage areas measured in the field to determine the applicability of this new technique.

The study was carried out in the Duursche Waarden–Fortmond flood plain (Fig. 1), located about 10 km north of Deventer on the right bank of the River IJssel, the smallest distributary of the River Rhine in The Netherlands. This flood plain includes a variety of land cover and vegetation types (Fig. 1).

HYDRAULIC ROUGHNESS OF VEGETATION

The hydraulic roughness of submerged vegetation is determined by the roughness of the top of the vegetation, by the roughness of the stems and leaves through which the water flows, and by the roughness of the ground surface and undergrowth. An extensive review of the determination of hydraulic roughness of vegetation is given by e.g. Stolker *et al.* (1999) and Stolker & Verheij (2000). Their equations to determine the hydraulic roughness k_N for submerged vegetation (flow through and over vegetation) are:

$$q = q_v + q_o = k \cdot \sqrt{\frac{2g}{C_D \cdot k \cdot A_v}} \cdot \sqrt{k \cdot i} + (h-k) \cdot C_v \cdot \sqrt{(h-k) \cdot i} \qquad (1)$$

$$q = C \cdot h\sqrt{hi} = 18\log\left(\frac{12h}{k_N + 3.3\nu / u_*}\right) \cdot h\sqrt{hi} \qquad (2)$$

in which q is the specific discharge (m^2 s^{-1}), q_v and q_o are the specific discharges through and over the vegetation, k is the vegetation height (m), g is gravitational acceleration (m s^{-1}), C_D is the drag coefficient (dimensionless), i is water level slope (dimensionless), A_v is the blockage area of the vegetation per unit area (m^{-1}), ν is kinematic viscosity (m^2 s^{-1}), u_* is bed shear velocity (m s^{-1}) and h is the water depth (m). C_v and k_v are the Chézy coefficient and the Nikuradses roughness length for the hydraulic roughness of the top of the vegetation, computed as:

$$C_v = 18\log\left(\frac{12(h-k)}{k_v}\right) \qquad (3)$$

$$k_v = 0.52k^{0.44} \qquad (4)$$

For non-submerged vegetation the roughness caused by the top of the vegetation is zero and k is replaced by h. Thus, for the computation of the hydraulic roughness, the following variables must be determined from laser altimetry data and field measurements: distribution of vegetation height (k), stem diameter (D) and number of stems (N) per m^2, which together determine the blockage area per unit area ($A_v = N * D$), and the percentage of a certain area covered with trees, shrubs, or grass.

The hydraulic roughness expressed as the Nikuradses k_N-value was computed for water levels that occur at the design discharge for flood protection (recurrence time = 1250 year). Under these conditions the highest parts in the hardwood production forest are not inundated, whereas at the lower parts such as in the softwood flood plain forest the water depth exceeds 4 m. The water level gradient is about 1 cm per km.

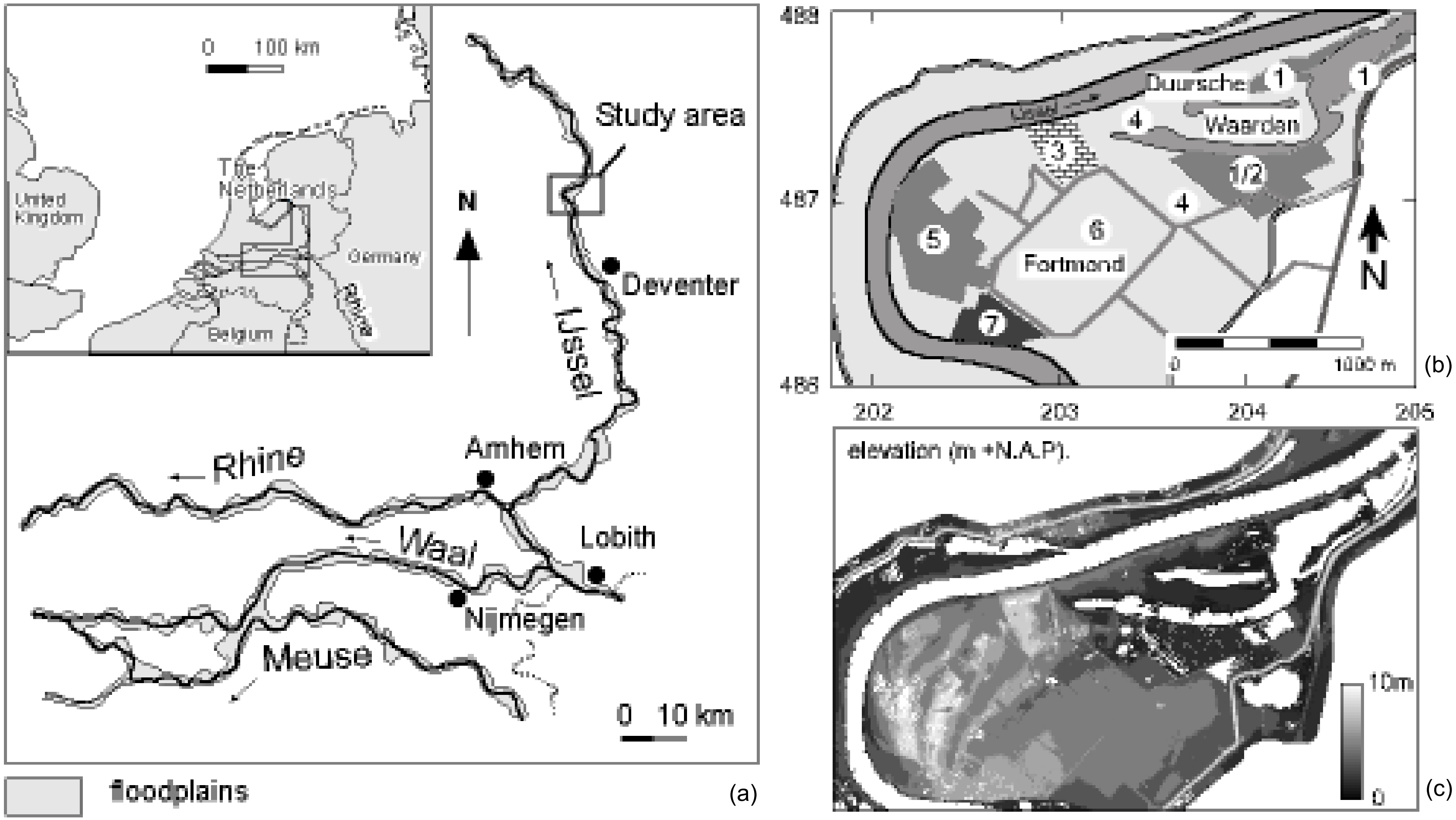

Fig. 1 The study area: (a) location; (b) land use (1 = softwood flood plain forest (high), 2 = softwood flood plain forest (low), 3 = uncultivated area near former brick works, 4 = grassland, 5 = hardwood production forest, 6 = arable land and meadows, 7 = camp site; water and swamp vegetation are not shown on the map but occur in narrow zones along the secondary flood plain channels); (c) elevation.

LASER ALTIMETRY

The laser altimetry data used in this study were acquired in March 1997. The timing of acquisition allowed collecting information on vegetation height during late winter, when most floods in the River Rhine occur. The image was taken from a helicopter, at 70 m above the ground with a ground speed of 14 m s^{-1}. Pulse repetition frequency was 8000 Hz. Maximum scan off-nadir angle was 30°, which corresponds to a swath width of 61 m. Parallel flight lines were flown at a spacing of about 50 m, resulting in a 20 m overlap and a minimum sample density of about 7 points per m^2 (Gomes Pereira & Wicherson, 1999).

The laser scan data were firstly used to derive a digital elevation model (DEM) with a 1 × 1 m^2 grid (Fig. 1). Vegetation heights were computed by subtracting the flood plain elevation (DEM) from the laser altimetry measurements. Distributions of vegetation height and density were derived from the laser altimetry measurements using frequency distributions. The percentage of a certain area covered with trees, shrubs and grasses can be estimated from these frequency distributions.

Figure 2 shows cumulative frequency distributions of measured heights in different types of vegetation. Maximum tree heights in hardwood production forest are the same as in softwood flood plain forest, but tree crowns are denser. In softwood flood plain forest, few pulses are reflected at heights of about 10 m or more above the flood plain. Instead, branches are present at different elevations, especially in the lowest 5 m above the ground. The difference between forest, shrubs and grass also becomes clear from the frequency distributions in Fig. 2.

Based on the distributions of measured vegetation heights as shown in Fig. 2, a set of "decision rules" was established to classify the laser altimetry image. An example of

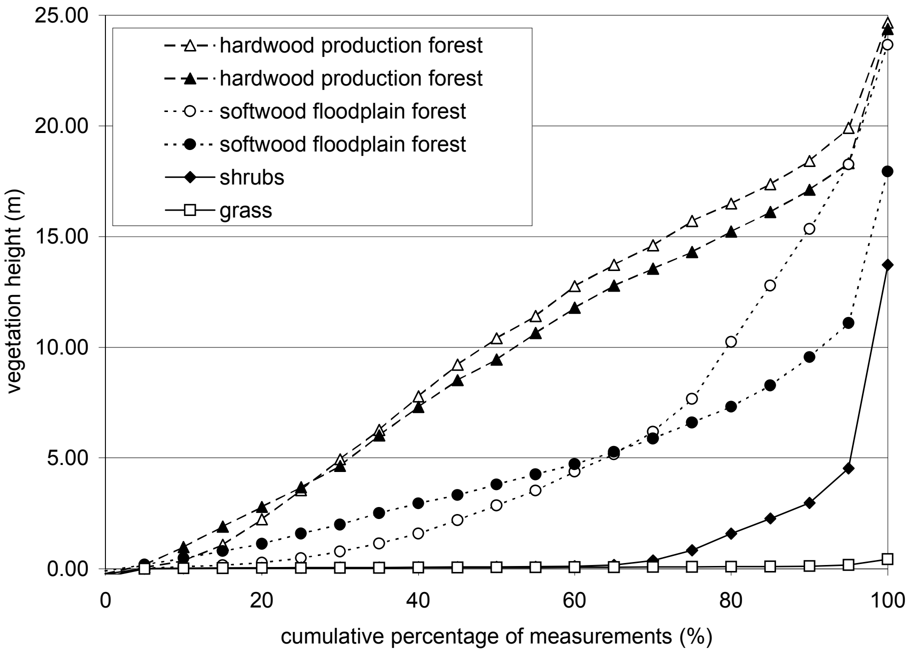

Fig. 2 Cumulative frequency distributions of measured vegetation heights (average per m^2) for different vegetation types. Two curves are shown for different plots of softwood flood plain forest and hardwood production forest.

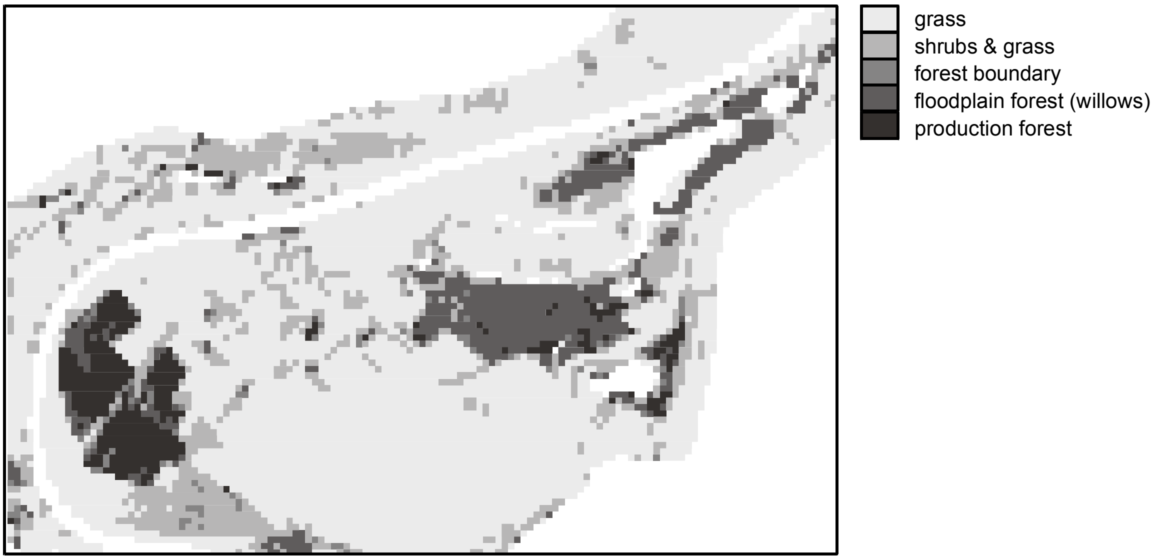

Fig. 3 Vegetation types obtained by classification of the laser altimetry data using the frequency distribution of measured average vegetation heights per m^2 in 25 × 25 m^2 windows.

Table 1 Blockage areas of different types of vegetation from Pedroli *et al.* (1999) and Stolker *et al.* (1999).

Vegetation type	Blockage area (m^{-1})
Grass	2.00
Shrubs	0.17
Softwood flood plain forest	0.13
Hardwood production forest	0.02

such a decision rule reads "IF 95% of the measurements in a 25 × 25 m^2 window indicate vegetation heights of less than 0.25 m, THEN the vegetation is grass". Application of the decision rules resulted in the classified map shown in Fig. 3.

Comparison of the classification results (Fig. 3) with the topographical map (Fig. 1) shows that classification of vegetation using laser altimetry data enables differentiation between shrubs and different types of forests. However, due to the irregularities in the soil surface and inaccuracies in the laser altimetry measurements, it is not possible to differentiate between bare soils and areas covered with short grass.

Information on blockage areas cannot be determined from the laser scan data. Blockage areas for different types of vegetation therefore were derived from the literature (Pedroli *et al.*, 1999; Stolker *et al.*, 1999) (Table 1).

The hydraulic roughness map computed using laser altimetry data indicates that k_N for grass as well as bare arable land (winter condition) generally is less than 0.1 m (Fig. 4). Hedges between fields have k_N values that vary between about 0.2 and 10 m. The hardwood production forest contains a range of hydraulic roughness lengths (k_N) from about 0.2 m to more than 5 m. Low values occur in places where inundation is shallow. Maximum values for the hydraulic roughness (k_N values vary between 5 and 40 m) are found for softwood flood plain forests, due to a combination of large water depth and dense vegetation.

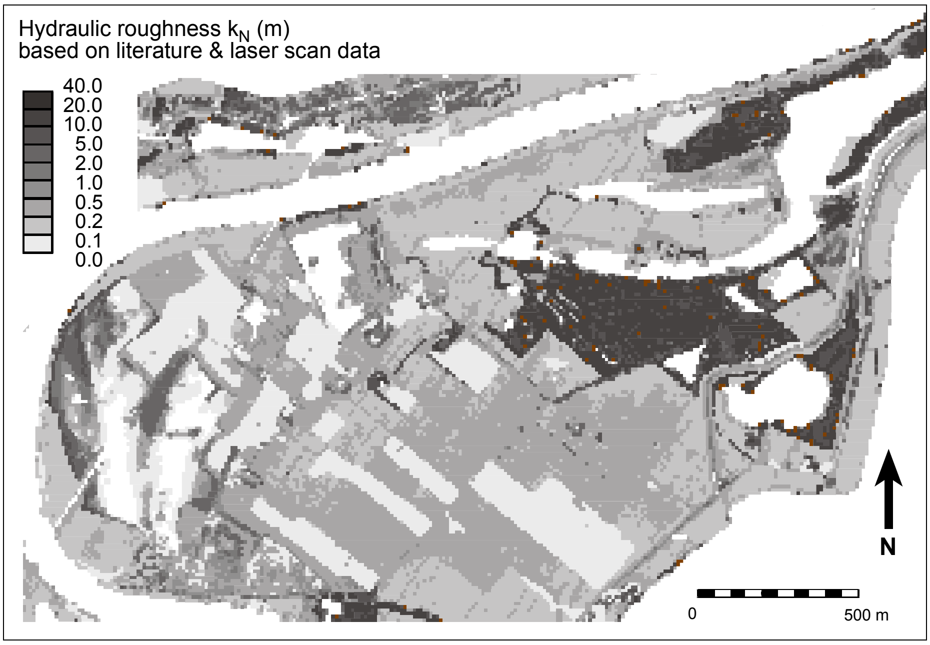

Fig. 4 Map of the hydraulic roughness of vegetation based on literature and laser scan data.

FIELD MEASUREMENTS

Using existing vegetation maps, aerial photographs, and field surveys, a vegetation map at a scale of 1:5000 was made of the study area. The field surveys were carried out in June and July of 2001. On grassland and arable fields, the length of vegetation was determined on 126 randomly selected plots by measuring the lengths of grasses and small plants using a ruler. In addition, variations in the elevation of the flood plain surface were determined. In forests, where the trees are not submerged during floods, 104 representative plots were selected, with each plot including at least 30 tree trunks. Trunk and branch diameters (D) were measured at breast height above the ground surface, using a measuring-tape. After counting the number of stems per unit surface

Table 2 Typical values of A_v and k of different vegetation types in the study area obtained by field measurements.

Vegetation type	Blockage area A_v (m^{-1})	Vegetation height k (m)
Submerged		
Natural grassland	0.03–0.17	0.1–0.6
Production grassland	-	0.1–0.2
Cut grassland	-	0.04–0.05
Reed	0.1–0.5	0.8–2.0
Hedges	0.04–0.16	1.0–2.5
Willow bushes	0.45	2.7
Non-submerged		
Willow forest	0.12–0.3	-
Hardwood forest (oak)	0.03–0.05	-
Mixed forest	0.02–0.06	-
Hedges	0.001–0.36	-

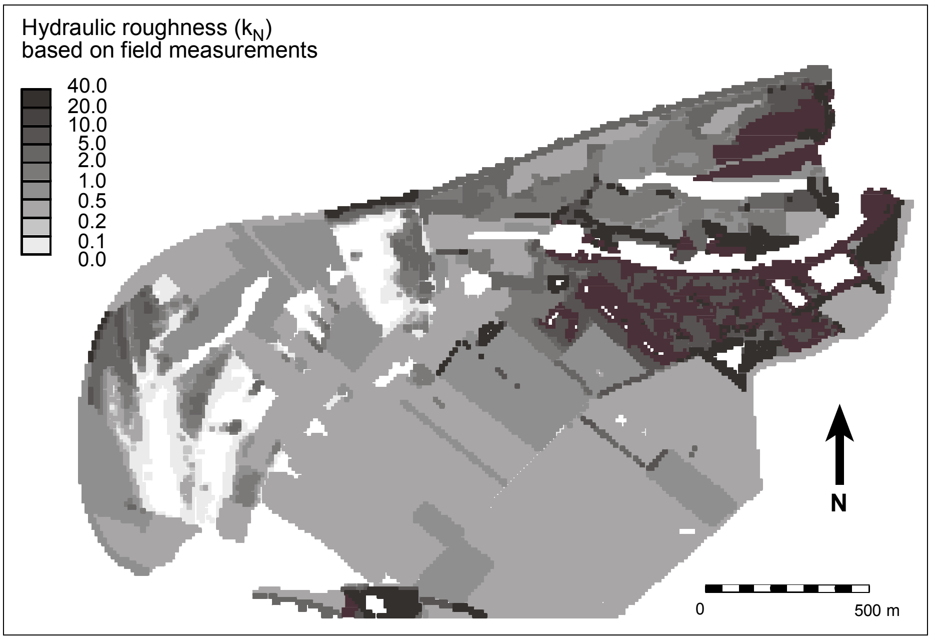

Fig. 5 Map of the hydraulic roughness of vegetation based on field measurements.

area (*N*), the blockage area A_v was determined as $N \times D$. Density and height of the undergrowth were determined on the same plots. For vegetation types with shrubs (mostly willows) and high plant shoots (willows, reeds), vegetation height as well as blockage area at breast height were determined on 38 sampling plots. Plot areas varied between 0.5 and 9 m^2, depending on vegetation density. On each plot at least 30 shoots were measured. Measured vegetation heights and blockage areas are summarized in Table 2. The resulting hydraulic roughness map is shown in Fig. 5.

DISCUSSION AND CONCLUSIONS

Comparison of the hydraulic roughness maps derived from the laser scan data combined with data reported in the literature (Fig. 4) and the field measurements (Fig. 5) indicates that for most vegetation types the computed and measured hydraulic roughness values are of the same order of magnitude. The largest discrepancies are related to grasses, arable land, and young softwood flood plain forests. A first cause of the differences is that blockage areas given in the literature for grassland are higher than those found in the study area. A second cause is the difference in the season during which the measurements were carried out: vegetation heights, especially of arable crops and natural grasslands, are different in summer and winter. Finally, field samples were collected 3.5 years after the image was acquired. Meanwhile, softwood flood plain forest, such as willows, may have significantly grown. For example, the northern part of the study area was covered with pioneer vegetation with maximum heights of about 1–2.5 m in 1997. In the summer of 2001 this area was covered with very dense willow brushwood with an average height of about 2.75 m.

The overall impression is that the laser altimetry can be successfully applied for mapping flood plain vegetation type, height, and pattern. These variables can subsequently be used to estimate the hydraulic roughness of the vegetation, which yielded reasonable results when compared with field measurements. This indicates that laser altimetry indeed is a promising tool for hydraulic roughness surveys of flood plains.

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REFERENCES

Blair, J. B., Rabine, D. L. & Hofton, M. A. (1999) The laser vegetation imaging sensor: a medium-altitude, digitization-only, airborne laser altimeter for mapping vegetation and topography. *J. Photogramm. Engng & Remote Sens.* **54**, 115–122.

Gomes Pereira, L. M. & Wicherson, R. J. (1999) Suitability of laser data for deriving geographical information—a case study in the context of management of fluvial zones. *J. Photogramm. Engng & Remote Sens.* **54**, 105–114.

Kraus, K. & Pfeifer, N. (1998) Determination of terrain models in wooded areas with airborne laser scanner data. *J. Photogramm. Engng & Remote Sens.* **53**, 193–203.

Menenti, M. & Ritchie, J. C. (1994) Estimation of effective aerodynamic roughness of Walnut Gulch watershed with laser altimeter measurements. *Wat. Resour. Res.* **30**, 1329–1337.

Næsset, E. (1997) Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sens. Environ.* **61**, 246–253.

Pedroli, G. B. M., Duel, H. & Vonk, M. (1999) Investigation of the hydraulic roughness of river ecotopes (in Dutch). *WL Report T2052/T2068, WL|delft hydraulics, Delft.*

Ritchie, J. C., Jackson, T. J., Garbrecht, J. D., Grissinger, E. H., Murphey, J. B., Everitt, J. H., Escobar, D. E., Davis, M. R. & Weltz, M. A. (1993) Studies using an airborne laser altimeter to measure landscape properties. *Hydrol. Sci. J.* **38**(5), 403–416.

Stolker, C. & Verheij, H. J. (2000) Comparison of computational methods of the hydraulic roughness of submerged flexible vegetation (in Dutch). *WL Report Q2693, WL|delft hydraulics, Delft.*

Stolker, C., Van Velzen, E. H. & Klaassen, G. J. (1999) Accuracy analysis of the hydraulic roughness of vegetation (in Dutch). *RIZA Werkdocument 99.192X, Arnhem.*

Weltz, M. A., Ritchie, J. C. & Fox, H. D. (1994) Comparison of laser and field measurements of vegetation height and canopy cover. *Wat. Resour. Res.* **30**, 1311–1319.