Advances in Water Resources 76 (2015) 11–28

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Flume experiments on wind induced flow in static water bodies in the presence of protruding vegetation

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ARTICLE INFO

Article history:
Received 5 August 2014
Received in revised form 22 November 2014
Accepted 22 November 2014
Available online 3 December 2014

Keywords:
Flexible vegetation
Lorenz curve
PIV
Vegetation drag
Wave turbulence interaction
Wind induced flow

ABSTRACT

The problem of wind-induced flow in inland waters is drawing significant research attention given its relevance to a plethora of applications in wetlands including treatment designs, pollution reduction, and biogeochemical cycling. The present work addresses the role of wind induced turbulence and waves within an otherwise static water body in the presence of rigid and flexible emergent vegetation through flume experimentation and time series analysis. Because no prior example of Particle Imaging Velocimetry (PIV) experiments involving air–water and flexible oscillating components have been found in the literature, a spectral analysis framework is needed and proposed here to guide the analysis involving noise, wave and turbulence separation. The experiments reveal that wave and turbulence effects are simultaneously produced at the air–water interface and the nature of their coexistence is found to vary with different flow parameters including water level, mean wind speed, vegetation density and its flexibility. For deep water levels, signature of fine-scaled inertial turbulence is found at deeper layers of the water system. The wave action appears stronger close to the air–water interface and damped by the turbulence deeper inside the water system. As expected, wave action is found to be dominated in a certain frequency range driven by the wind forcing, while it is also diffused to lower frequencies by means of (wind-induced) oscillations in vegetation. Regarding the mean water velocity, existence of a counter-current flow and its switching to fully forward flow in the direction of the wind under certain combinations of flow parameters were studied. The relative importance of wave and turbulence to the overall energy, degree of anisotropy in the turbulent energy components, and turbulent momentum transport at different depths from the air–water interface and flow combinations were then quantified. The flume experiments reported here differ from previous laboratory studies in the related literature involving vegetation in the sense that the wave forcing is only present on the water surface contrary to a full-body excitation by tidal wave simulators and thus important in advancing the knowledge regarding a wider range of water resource problems.

1. Introduction

The monetary value and multiple ecosystem services provided by static water bodies such as wetlands and marshes are rarely disputed [1–14]; however, characterization of the flow field, needed in all such ecosystem valuation, remains the subject of active research. Operational models for water flow in wetlands commonly assume the flow to be analogous to a wide and shallow open channel described by the so-called Saint–Venant equations that are then mathematically closed for the energy losses using a Manning-type formula with an associated friction factor as recently reviewed elsewhere [15]. Because the flow depth in wetlands is shallow, wind effects can be sufficiently large so as to induce flow even in the absence of any bed slope. These wind effects on the flow have traditionally been lumped into changes in the friction factor, with little theoretical or experimental underpinning, which is the main motivation for this work. By no means this is a unique criticism to such an operational framework. Another common criticism is the lack of explicit inclusion of the effects of vegetation on both – bulk and turbulent flow quantities needed for the purposes here. Such vegetation characterization on the bulk flow has often been directed to drag or flow resistance estimation for unidirectional flow but in the absence of wind [9,10,16–26]. A number of studies have also been concerned with detailed description of turbulent processes needed in modeling movement of particulate matter inside aquatic vegetation, characterization of dispersion,

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http://dx.doi.org/10.1016/j.advwatres.2014.11.010
0309-1708/

and lateral diffusion [27–32]. In unidirectional flow through a vegetation canopy, the shear layer on top of a canopy generates canopy scale turbulence that is pushed down to the canopy displacement length [10,33]. At the bottom of the canopy, turbulence is generated by stem scale wakes [10,33]. In dense canopies, the intensity of turbulence is reduced by sheltering [34,35], which plays a positive role in sediment retention and prevention of bed erosion [8,36–44]. However, all these experiments did not consider the problem of wind-induced flow within emergent aquatic vegetation, the main compass of this work.

Any wetland or channel featuring aquatic vegetation is naturally subjected to wind flow and wind-generated waves that can influence the flow-field inside the water body, which is further complicated by the presence of emergent vegetation also subjected to the wind and consequent oscillation depending upon their flexibility. In the absence of vegetation, the problem of wind blowing over a water surface is not particularly new and has a long history [45,46]. Wind flowing over a static water body such as a lake or reservoir (as in the original work of Charnock) is the main source of mechanical energy for turbulent mixing inside the water body. The wind flowing over the water surface causes a drift current in the direction it blows thus perturbing the water surface, which is called wind set-up [47,48]. This local pressure gradient generated due to the 'tilt of the surface' [48] creates a reversed flow at the bottom of the water body, as well as ensuring mass continuity in a vertical plane. Here, the difference of the physical process governing the propagation of gravity waves and the wind set-up should be noted. Gravity wave is a self sustained process initiated out of an initial perturbation before the wave is damped. Whereas the wind set-up is continuously sustained by air motion, which injects energy into the water and applies shear stress on the surface. Studies have reported experimental investigation of wind induced water currents, focusing on both the surface motion and the counter-current flow but without vegetation [48–59]. Some studies have discussed a simple analytical model of wind set-up by constructing one, two and three dimensional models and engineering models for wind induced counter-current flow but without any vegetation [60–71]. The role of waves in vegetated system has been considered, but in these cases, the entire wave was imposed on the vegetation primarily to mimic tidal systems so as to study wave attenuation, equivalent bed roughness and friction factor inside aquatic vegetation canopy under wave forcing [5,72–79]. Others have also discussed the nature of the flow field inside a flexible aquatic vegetation under the action of wave forcing by means of laboratory experiments [6,25,80–84] and by modeling [85–87]. Flapping motion of the vegetation, a generic feature of many aquatic vegetation under oscillatory forcing like waves, also appears to enhance nutrient uptake [88–91,79]. On similar lines, a few studies have addressed the characterization of turbulent structures and detection of sweep–ejection cycles and traveling vortex induced synchronous progressive waving action on aquatic flexible vegetation called 'Monami' [92–97].

It is evident from this literature survey that progress has been made in understanding (i) the dynamics of wind–shear–water interaction without vegetation, and (ii) the flow dynamics in presence of flexible vegetation under wave forcing. Yet, all these previous studies in the second category have dealt with wave forcing generated by wave-makers, i.e., the whole water mass has been subjected to a wave forcing. Under this condition, some studies [81,82,90] have used linear wave theory to interpret their results – for example the decomposition of the instantaneous flow-field into phase averaged, coherent and turbulent components. Other studies examining counter-current flow without vegetation [58,48] have analyzed their results without any regard to linear wave theory and employed parabolic mixing length models to close their turbulent stresses.

The present work related to wind induced flow in a water body falls in the middle of these two aforementioned approaches. The presence of oscillating flexible vegetation increases the complexity of the problem. No previous reference of this problem has been found in the literature where the emergent vegetation is subjected to a dynamic wind loading, while the wind applies a shear on the water simultaneously subjecting the whole system to a wave–turbulent interaction. Hence, the first goal of the present work is to describe the onset and magnitude of wind-induced water flow in a standing water body in the presence of emergent vegetation with varying density and rigidity. To build a theoretical framework assisting future model development, a second goal is to delineate under what circumstances the wave and turbulence dominated regimes are separable so as to allow standard turbulence theory and standard linear wave theory to be applied at those decoupled regimes.

To address these goals and issues experimentally, Particle Imaging Velocimetry (PIV) experiments have been conducted in the laboratory to explore the characteristics of turbulence induced by wind shear on a static water body systematically for different water heights (h) and mean wind speeds (U_a) for each of the following scenarios: no vegetation, rigid sparse vegetation, rigid dense vegetation, flexible sparse vegetation and flexible dense vegetation. Analysis of the experimental data facilitates the understanding of the effects of h, U_a, vegetation flexibility and vegetation density, all of which are external conditions needed in describing the flow-dynamics within the water body. Another important aspect of the present attempt is that no instance of PIV experiments of such a type involving flexible moving canopy and wind on water have been found in the literature although PIV experiments with rigid vegetation and moving water flow have been conducted in the past as reviewed elsewhere [98]. It is demonstrated in the present work that such a PIV experiment is possible indeed with proper handling and choice of materials and methods.

2. Experiment

The PIV experiments were conducted in the Fluid Mechanics workshop at the Institute of Hydroscience and Engineering (IIHR), The University of Iowa. The dimensions of the flume (of width 35 cm) can be found in panel (a) of Fig. 1. The wind was generated by a fan (with three preset wind speed settings) mounted above the flume. For the experimental runs with the canopy, nylon cable ties (4 mm wide, 1 mm thick) 'planted' on a test bed were used as model vegetation. Two different vegetation densities, $\lambda_d = 0.39$ for sparse and $\lambda_d = 1.04$ for dense, were used. Full tie (or canopy) height $h_c = 27.3$ cm was used for flexible vegetation, while the same ties and same vegetation density cut to $h_c = 7$ cm represent the rigid vegetation (but $h < h_c$ in all experiments except the deepest water conditions for rigid cases). It is to be noted that the property of the nylon cable ties is such that when cut to a smaller length, they become quite rigid thus obviating the necessity to use other materials for stiff vegetation and reducing cost. Moreover, the rigid cases are submerged for deepest water conditions, however, they server the main purpose of applying drag for most part of the fluid, since the protrusion length does not matter in those cases. The λ_d was calculated as $\lambda_d = n w_t h / s_v$, where n is number of cable ties, w_t is the width of each tie, and s_v is the test bed 'vegetated' area [98]. The h was used here in the estimation of λ_d instead of h_c because the vegetation was emergent for all runs as earlier noted. The selection of an optimal λ_d is not trivial given that it is an optimization between maintaining realistic vegetation densities, as well as maintaining sufficient open area to allow particle imaging that can be challenging where the vegetation is flexible