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The impact of macroalgae on mean and turbulent flow fields*

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Abstract: In this paper, we attempt to quantify the mean and turbulent flow fields around live macroalgae within a tidal inlet in Norway. Two *Laminaria digitata* specimens ~ 0.50 m apart were selected for detailed study and a profiling ADV was used to collect 45 velocity profiles, each composed of up to seven 0.035 m-high profiles collected for 240 s at 100 Hz, at a streamwise spacing of 0.25 m and cross-stream spacing of 0.20 m. To quantify the impact of the macroalgae, measurements were repeated over a sparser grid after the region had been completely cleared of algae and major roughness elements.

Key words: dealiasing, laminaria digitata, turbulence, vectrino profiler, velocity profile

Introduction

In recent years, a significant amount of research has examined the interactions between immersed vegetation and flowing water[1,2]. Whilst early physical modeling and theoretical studies employed rigid structures such as wooden dowels, recent studies have progressed to flexible surrogate plants[3-8]. However, even appropriately-scaled flexible surrogates fail to capture the variability in thallus morphology, flexibility and strength, both within and between individuals[9], and frontal area (for rigid organisms) or planform area (for flexible organisms like macroalgae[10]) over space and time[11] that may force spatio-temporal variability in mean and turbulent flow fields[7]. For example, in their flume experiments, Siniscalchi and Nikora[12] found that different species of aquatic plants responded differently to similar hydrodynamic forcing.

Aquatic vegetation can form dense, uninterrupted canopies as well as distributed patches. There have been a number of experimental and computational studies on the mean fully-developed flow and turbulence characteristics through and over large, uniform stands of vegetation[3,6,13-16]. However, macrophyte growth in rivers and macroalgae colonization of coastlines is typically patchy and, therefore, Naden et al.[17] appealed for experimental work to improve understanding of the effect of vegetation patches or individual large plants and their arrangement on flow fields. Experimental studies suggest that the extent to which a patch modifies the flow field is dependent upon the frontal or planform area. Zong and Nepf[18] reported that the effect of a dense patch is equivalent to a solid body of the same width, streamwise velocity begins to decrease approximately one patch width upstream of the patch. Conversely, turbulence levels increase at the leading edge of a patch[18]. As the frontal or planform area tends to zero, the adjustment length also tends to zero. Velocity is strongly reduced within a patch, whereas the flow is highly accelerated above and around it[17]. However, at low-speed flows, a zone of increased velocity occurs near the bed that extends along the length of the patch[8]. Velocities tend to be laterally uniform over most of the patch width, increasing toward the free stream within a few stem diameters of the patch edge[18]. A horizontal shear layer with a width comparable to the patch width[19] develops between the water-surface and a specific depth within the canopy[4], while a near-vertical shear layer may also form at the patch edge[20]. Coherent vortices in these shear layers may dominate the turbulent flux of momentum across the patch edge[20], but the three-dimensionality of the wake and high background turbulence levels should disrupt periodic vortex formation[21]. At the downstream edge of a patch, velocity

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profiles slowly return to the undisturbed upstream condition. Folkard[5] studied the effects of the wake caused by one patch on an adjacent downstream patch and found that patch spacing relative to total wake length and the location of the wake Reynolds stress maximum controlled the turbulence within the downstream patch. Wake length was a function of discharge, leaf length, flow depth, and patch separation[5]. Maltese et al.[7] focused on the spatial patterns of coherent turbulent structures in vegetation gap environments.

Although a number of field studies have been carried out[17,19,21,22], measurements of hydraulic variables have generally been limited to time-averaged at-a-point measurements that aim to approximate the depth-mean velocity. This is problematic because in spatially heterogeneous flows, point measurements are dependent upon the sampling location[23,24]. For example, measurements over entire channel cross-sections[17,19] indicated that velocity profiles are highly variable and dependent on the locations of plants and the type of plant assemblage. Fairbanks and Diplas[4] examined turbulence statistics in the vicinity of a rigid canopy and found that both the longitudinal and vertical turbulence intensity profiles were variable and dependent on the spatial sampling location. Such sensitivity may be ameliorated through application of the double averaging methodology over an appropriate spatial averaging volume[23,24].

Thus, there is a need to undertake experimental work using live plants, in order to quantify the mean and turbulent flow fields within and around different plant forms under different flow velocities and depths, especially in natural environments[17]. Furthermore, although marine macroalgae tend to have morphologies that are significantly different to those of freshwater macrophytes, no studies have sampled the flow patterns and turbulence characteristics around macroalgae and their impact upon flow fields has thus not been quantified. In the present study, we therefore quantify: (1) the mean and turbulent flow fields around macroalgae at a vegetated field site, (2) the locations and biomechanical properties of the algae[25], and (3) the mean and turbulent flow fields after algae were completely removed.

1. Methods

The study site is a small tidal inlet located at the entrance of Trondheimsfjord, Sør-Trøndelag, Norway (see Figs.1 and 2). The inlet is approximately triangular in planform, with its mouth to the northwest. The deepest parts of the inlet are to the centre and northeast, where the depth is between 25 m and 30 m. A delta, formed of coarse sand and broken shells, has been deposited in the northwest corner of the inlet (Fig.2). This delta is fed by a channel with a gravel-cobble bed that is 15 m wide and up to 4 m deep at the bridge that marks the seaward margin of the inlet (Fig.2). This outlet channel is pinned to the northern edge of the delta and thus the depth of water over the delta shallows from west to east and from north to south. For much of the delta, the average water depth above the flat sandy bed is $\sim 0.5\ \mathrm{m}$.

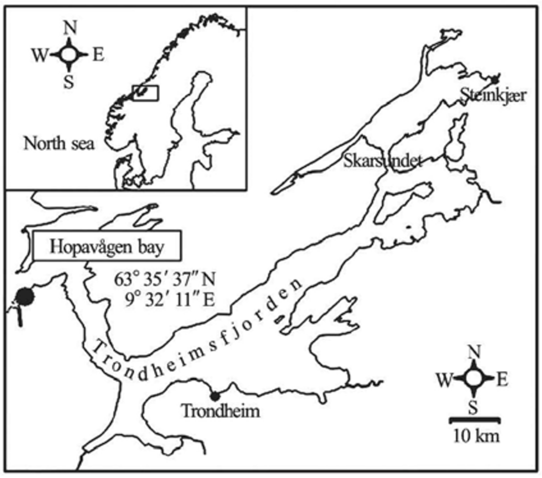

Fig.1 Location of the study area in Norway

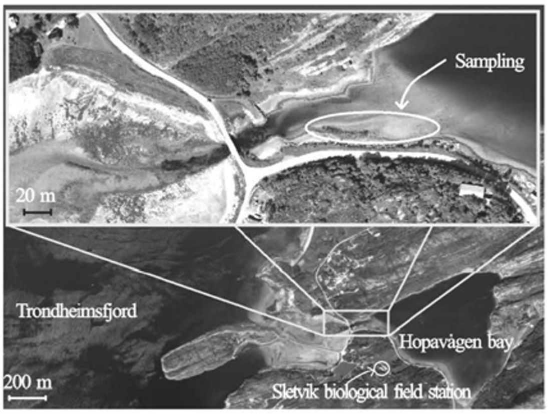

Fig.2 Aerial photographs of the study area (from www.norgeskart.no)

An 11 m long×6 m wide region in the south-western part of the delta was selected for intensive study. Due to the dimensions of the inlet (370 000 m^2) and the small cross-sectional area of the outlet channel, the tidal range is relatively small, during the sampling period (May 2012), the water level in the study area varied by $\sim 0.5\ \mathrm{m}$. Tides are semi-diurnal, strongly asymmetric and flood-dominated, the flood tide lasts for $\sim 3.5\ \mathrm{h}$ while the ebb lasts for $\sim 8.5\ \mathrm{h}$. All velocity measurements were made during the ebb tide. The catchment area of the bay is negligible (1.9 km^2). Therefore, the salinity in the inlet is close to the values found in the fjord $(31 \pm 4\ \mathrm{ppm})$, and varies depending on the thermal and tidal conditions. Within the 11 m×