RESEARCH ARTICLE OPEN ACCESS

The construction of turbulent flow through sub merged flexible vegetation

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ABSTRACT: The hydrodynamics of violent course through lowered adaptable vegetation is researched in a flume utilizing acoustic Doppler velocimetery (ADV) estimations. The stream attributes, for example, the energetics and force move got from regular otherworldly and quadrant examinations are considered as the stream experiences a limited vegetation fix. Steady with various shade stream tests, a shear layer and intelligible vortex structures close to the overhang top arise brought about by Kelvin–Helmholtz hazards after the stream equilibrates with the vegetated layer. These hazards are usually ascribed to speed contrasts between non-vegetated a lot shelter layers in concurrence with various analyses and recreations led on thick unbending overhangs. The force ghastly thickness work for vertical speed tempestuous vacillations at various downstream positions beginning from the edge of the vegetation layer are likewise registered. For a preset water profundity, the prevailing dimensionless recurrence is discovered to be shockingly invariant around 0.027 notwithstanding huge contrasts in vegetation densities. The discharge and clear occasions altogether add to the Reynolds stresses close to the highest point of the vegetation. The energy transition conveyed by discharges is bigger than its partner conveyed by the ranges over the covering top. Notwithstanding, the energy transition conveyed by clears is bigger beneath the highest point of the covering.

Keywords: Artificialflexiblevegetation,coherentvortexstructures,dragforce,openchannelflow,velocitydistribution

I. INTRODUCTION

Withrapidurbanizationandindustrialization ,waterqualityinriversandstreamsisbecomingseriously polluted resulting in gradual degradation ofecosystem services. How to restore such degraded ordamagedecosystemsandeffectivelycontrolthedeterioratingwaterqualityisbecomingamajorresearch issue of societal significance[1-2]. Ecologicalrestorationofriversandstreamsisconcernedwith

eco-hydraulicsandecologicalengineeringsoastoensure optimalflowconditionsneeded tosustain aresilientfood-web[3-4].Theengineeringconcernsinclude ecological bank and slope protection and flowregulation. Aquatic vegetation is an intrinsic part ofsuch efforts given its role in purifying water throughabsorptionandmicrobialmetabolism[5].Infact ,phytoremediationisnowwidelyusedinriverandwetlandwatertreatmentandremainskeytomanyrestoration projects[6].

While few dispute the ecological significance ofwater movement through vegetation, describing suchcomplexflowremainsadauntingtask[7-9].Allecologicalrestorationmeasures,includingnutrientand contaminant transport[10-11], require description offlowthroughvegetation.Inparticular,non-uniformflowthroughvegetatedsectionsisbecominganecessaryfirststepwhenaddressingthemany

engineeringchallengesforthefollowingreasons: (1)Aquaticplantscanresist waterflushing,protecttheriverbankslopeandmaintain theriverbedstability.

(2)Thestems,theleavesand theepidermisofaquaticplantshavestrongabsorptioncapacitythatcanpurifywaterthroughbiochemicalandphysicalmethods[12].Emergentvegetationcanfixnitrogenandphosphorusthroughmicrobialmetabolismandself-absorption,whichisoftenusedinwetlandrestoration[13].(3)Aquaticvegetationprovidesanattachmentmatrixandahabitatforaquaticorganisms,thusplayinganactiveroleinthemaintenanceandprotectionofbiologicaldiversity.Hence,itcanbesurmisedthatrestorationordesign ofaquaticecosystemsandwetlands[14-19]mustconfront all the complications encountered asturbulentflowstraverseavegetatedsection .Theworkhere primarilydeals with theeffects of vegetationontheincreasedflowresistance,thereduced bulkvelocity,andthegenerationofwakesandothercoherenteddiesthattransportnutrientsorsediments.Tobeclear,studiesofflowthroughandabovevegetatedcanopiesisbynomeansanewtopic.Itwasstudiedforwellover60yearsinbothterrestrialandaquaticenvironments[20-

26]andcontinuestodrawsignificantresearchattentiontoday.Reviewingallthisliteratureiswelloutsidethescopehere;however,salientfeaturesaboutkeytheories,experiments,andsimulationsmostpertinenttothestudyobjectivesarecoverednext.

Interrestrialandseveralaquaticsystems,thecaseofrigidvegetationimmersedinadeepfullydevelopedturbulentboundarylayerhasbeenConsidered,wherethevegetationheightismuchsmallerthantheboundarylayerheight.Theflowthrough aquatic vegetation differs from their terrestrialcounterpart in that the water depth can be smaller (i.e.,emergentvegetation)orlarger(i.e.,submergedvegetation) than the vegetation height[27-28]. Moreover,themulti-scalednatureofvegetationaswellasflexibilityfurtherincreasesthecomplexityofsuchflows.Nonetheless,for steady-uniformflowoversubmerged rigid vegetation, a number of features wererevealedusingReynolds-averagedNavier-Stokes(RANS)budgets[29-30].Thewaterdepthcanbedivided into three distinct layers labelled as (1) thevegetationlayer,dominatedbywakesresemblingKarman vortex streets, (2) the shear layer, dominatedbyKelvin-Helmholtz(K-H)instabilities,and(3)anon-vegetationlayerresemblingacanonicalrough-wallboundarylayer,whereattachededdiesdominate the mixing length for momentum exchange.Numerous experiments on dense canopies reportingmean and turbulent flow properties suggest that: (1)Themeanvelocityprofileischaracterizedbyaninflectionpointnearthecanopytop,spawningvorticesthatresembleK-Hinstabilities.These

vorticestopologicallydifferfromattachededdiesdominating canonical turbulent boundary layers. (2)Thesecond-orderflowstatisticsallexhibitsomeattenuation with reduced depth inside the canopy. (3)Whilebothejectionsandsweepscontributetomomentumtransport,sweepscontributemorethanejections to the overall momentum flux in virtually alllayers inside canopies. (4) The spectral shapes of thevelocitycomponentsareimpactedbytwonewprocessesthatareentirelyabsentincanonicalboundarylayers:(a)theworkthatthemeanflowexercisesagainstthefoliagedragandproducesturbulentkineticenergybywakes and(b)theshort-circuiting of the energy cascade representing thesame physical process but acting on turbulent eddiesrather than on the mean flow[31-34]. The flow is partlyblocked by vegetation and the fluid-solid interaction isoften represented by a drag force with an associateddragcoefficient.Unsurprisingly,therearesveralmodelsrepresentingsuchdrageffectincludingthe drag coefficient for an isolated cylinder, the bulk dragcoefficient for an array of cylinders and an explicitverticallyvariablelocaldragcoefficient[35-37].Inadditiontothis“vertical”picture,flowsinnaturalrivers also encounter a discontinuous vegetation patchof a finite length. This additional length scale makesthe problem of describing flow statistics within andabove vegetation difficult because multiple horizontalandverticallengthscalesmustbesimultaneouslyconsidered.

Laboratoryexperimentshavepreviouslycontributed data to the development of theories forsuchcomplexflowsandarethemaintoolstobeemployedhere[38-42].Inlaboratoryexperiments,thewater level and/or the vegetation density must vary ascontrolparameters.Theexperimentsreportedherealsoconsiderflexiblevegetationwitharangeofflexibility commensuratewiththoseencounteredinnaturalsettings[43-51].Forfinitevegetationpatches,longitudinaladvection affectsmomentumandmasstransport in a zone where the flow first encounters thepatch and equilibration with vegetation has not fullyoccurred[52-53]. Okamoto and Nezu[54] performed earlyseminal experiments in an open channel covered byrigidsubmergedvegetationtoinvestigatethetransition process from a boundary layer (prior to thevegetationpatch)toamixinglayer(aftertheflowequilibrated with the vegetation patch) along the flowdirection. They proposed a model composed of fourzones, namely, the smooth river bed, the divergingflow, the development, and the completely developedzones. These experiments, while beginning to shift thestudiesofcanopyturbulencefrom1-D(mainlyvertical)to2-D(verticalandhorizontal),donotcapture the complexity encountered in natural streamsorwetlands.Howflexiblevegetationwithcomplex

morphology alter the emerging picture put forth byOkamoto and Nezu is the main concern of this paper.Flowthroughuniformflexiblevegetationwasthefocusofseveralpriorstudies[36,55-59]asbrieflyreviewednext.Comparedwiththerigidvegetationthat remains erect, flexible vegetation exhibits certainmovement and bending under the influence of waterflow. Fathi-Maghadam[48] experimentally showed thatflow within flexible vegetation with different shapesdifferfromtheirrigidcounterpartsandthatsuchvegetationattributescannotbeignoredwhencharacterizing flow statistics. Through experiments onuniform flow, Kouwen[60-61] also showed that differentvegetation characteristics such as vegetation densityandshape,flexibilityand flowvelocity changethebending degree of flexible vegetation and subsequentfrictionallosses.Jarvela[62]evaluatedtherelationbetweendifferenttypesofflexibleplantsandtheso-called Darcy-Weisbach resistance coefficient, therelative roughness, the average cross-section velocity,andthewaterdepthandreportedthatthefrictionfactor is decreased with increased Reynolds number,except in a series of leafless willows on a bare bottomsoil,forwhichthefrictionwasmoreorlessindependentoftheReynoldsnumber.Fromthoseexperiments,itisconcludedthattheplantrigiditydoes affect the Darcy-Weisbach friction factor, whichcannot be ignored. Ghisalberti and Nepf[63] comparedtwo flow characteristics for the upright state and themonamiphenomenonofflexiblevegetationandinvestigated the effects of the vegetation flexibility onthe flow structure. The coupling effect between thevegetation and waterflow reducesthe dragforce ofthe vegetation and increases the flow velocity and theturbulentstress.Thatis,vegetationdeflectionmaybeapassive“drag-reduction”strategyemployedbyvegetation. Righetti[64] conducted experiments in anopen channel covered by two kinds of flexible bushesof different densities. They found that the net upwardmomentum flux and the associated suspended masstransport flux decrease with increases in bush density.Nepf and Vivoni[65] evaluated a flow through flexiblevegetation of limited water depth. They divided theflow in the vegetation layer into a vertical exchangezone,locatednearthetopofavegetation,anda longitudinal exchange zone, located below the verticalexchange zone. The shear layer generated at the top ofthe vegetation causes the water in the vertical zone tohaveastrongverticalturbulentexchangewiththenon-vegetationlayer.Theflowinthelongitudinalexchange zoneissimilartotheflowaroundthecylinder[66] and experiences advection relative to thesurroundingwaterbody.Interestingly,thesameexperimentssuggestonlyaverticalexchangezoneexistsin thenon-submerged vegetation.

In the last three decades, flow through vegetatedpatches were analyzed using both Reynolds averagedNavier-StokesequationsorRANSandlargeeddysimulations or LES[67-70]. In RANS, different discretemethodstoiterativelysolvethethreemainflow equations, i.e., the mean continuity equation, the meanmomentum equation and the turbulence kinetic energyequationhavebeenproposed.Themainissueshe rearehowtorepresentthevegetationpatchanditseffects ontheflowformodelingorsimulationpurposes.

Rowiński et al.[71] investigated water flow withinnon-submerged rigid vegetation using a mixing lengthmodel, which treats vegetation as a drag force withprescribeddragcoefficient.Noatetal.[72] appliedathree-dimensional turbulent algebraic stress model toinvestigate flow in riparian vegetation using similarapproachestoRANS.UsingLES,Mattisetal.[73] derived a macroscale vegetation resistance model forhighReynoldsnumberflowsandshowedhowsub-gridscaleeffectsmayberepresentedinLES.Zhang et al.[74] studied the interaction between wave,current, and vegetation by numerical approaches andproposedanexplicitdepth-averagedhydrodynamicmodelcoupledwithawavespectralmodel(CMS-wave) to represent wave and wave-induced currents incoastalwaters.Suetal.[45] conductedanLESforvegetationflowtoassesshowvariationsinwaterdepthimpactflowthrough vegetation. Fischer-Antzeet al.[75] numerically solved the RANS equations usingthe SIMPLE algorithm along with ak - □ turbulencemodel for cylindrical vegetation and showed how tooptimallyparameterizetheeffectsofvegetationinsuchk - □ modeling. Wang et al.[76] adopted a 3-Dhydrodynamicmodelwithanadditionalhydraulicresistanceforaquaticplants.Thenumericalmodelwasusedfor South-NorthWaterDiversionintheNansi Lake. Their results showed that their proposedhydraulicresistanceforaquaticplantsisfeasiblewithacalculationerror less than15%.

The work here focuses on differences betweenturbulent flow through rigid vegetation and flexiblevegetationcharacterizedbyverticallynon-uniformplant area density. Sedge was selected to allow for theinfluenceofrigiditytobecontrolled.Theflowcharacteristics to be considered are the shape of themeanvelocityprofile,theattenuationofthesecond-order statistics within the canopy, the relativesignificanceofejectionsandsweeps,thespectralshapes of the vertical velocity, and the development ofthe shear layer longitudinally as the flow adjusts to thepresenceofflexiblevegetation.Thesedgeisagrass-likeflexibleplantwithanirregularleafareashape characterized by an approximate triangular stemandaninconspicuousflower.Hence,itsmorphology

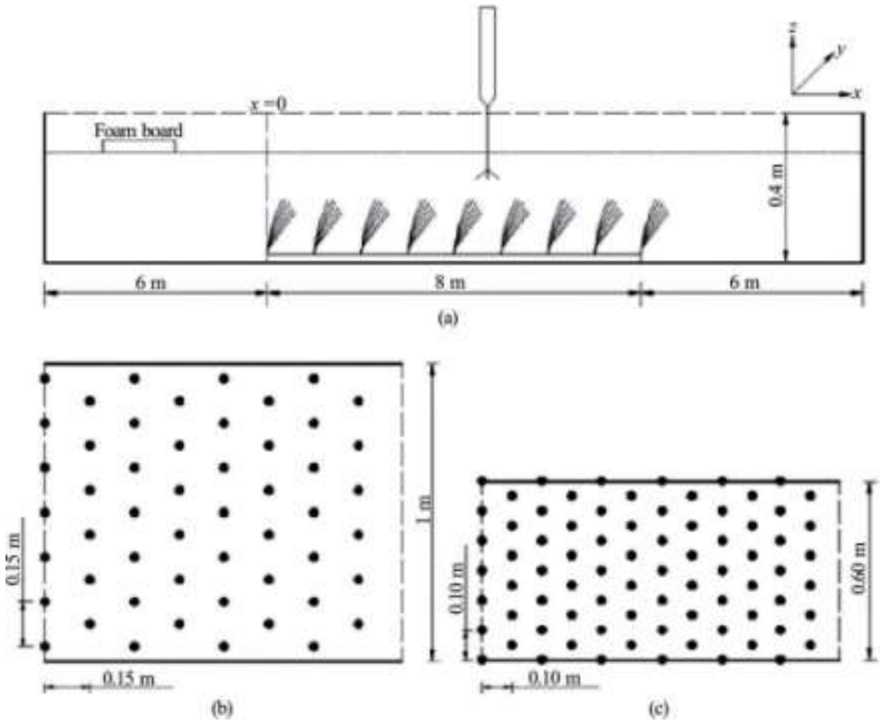

Fig.1The experimentalsetup and vegetationplacement ina rectangularchannel (thelayoutisnottothescale)showingthe longitudinal(a),plane(b)andcross-sectional(c)views.Thezisthedistancefromthebottom ofthechannel,andh_V is the deflected height of the vegetation and b is the lateral spacing between vegetation elements whereasl is the longitudi-nal spacing.Thevegetationelementplacementis showninpanels (b)and(c).

deviates appreciably from “slender” cylinders used inprior studies. The experiments are conducted to clarifyhow the Okamoto and Nezu picture is altered becauseofnon-uniformityinplantareadensityandplantrigidity. It is envisaged that the results from the flumeexperiments here provide a benchmark reference dataset to be employed in testing future numerical modelsandsimulations.Itisauniquedatasetbecauseth eflowisstationary,highReynoldsnumber,non-uniform in the longitudinal and vertical directions,and wide ranging vegetation rigidity are featured thatimpacttheflowstatistics.

Experiments

otherhasacross-sectionof1.0m×0.4mwithS=

The experiments are conducted using two glasschannelsattheStateKeyLaboratoryofWaterRes ourcesandHydropowerEngineeringScienceinWuhan University, China. The two channels are both20mlong.Oneofthechannelshasacross-sectionof 0.6m×0.4mwitha0.04%bedslope(=S),and the and the water level is adjusted by a tailgate located attheendofthechannels.Thetotallengthofthevegetatio nzoneis8mtoensureacompletedevelopmentoftheflo wwithinandabovethevegetation zone. The distance between the inlets of theflume and the vegetationzone is 6m. The layout oftheexperimentaldeviceisshowninFig.1.Thevegetat ion, fixed on a perforated board with wire andglassglue,isinastaggeredarrangement,asshownin

0.01%.Thedischargeiscontrolledbyanelectro- magneticflowmeterinstalledatthestartof thechannel,

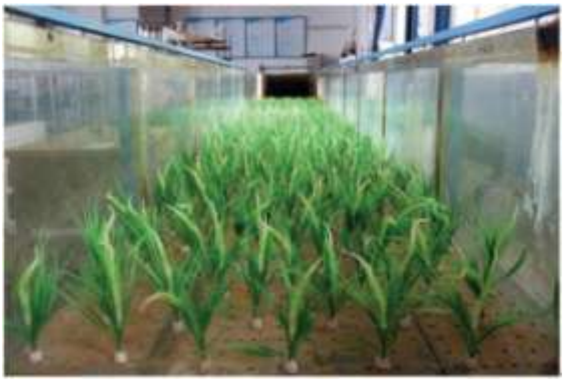

Fig. 2 (Color online) Arrangement of the plasticmodel plants re-presentingthesedge.

Fig. 2. The velocity measurements are conducted afterthe flow reaches steady state conditions. The velocityprofilesaremeasuredusinganacousticDopplervelocimeter (ADV), placed at the mid-perpendicularline of two vegetation rows, which can be laterallymoved. Each vertical line has 25-35 measuring points,andtheverticaldistancebetweentwomeasuring points is 0.005 m-0.010 m. The sampling frequencyandthemeasuringtimeoftheADVare50Hzand120s,respectively, resulting in 6000 instantaneous velocitiesforeach measuring point.
PreviousstudiesemployedglassrodsorPolyvinylchloride(PVC)thinbladesofregularshapestorepresentthevegetationinrivers.However,realvegetation are flexible and irregular, and are far fromthe “niceties” of slender rods. Therefore, a meadowmodel plant is used to represent the natural vegetation(sedge shape). Each model plant has 11 plastic slipsandthediameterofthetrunkisapproximately0.015m.Theaverageheightofthesedgemeadowmodelis 0.210 m and the lateral and longitudinal spread widthsofthesliparеapproximately0.170m,0.045m,respectively.The11plasticslipsareindividuallyfixed to a 0.01 m-thick ceramic elliptical bottom asshowninFig.3.Themodelplantshaveacertaindegree of flexibility and can swing when the waterflowsthroughthem.Thesemodelplantsaresuitableto represent the sedge because they do not have largedeformationorbending.
the lateral distance between two adjacent model plants,listhelongitudinaldistancebetweentwonearby plants,His the water depth, and u is the time- andcross-sectionallyaveragedvelocityandcanbecalculatedasu =Q/(B□ H),whereQistheflow rate,andBisthetotalwidthofthechannel.Meanwhile, $h_v$is the real average height of each plantafterbendingisaccountedfor.Thewidthtodepthratio is expressed asB / Hand varies by a factor of 2(1.8-3.7).TheFroudeandReynoldsnumberscovered by the experiments are 0.061-0.080,15008-18127respectively.

II. RESULTS AND DISCUSSIONS

Theresultsareorganizedasfollows:theinfluenceof flexible submerged vegetation on the mean flow isfirst considered (Section 2.1) followed by its effect onthe turbulent structure (Sections 2.2, 2.3). Next, thepropagationfrequencyofthevorticesandthedominantflowpatterninthesubmerged-vegetatedfloware computed andreported.
Throughout, the data presentation convention is asfollows: The vertical distances(orz)are normalizedby $h_V$andthelongitudinaldistances(orx)arenormalizedbythetotallongitudinallengthofthevegetationzonemodel(L_V=8m).Thevelocitiesare normalizedbythelocaldepth-averagedvelocity(U_m),

andtheReynoldsstressesarenormalizedbythe frictionvelocityu□=[(□ u□w□)] .
½

1.1 Influence of flexible submerged vegetation on themeanflow
Themainresistancetotheflowisfromthevegetation. The distributed drag force associated withthe vegetation is shown to be much greater than theground stresses as discussed elsewhere[36,77].
max
Differentwater flow conditions and vegetation characteristics(mainlythenumber)arevariedtochange thedrag force.ThedragcoefficientC$_d$ alongthewaterdepth

Fig.3(Coloronline)Photograph ofthesedgevegetationmodelusedinthe experiments

withinthevegetationlayerisanalyzedunderthreedifferentworkingscenariossummarizedinTable1.

Theexperimentsareconductedfor3different
The
C$_d$iscloselyrelatedtothenumberofplantsper
plantdensitiesandwaterdepthconditions.Theseexperimental parameters are summarized in Table 1,wherenisthenumberof plants ina unit area,bis unit area, and the frontal area that blocks the flow. Inecological studies, these quantities are combined andexpressedastheplantdensitya,whichisthepositive

Table1Experimentalparametersforthethreecasesdiscussedinthispaper

Case	n/m^{-2}	b/m	S/%	l/m	H/m	U/m·s^{-1}	h_v/m
1	43.3	0.15	0.01	0.15	0.27	0.12	0.185
2	108.3	0.10	0.04	0.10	0.27	0.13	0.195
3	108.3	0.10	0.04	0.10	0.33	0.11	0.210

area blocked by the vegetation per unit volume[78]. Inthe experiments here, the number of plants consideredvariedbytheconditionslistedinTable1and are
n=43.3plants/m^{2}and n=108.3plants/m^2.The
1 waterblockingareaonthefrontofthevegetationcannot be directly calculated because of the irregularverticaldistributionof theplasticwaterweed area.
v
density in the experiment here is that the leaves arenarrow-on-side and wide-in-the middle. By
C$_d$(z)

remainsconstant first, increases in the interval 0.1<z/h$_v$<0.5,andreachesamaximumvaluewhen z/h>0.5.Thereasonfortheincreaseoftheplant

contrast,thevegetationmodelbyNepfandVivoni[65]iscomposedofsixrectangularnarrowplasticsheetswithregular shapes.Thus,thetrendsofvegetationdensitybetweentheexperimenthereandtheNepf-Vivoniexperiment aredifferent.
Theeffectivedragcoefficientofthevegetation

canbe obtained basedonthemeanmomentum

equationofthevegetatedflowforcompletelydevelope
d stage (x/L> 0.58,see Section 2.2)[29]

v

□ (□ u□w□) +gS□ 1 CaU^2=0

(2)
□ z 2^d

Fig.4Illustrationoftheprojectedareaofavegetationelementusedto computethefrontalareaA$_f$(blackcolor)

wheretheviscousstressesandthebottomroughnessareignored.ThemeasuredrelationbetweenC$_d$ and
z/h$_v$
isshowninFig.6.Anempiricalexpressioncan
befittedtothemeasurementsbasedonaparabolicshapeandis given as

C=8 □z
h d |—
1□ 2 1
□ 2□+ 3 — —

(3)

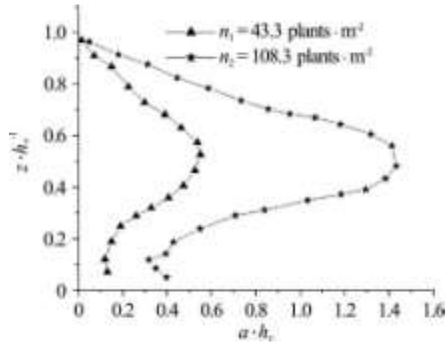

Fig.5Variationofvegetationdensityalongtheverticaldirec-tion,wheretrianglesindicaten=43.3plants/m^2,and

□ v □ 1
starindicatesplantnumber 2
n=108.3plants/m^2.

AMATLABimageprocessingsoftwareisused
forthecalculationoftheprojectedfrontalareaA$_f$

derivedforasinglevegetationelement(showninFig.4),andtheplant areadensityis thenexpressedas

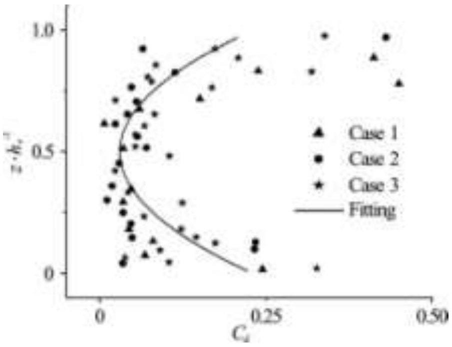

Fig.6RelationbetweenmeasuredC$_d$andz/h$_V$inallthree

casesfor a completelydevelopedstage(x/L$_V$
>0.58).

$$a(z)=\frac{nA_f(z)}{\Delta z}$$

(1)

FromFigs.5,6,itcanbeseenthattheprofileofthefrontal widthinfluencesthecomputedvegetation

where Δz = 0.01 m . The computed vertical distribu-tion of the plant density is far from uniform as showninFig.5.Theplantdensityfirstincreasesfromthe drag.Nearthecenterofthevegetationstem,thefrontal area reaches its maximum value whereas thevegetationdragreachesitsminimum.Thisfindingdi functionofz/h$_V$
inatypicalcross-section(approxi-matelyx / L$_V$= 0.58)forallthreeexperimentalconditions.Asshownin Fig.7,themeanvelocityprofileassumesan“S”shapewi thaninflectionpoint belowthetopofthevegetationlayer.Themean velocitycomponent,thatis,
velocitygradientreachesamaximumvalueatappro-ximatelyz/h$_V$=0.6
correspondingtothelocationof intensityprofilesareshowninFig.8.

ffersfromthecasesofaflowthroughrigid

channelbottomto
z/h$_V$=0.5
andthendecreasesto vegetationwithauniformfrontalwidth.Infuture the vegetation top. The plant density increases with nunliketheexperimentsconductedbyNepfandVivoni[65].Intheirexperiment,theplantdensity models, it becomes necessary to consider variations inthe drag coefficient for various shapes of a vegetationarrayalongthe verticaldirection.

2.2 Flowinthestreamwisedirection

Figure7showsthemeanvelocityprofileasa velocityabovethetopofthevegetationlayervariesapproximatelylogarithmically.Theexistenceofthe

vegetationalters the Reynolds stress, and the

turbulenceintensityprofilesasexpected.Theturbulence intensity is conventionally defined as therootmeansquareddeviationvalueofaturbulent

$U_{irms}=\sqrt{\overline{u_i'^2}}$
.Themean velocity,theReynoldsstress,andtheturbulence

the maximum mean vorticity. Within the vegetationlayer ($z / h_V < 1$) , the dimensionless velocity profiles inallthree casesare similar.

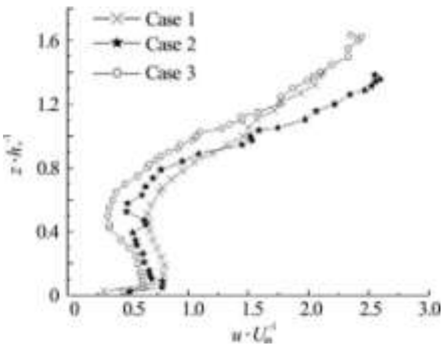

Fig.7Variationofthemeanlongitudinalvelocityprofileat

x/L_V=0.58
forthethreecaseshighlightedinTable1.

NotetheapproximateSshapeinall3cases.
Hence, on the basis of these measurements andthesimilarityintheshapesofthemeanvelocityprofilesinall3cases,wehaveidentifiedthreesubzonesfromthebottomtothetop:(1).The vegetationlayer($0<z/h_V<0.6$) inwhichthemean

velocity profile assumes roughly an “S” shape. The Sshape is the result of the interplay between the dragforce, the gravitational potential, and the momentumfluxgradientduetothevegetation.Inthelowerpart($0 <z / h_V< 0.2$) , the leaf area density is sufficientlysmallthatthemeanvelocityisshapedbythe gravitational potential and the mean momentum flux.This balance results in a mean velocity profile thatincreaseswithz.Inthemiddlepart($0.2< z/ h_V< 0.6$) , the leaf area is near its maximum. Here,the drag force causes an appreciable slow-down of themean velocity in this zone. (2). Above the vegetationzone($z / h_V> 1$) , the drag force is entirely absent, themagnitude of the shear stress declines and approacheszeroatthefreewatersurfacecausingthemeanvelocity to rapidly increase with z . (3) Near the topof the vegetation layer($0.6 <z / h_V< 1.2$) , where oneseesthevelocitydifferenceattheinterfacebetweenthe vegetation layer and the non-vegetation layer, ashearlayerforms.AsshowninFig.7,themean

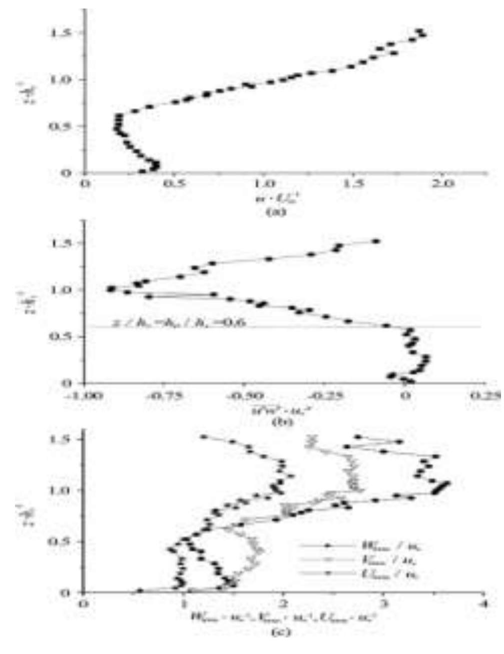

Fig.8Verticalvariationof the meanvelocity(a),theReynoldsstress(b),andtheturbulenceintensity(c)at x/L_V= 0.58incase1

Comparedtothemeanmomentumflux-andmean velocity profiles, the turbulent intensities do notvary as appreciably and the attenuation of these flowstatisticsremainsmodest.Thestrongmomentum

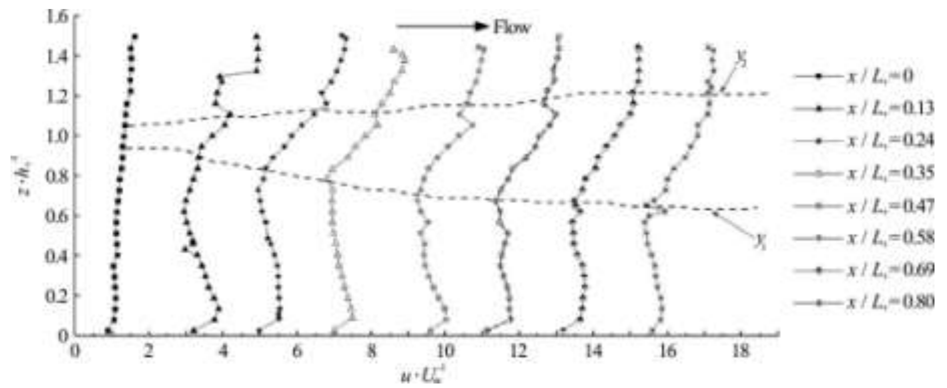

Fig.9Developmentof themeanlongitudinal velocityat various cross-sectionsincase1. Thethickness ofthemixinglayer is

denotedbydashedlines,
y_1,
y_2.

vertical exchange near the top of the vegetation layercauses the turbulent shear stress to "invade" into thevegetation layer. The depth where the turbulent shearstresswithinthevegetationlayerdecreasestosome 10%ofthemaximumshearstressvalueisdefinedasthe equilibrium phase is a stable vortex structure, which isslowly being produced when the water flows throughthevegetationsection(asshowninFig.9).Thed ownstream distance and the longitudinal velocity arenormalizedbythelengthofthevegetationmodel

intrusiondepth
h[65],asshowninFig.8.The
patch
$L_v$andthecross-sectionalvelocity
U_m.The
Reynolds stress reaches its maximum at the interfacebetween the vegetation layer and the non-vegetationlayer, indicating the existence of a strong shear effect,andgraduallydecreasestowardthewatersurface (approximatelylinearly,asconsistentwithEq.(2))and the bottom of the channel (due to the momentumabsorption by the vegetation). Inside the vegetation,the Reynolds stress approaches zero below the intrusiondepth$z/h_v=h_p/h_v=0.6$.Inthislayer,the

gravitational force is only balanced by the vegetationdrag force, thereby dictating the value of the meanvelocityin this zone (asearlier discussed). Fortheturbulenceintensity,thelongitudinal,lateral, and vertical turbulence intensities reach theirmaximumvaluesattheinterfacebetweenthevegetationlayerandthenon-vegetationlayeranddecrease toward the water surface and the bottom ofthe channel. An interesting feature is that the flow isenergetically more "isotropic" inside the vegetation ascomparedtothevegetationfreezone.Thatis,thepresenceofthevegetationseemstoenhancethereturn-to-isotropy through the generation of fine-scalewakes. After the discussion of the profile shapes of thefirstandsecondmomentsoftheflow,wenowturnour attention to the longitudinal development of themean velocity profile. Starting from an approximatelywell-mixedmeanvelocityprofilepriortoencountering the vegetation section, the longitudinaldistancetoattainanequilibriumzonewiththevegetation can be determined. Beyond this distance,the profile shapes of the flow statistics become nearlyindependentofx.Thefirstfeaturetonoteduringthis mixinglayerisshownastheregionbetweentwoinflectionpoints(y_1,y_2)ofthetime-averaged velocity along the downstream direction. As shown inFig. 9, the adjustment process is divided into threestages:

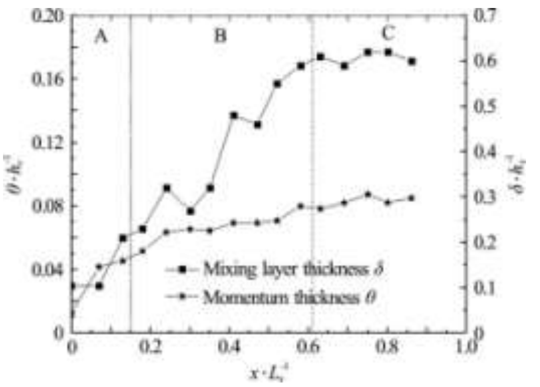

Fig. 10 Growth of the mixing layer and the momentum thick-ness downstream along the edge of the vegetation modelpatch in case 1, where A denotes diverging flowstage,B denotes development stage, and C denotes completelydevelopedstage

(1) The first stage is the diverging flow stage.Thepressureinthefrontpartofthevegetationincreasesduetothepresenceofthevegetation,andthevelocityinthevegetationlayercontinuestodecrease. A strongoutward fluxoccurs atthetop ofthe vegetation layer due to the drag force within thevegetation. The shear layer is not formed in this stageyet, and the turbulent stress remains weak and can beneglected.

(2) The second stage is the development stage, inwhich the mixing layer at the top of the vegetationlayer gradually develops, and the shear stress starts toincreaseand reaches anequilibrium.

(3) Thethirdstageisacompletelydevelopedstage,wherethemixinglayerisnowdevelopedand
which is consistent with the experimental results ofRomingerandNepf[81].Theyproposedthatthelength scale$X_D$inthelowflow-
blockagecases($C_d a h_v < 2$,whereh_v= 0.185 misthe heightofthevegetationpatchintheverticaldirection,aisthedepth-

its growth is almost independent of the longitudinaldistance.Thelayersabovethemixinglayer areadjustedbasedontheboundaryconditionsandare

averagedvegetation density,andC_d
averageddragcoefficient)isgivenby
isthedepth-

alsoequilibratedwiththepresenceofthevegetation.Thedownstreamvelocityisroughlyunchanged

X=(3□0.3) □2
2□
[1+(CaB)]□

(5)

(□ U/□ x □ 0)
beyondthispoint.Onthebasisofthe D
□Ca
d v

adjustment flow process, the flow region is reasonablyapproximated by three longitudinal sub-zones,
namely,thedivergingflow,thedevelopment,andthecompletelydevelopedzones.
Figure 10 presents the longitudinal developmentofthemixinglayerdepthandthemomentumthickness, which gradually increase and then stabilize(i.e.,becomeindependentof x).Themomentumthicknesscanbe calculatedas

□1□ U□ U□
□ d □

Based on this expression, the calculatedX_D□ 3.9 misinlinewiththeindependentlymeasured length scale here. Hence, the vegetated flowcanbeassumedtobecompletelydevelopedatdistancesgreaterthanX_D / L_V= 0.52fromtheleadingedgeofthevegetation patch.

2.3 Mechanicsofturbulentstructureinvegetated flow

Theenergy spectra and quadrant analysis

□ □□ □4□ □ U
□ □dz
(4)
methodsarecommonlyusedtoanalyzeturbulentflow

0□□ □□

structures.Thesetwomethodsareusedtoquantifysize, energetics,andmomentumtransportingevents.

where ΔU isavelocitydifferenceandcanbe

obtained from $\Delta U = U_2 - U_1$,U_1 ,U_2 are low-andhigh-streamvelocities,and $\bar{U}$ isdefinedastheir mean $\bar{U} = (U_1 + U_2) / 2$ .Asshown inFig.10,themixing layer and momentum thicknesses stabilize atapproximately $x / L_V = 0.52$ from the leading edge ofthevegetationmodelpatch(recallthattheprioranalysisofthemeanvelocityandtheturbulentstressisconductedat $x / L_V = 0.58$).Thestabilizationdistanceofthemixinglayerthicknessisalsoconsistent with prior experiments by Ghisalberti andNepf[79]. Itisexpectedthatthedevelopmentofthemixing layer thickness be confined by the boundaryconditions, namely, the water depth and the channelbottom. It is to be noted that a canonical mixing layerthicknesscontinuallydevelopsdown-streaminan unobstructed shear layer. The ratio of the mixing layerthickness δ to the momentum thickness θ is approximately7.5,whichagreeswiththeresultofNezu andSanjou[80], giving $\delta / \theta \approx$ (7-8). Thedevelopmentofthemixinglayerandthemomentum thickness along the longitudinal distancehaspracticalengineeringsignificancewhendeterminingdistancesoftheadjustmentzonesfromthevegetationinlettotheequilibriumzone.Thislongitudinal distanceishereafterlabeledas X_D.The measuredlengthscale X_D isabout4.1mhere,

2.3.1 Powerspectraldensity

As earlier noted, the K-H instability occurs nearthe canopy top and is responsible for the attainment ofthemixinglayer.Thescaleoftheshearlayergradually increases with the downstream distance andremainsconstantuntilthedissipationtermoftheturbulent kinetic energy of the flow is balanced by themechanical and wake production generation terms.

Acoherentvortexstructurecanbeidentifiedbytheperiodicoscillationinthelongitudinalandverticalvelocity component time series. Figure 11 shows thetimeseries ofthe longitudinal andverticalvelocitiesattheinterfacebetweenthevegetatedandnon-vegetated layers at a representative cross-section(near $x / L_V = 0.58$)inthethreedifferentcasesofTable1.Thefluctuationsofthelongitudinalandvertical velocities are anti-correlated, which indicate astrong vertical momentum exchange. The oscillationfrequency of the longitudinal velocity is the same asthat of the vortex propagation. The frequency of themomentumtransportoscillationistwicethevortexfrequency.

As mentioned above, the vegetation layer createsa coherent vortex, which induces periodic fluctuationsof the velocity at the top of the vegetation layer anddominates the vertical momentum transport (as seen inFig.11).Theoscillationofthevelocity causesthevegetationalsotoperiodicallyoscillate,andtheoscillationfrequenciesofthetwoarethesamewhen in resonance, which are consistent with the frequencyof the vortex diffusion. To determine the frequency ofthevortexdiffusion,aspectralanalysisisconductedto analyze the vertical fluctuation velocity w' at thetopofthevegetation layer.

structure in the large-scale region appears as a “bump”in the vertical turbulent kinetic energy component. Fortheinertialsub-region,theenergyspectrumapproximatelysatisfiesthe Kolmogorovturbulencespectrumwitha□ 5/3powerla wscalingathighfrequencies. In this sub-region, the viscous dissipationoftheflowcanbeignored.Mostturbulentki neticenergy dissipation occurs in the high-frequency range,which cannot be resolved by the ADV. In fact, anapproximateinstrumentwhite-noiseflatspectrumappearsto dominatethefrequencies beyond 20Hzdemonstratingthesamplinglimitsoftheexperim ent.

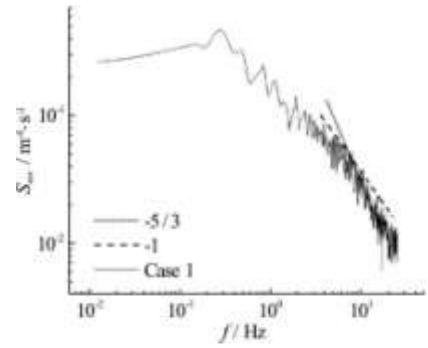

Fig.12Powerspectraldensityofverticalvelocitysampledatthetopofthevegetationlayerandatarepresentative location(x/L_V=0.58)

incase1. Theexponentofthe lineassociatedwiththelocallyhomogeneousandiso-tropicturbulencepredictedfromKolmogorov’stheory Anapproximate f□ 1 followedbyanapproximate−5/3withincreasingfrequ ency. Typically, a □1 power-law scaling in thespectrum (either in f or the wavenumber k) theenergy(=L_E),Here,L_E mayberegardedasthe

is□ 5/3.The□ 1power-lawis shownfor reference

power-lawscalingemerges

suggests that the spectrum in this range of eddy sizesbecomesindependentofthelengthscalethatprodu ces momentumthickness(seeFig.12(a))orthestem diameter(seeFig.12(b))dependingon y/b.The

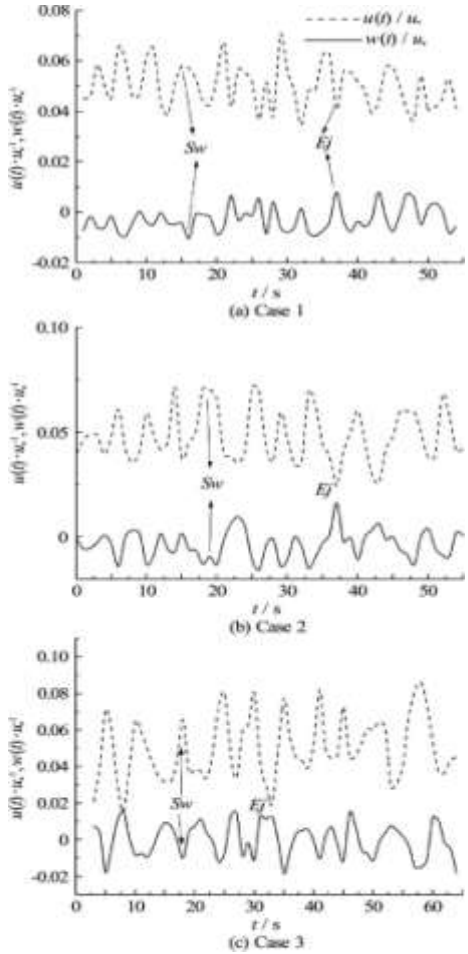

Fig. 11 Time series of longitudinal velocity and Reynolds stressversustimeatacompletelydevelopedcross-sectionin

following dimensional assumptions may be adopted todiscusstheplausibilityoftheoccurrenceofa 1power-lawatscalessmallerthanL_E.Considering

all three cases($\bar{x}/L_V$=0.58,y/B=0.5 and z/h_V= thatthevelocityvariancesareultimatelyproducedby

1).StrongReynoldstressesaremarkedasejection(Ej) thegravitationalforcethatdrivestheflow(i.e., 2 ,b and sweep(Sw) . Details about the two flow types arediscussedin Section2.3.2) Theenergyspectrumoftheverticalvelocityfluctuation satthetopofthevegetationlayeriscomputedandshowninFig.12.Theenergyspectrum the dimensionless energy spectrum at the large andintermediate ranges of scales relevant to the energyproduction (i.e., where the majority of variance lies)maybe normalizedas[82-83]

S (k)

canbedividedintothreesub-regions:thelarge-scale

$$\frac{S_{ww}(k)}{u^2 L_s} = F(kL_E) \quad (6)$$

coherentvortexsub-region,theshearproductionsub-region,andtheinertialsub-region.Thevortex

b E u),

wherek isawavenumber,and

$F_S(kL_E)$ isa similarityfunctiontobedeterminedasafunctionofthed imensionlesswavenumber(kL_E).Theonly meanstocancel L_E fromthetwosidesofthis expressionisbysetting $F_S (kL_E) = A_E/(kL_E)$ thereby producinga 1power-lawscalingwhenthespectrum ofeddieswithsizessmallerthanL_E becomesinde- pendentofL_E (theyhavenotcompletelyattained theirnear-isotropicstategivenbyKolmogorov's 5/3 scalingwithincreasingf),whereA_E isasimilarity constant that may vary withH . Specifically, the −1power-law scaling is expected to occur at eddy sizessmaller than $L_E$but larger than eddy sizes associatedwith Kolmogorov inertial regime. The range of scalesthat are described by a near 1 power-law scaling inFig.12appearsconsistentwiththeaforementionedanalysis.However,thisanalysisshouldbefurtherinvestigatedusingLESandlaser-Doppleranemometrymeasurements.

The periodicity of oscillations in the longitudinaland vertical velocities means the existence of a singledominantfrequencycomponent,whichwenowseektoexplore longitudinally. The spectrum of the verticalvelocityfluctuationsatthetopofthevegetationlayerisnowcomputedatvariouslongitudinalpositionsandthecalculatedfrequencyisnormalizedbythemomen-tumthicknessandthespatially-averagedvelocity,asshownin Fig. 13. The peak in the energy spectrum curveallowsthedeterminationofthefrequencyofthecoherentvortexstructureinthemixinglayer.AsshowninFig.13,thedominantfrequencyofthevortexremains basically unchanged during its developmentalongtheflowdirection.Thepeakoftheenergyspectrumcurveismainlyconcentratedatf /U= 0.027whenthewaterdepthisthesamebutthevegetation densityisdifferent(asshowninFigs.13(a),13(b)),Howeverthepeakoftheenergyspectrumcurve becomesconcentratedatf /U=0.04withincrease

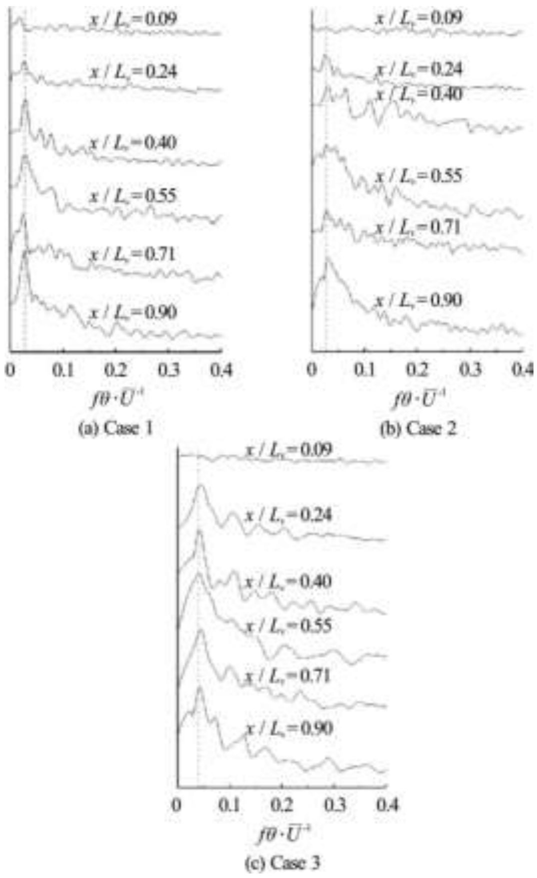

Fig.13Non-dimensionalizedenergyspectraatvariousx-po-sitions from the leading edge of the vegetated patch forthethreedifferentcaseslistedinTable1.

turbulent structures that contribute to the momentumtransport.LuandWillmarth[85]firstadoptedthismethodwheninvestigatingtheshearstresscharac-inwaterdepth.Thisisbecausethemomentum planebasedonthesignsofthelongitudinalvelocity thickness□ increaseswiththeincreaseinwaterdeptha, ndsowillf□ /U.Comparedwiththerigidvegeta-tion,thedimensionlessfrequencyf□ /Uisconstan-tly maintained at 0.032 regardless of the experimentalparameters such as water depth and vegetation density[84],whereasthedimensionlessfrequencyf□ /Uof

interaction(u□>0 , w□>0),whichistheupwardmovementofthehigh-speedfluid,Q_2beinganejectionevent(u□<0,w□>0), whichistheupward movementofthelow-speedfluid,Q_3istheinward

teristics at the boundary layer outside the turbulentviscous layer. The basic principle of quadrant analysisisdecomposingtheReynoldsstressintofourflowtypeslabeledasQ_1,Q_2,Q_3andQ_4intheu□-w□

fluctuationu□andtheverticalvelocityfluctuation

w□(asshowninFig.14).Atagivenpoint,thesequadrants correspond to Q_1 beingtheoutward theflexiblevegetationmodelchangeswithwaterflow. Thismaybeattributedtotherigidvegetationnotswaying with the flow, whereas the flexible vegetationhereisirregularinshapeandswingsrandomly.

2.3.2 Momentumtransferandquadrantanalysis
Thequadrantanalysisisusedforanalyzingthe interaction (u□<0 ,w□<0), which is the downwardmovementofflow-
u□w□=$H_0\overline{u'w'}$

speedfluid,andQ_4beingthesweepingevent(u□>0 ,w□<0),whichisthedownwardmovementofthehigh-speedfluid. Figure14presentsasketchofthefourquadrants responsibleforthemomentumexchangeatagiven

pointalong withtheso-calledhyperbolichole.Thefourquadrantsareseparated bya“hole”definedby ,whereH_0 isthethresholdvalue

thatrepresentsthe“hole”size.Theimportanceofestablishing a “hole” domain is that large values of theReynolds stress in each quadrant can be extracted withtheback-ground smallevents removed.

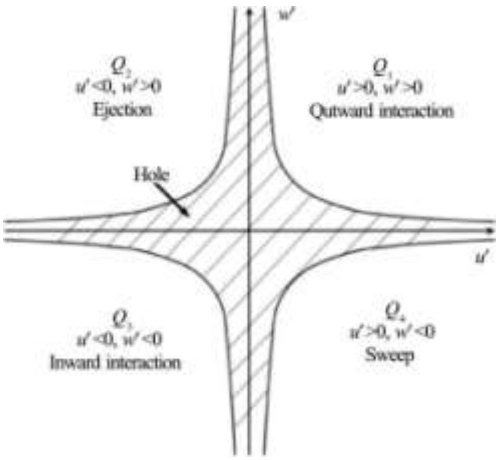

Fig.14Schematicdiagramofthequadrantsandthe“hole”region

ThecontributionofeachflowtypetothelocalReynoldsstressiscalculated as:

S =^{1} ^{T}C

—

(t)u□(t)w□(t)dt
(7)
i,H0
т□0
i,H0

Ci,H =1,
u□(t)w□(t)>H0
and[w□(t),w□(t)]| $|\overline{u'w'}|$

inthequadrantQi
(8a)

Ci,H =0 otherwise (8b)
0

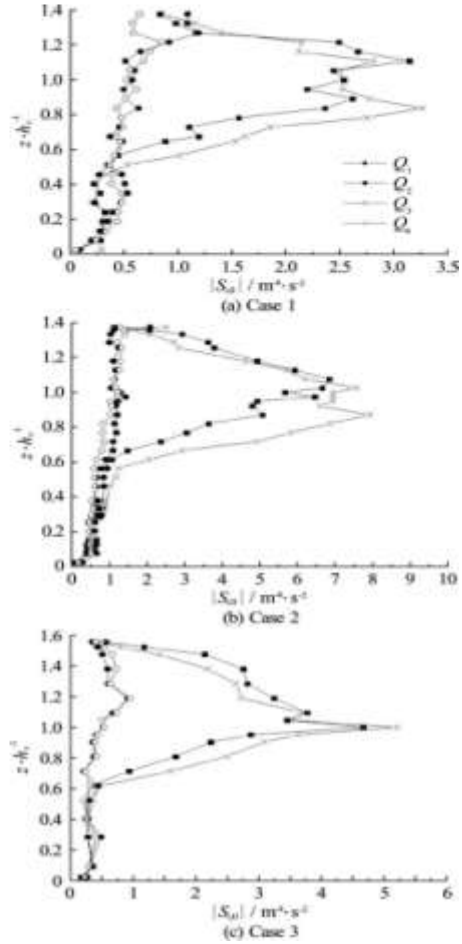

Fig.15Contributionsofeachquadranttothe Reynoldsstress

whereTisthemeasurementduration,
$C_{i,H}$ isthe
forthethreecaseslistedinTable1.
$i,0$ 0
averagecondition,andu and w arethelongitudinal and vertical fluctuation velocities at themeasurement point, respectively. Contribution values$S_{i,H}$arenormalizedbythe Reynolds stress sothat
Figure 15 shows the vertical distribution of theabsolute contribution values for various water depthsand vegetation densities in the completely developedzone(i.e.,x/L_{veg}=0.58).Asshowninthisfigure,

theReynoldsstressinthevicinityofthetopofthe

$\hat{S}$ = 1 T C
*
(t)u (t)w (t)dt
vegetationlayer (z/h_V 1)
isdominatedbyboth

i,H_0
and

4
Tu^2 0
i,H_0
ejectionsandsweeps.Thecontributionofejections and sweeps to the Reynolds stress reaches a maximumat the top of the canopy and decreases toward the freewater surface and the channel bed. The contribution ofejectionstotheReynoldsstressabovethetopofthe bladeenhancestheverticaltransferofturbulentkineticenergy.

withincreasingH_0,whichindicatesthatejectionsand sweeps contribute more to the Reynolds stress. Theholeregioneliminatesmorelargevaluesof theReyn outwardinteractionswhenthethreshold

$\hat{S}$ = 1
when
H_0=0
(9)
vegetationlayer(z/h_V>1)isgreaterthanthatofthe
i=1
sweps,andtheejectionisthedominantflowtypeinthiszone.Meanwhile,thesituationbelowthetopof

thevegetation layer(0.6 <z / h_V< 1) isoppositeandsweepsaredominant.Thecomparisonof theresultsfor the three cases in Table 1 shows that the peak incase 3 is sharper than the peaks in cases 1, 2. Thisfindingisbecausethevegetationdoesnotshowamonami(or waving) phenomenon in case 3, and thevegetation maintains an upright state similar to rigidvegetation. In this case, the flow structure is similar totherigid-vegetatedflow,wheretheejection-sweeptransition near the peak is rapid[86]. In cases 1, 2, thevegetationswayswiththeflowandtheswingofthe H_0.Figure17presentstheprofileratioofinwardand outwardinteractionstosweepsandejectionsfordifferent threshold values ranging from 0 to 6. Thecontributionsofejectionsandsweepsinsidethevegetationlayerandnearthewatersurfacearebasically equivalent to the contribution of inward andoutward interactions (where the mean momentum fluxisalmostzero).Thecontributionsofejectionsandsweeps to the Reynolds stress in the vicinity of the topofthevegetationlayerisremarkablygreaterthanthoseoftheinwardandoutwardinteractions.The
ratio(S_{2,H_0}
+S_{4,H_0}
)/(S_{1,H_0}
+S_{3,H_0}
)graduallygrows
olds stress in each quadrant with increasing holesize.Thecontributionofejectionsandsweepsto Reynoldsstressesisgreaterthanthatofinwardand
H_0=0

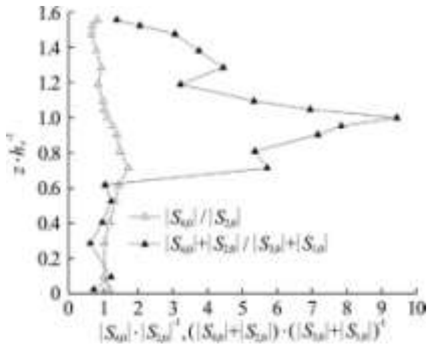

Fig.16Ratio ofcontributionsofvariousquadrantstomomen-tumtransferatarepresentativecross-sectionincase3

Figure16illustratestheratiosoftheinwardandoutward interactions to sweeps and ejections nearthetopofthevegetationlayer.Hence,theeliminatio

$(S_{2,0}+S_{4,0})/(S_{1,0}+S_{3,0})$

sweeptotheejection

$S_{4,0}/S_{2,0}$

tative cross-section (x/L_V=0.58)

shown in Fig. 16, the contributions of ejections andsweepsareequivalenttothoseoftheinwardandout

n of large events from each quadrant makesthe sum of ejections and sweeps larger than that ofinwardand outward interactions.

andthe ratios of the

attherepresen-

incase3.As

wardinteractionsbelowz/h_V=0.6.Thecontri-

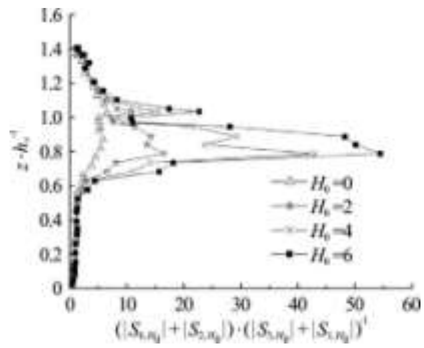

Fig.17The ratio

$(S_{2,H}$

$+S_{4,H})/(S_{1,H}$

$+S_{3,H})$

forincrea-

butionsof ejections and sweeps are prominent singthresholdsH_0

incase3.

whenz/h_V>0.6,especially at the top of the

vegetationlayer, and gradually decrease towards thewater surface and the bottom of the channel. For theratio of ejections to sweeps, sweeps dominate insidethevegetationlayer,whereasejectiondominates Thesumofejectionsandsweepscontributionsatthe top of the vegetation layer for different thresholdvalues(H_0= 0-8)isnormalized,as shown below
inside the non-vegetation layer. The sweep strength isremarkably greater than that of its ejection counterpart.Thesefindingsindicatethatsweepsandejectionsare dominant,andsweepsarestrongerthanejectionsin

$$S^*(H_0)=\frac{S_{2,H_0}+S_{4,H_0}}{S_{2,0}+S_{4,0}} \quad (10)$$

thevicinityofthetopofthevegetationlayer(i.e.,inthemixinglayer).Theseresultsaresimilartothe andwedefine $T^*(H)$as

findingsreportedforrigidrodsandcanopieswithcomplexmorphologies suchas forests[32,87-88].

$$T(H_0)=\frac{1}{T^*}\int_0^T [C_{2,H_0}(t)+C_{4,H_0}(t)]dt. \quad (11)$$

Thedevelopmentof $(S_{2,H_0}+S_{4,H_0})/(S_{1,H_0}+S_{3,H_0})$

isdifferentforvaryingthresholdvaluesof ArelationbetweenS*(H$_0$) and T*(H$_0$) canbe obtained and is shown in Fig. 18. Here,S*indicatesthe proportion of total contribution of ejections andsweeps occupiedbylargevalues.However,T*measures the ratio of times taken to generate ejectionsandsweepsnormalizedbythetotalsamplingtime.As shown in Fig. 18, 80% of ejections and sweeps occurwithin 30% of the recording time. This short durationandlargemomentumtransportcontributionis suggestive that ejections and sweeps are caused bylargecoherentvortexmotion.ThisfindingisconsistentwiththeconclusionofGhisalbertiandNepf[86]andmanyothersasreviewedelsewhere[32].

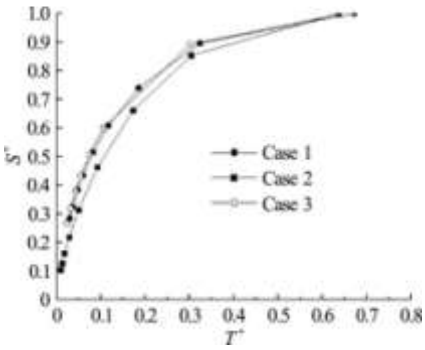

Fig.18Relation betweentheratioofejectionsandsweepstofractionaltimeforthethreedifferentcasesinTable1.

expectedwithsweepsmoredominantinthevegetation layer and ejections more dominant in thevegetationfreelayersimplyduetotheturbulentintensities.

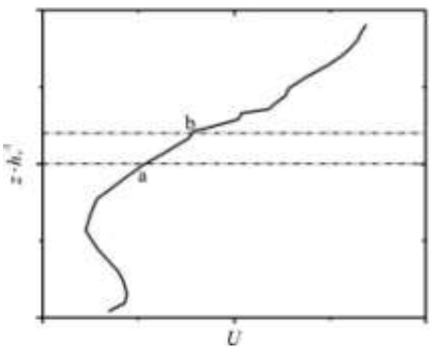

Fig. 19 Profileofthemeanlongitudinal velocityalongthewater depth direction as well as two points illustratingthe expected contribution to the Reynolds stress of sweepsand ejections when the vertical velocity fluctuations aresymmetric.

III. CONCLUSIONS

Themainresultsandconclusionsareasfollows:

(1) The dimensionless vegetation drag coefficientprofileassumesanapproximate parabolicshapewithadecreasingtrendintherange0 < z /h_V<0.5 andan Fromtheabovequadrantanalysis,itcanbeconcludedth attheflowpatternatthetopofthevegetation layer is mainly characterized by ejectionsandsweeps,andsweepingeffectsarestronger thanthat of ejections. This phenomenon may be analyzedfromtheperspectiveofmeanlongitudinalvel ocityU,theReynoldsstress u□w□,andthevertical distributionoftheturbulenceintensityw$_{irms}$.Themea nvelocitydistributionisinan“S”shape,asshown in Fig. 19. Two adjacent layers, namely, a andb,areusedatthetopofthevegetationlayerforillustra tion. The vertical velocity fluctuations(w□>0)areobservedwhenaunitvolumeo fawater body moves to the upper layer. Meanwhile, the waterbody in the lower layer entering the upper layer willreduce the upper flow velocity (relative to the mean)because the longitudinal velocity gradually increasestowardthewatersurface.Hence,thelongitudi nalfluctuation velocityu□<0is observed. An ejectionevent in the second quadrant (u□<0 ,w□>0) is theoutcomeofsuchamotion.Similarly,whenthevertic al fluctuation velocity w□<0 is observed,u□>0 . At this instant, the flow type corresponds to asweepingeventcontributingtothefourthquadrant(u□>0 ,w□<0). To summarize, the two main flowtypes at the interface of the vegetation layer and thenon-vegetationlayerareejectionsandsweepsas increasingtrendintherange 0.5 <z / h_V< 1 .Theheight at which the drag coefficient is most reducedcoincideswiththelocationofmaximumleafare aandis suggestive of an enhanced sheltering at this location.For future studies of the mean velocity

profile, it isnecessarytoconsidertheinterplaybetweenthevegetationdensity,thefoliagetype,anddragreductionsvertically.

(2) Thepresenceofvegetationcausesadiscontinuousresistanceintheverticaldirection,andin turn a vertical variation in the mean longitudinalvelocitywithaninflectionpoint(fastabove,slowinsidethevegetation).Hence,acoherentvortexstructure is produced at the top of the vegetation layer,as is consistent with numerous canopy flows (aquaticand terrestrial alike). On the basis of the measuredmeanvelocityinequilibriumwiththevegetationsection,thewaterflowcanbedividedintothreedistinct zones: inside the vegetation layer, near the topof the vegetation layer, and above the vegetation layer.In the vegetation layer, the velocity distribution is "S"shapedandthemeanvelocitygradientisnegative.The mean velocity near the top of the vegetation layervaries approximately logarithmically. In the upper partof the vegetation layer, the water flow is similar to acanonicalopenchannelflow,andtheverticalvariationofthemeanlongitudinalvelocityissimilartoa"J"shape. TheReynoldsstressandtheturbulent

intensity reach their maximum at the interface of thevegetationandnon-vegetationlayersandgraduallydecrease towards the water surface and the bottom ofthechannelasexpected.Theturbulentintensitieswithinthevegetationlayerdecrease,whereasthevelocity in the non-vegetation layer increases with theincreaseinheight.Thelongitudinaldevelopmentofthe momentum thickness is consistent with that of thethicknessofacanonicalmixinglayer.

(3) Themainflowtypenearthetopofthevegetation layer is ejections and the sweeps, and theintensity of sweeps is greater than that of ejections,againconsistentwithnumerousstudiesofflowthroughvegetation.Eachstrongsweepisaccompanied by a weak ejection. The power spectraldensity for vertical velocity fluctuations at the top ofthevegetationlayersatisfiestheKolmogorovturbulent kinetic energy spectrum with a 5/3 powerlaw at high (resolved) frequencies. New sets of powerspectraldensitycurvesareobtainedafterthefrequencyoftheenergyspectrumcurveisnormalized

bythespatial-averagedvelocity$\bar{U}$andthemomentum thickness of themixing layer.Fromthepowerspectralanalysis,thepeaksofthedimensionlesspowerspectraldensitycurvesareconcentrated at 0.027 for different flexible vegetationdensities but for the same water depth. The peaks arelocated at 0.04 for the same density but different waterdepths. The findings here show that the variations ofthe dimensionless power spectral density curves arecloselyrelatedwiththeflowdepthinsteadofthevegetation density. However, the dominant frequencyfor the rigid vegetated-flow remains unchanged underdifferentexperimentalconditions.Thisshiftisbecausetheshapeoftheflexiblevegetationmodeltendstorandomlyswingwith theflow.

(4) The ejections and the sweeps are dominant atthe top of the vegetation layer, and the sweep eventsare stronger than the ejection events inside the canopy.Ejectionsandsweepsarebothshortandintense. Approximately80%ofejectionsandsweepsarecompleted within 30% of the sampling time near thecanopytop(i.e.,thelocationofthemaximumturbulent stress). These results are in agreement withnumerouscanopyflowexperiments,includingforestedcanopies.

IV. FUTURE WORK

Futuremodeldevelopmentsthataccommodatethe aforementioned findings, especially regarding therole of ejections and sweeps, are aimed at new closureschemes for momentum flux transport terms (i.e., thetriplemoments).Inparticular,relationsbetweenquadrantanalysis,momentumfluxtransport,andcumulant expansionofthejointprobabilitydensity functionofw,u pave the way for the so-calledstructural turbulence closure schemes. These schemescan take full advantage of the experiments reportedhereandofferadifferentperspectivethangradient-diffusionclosure.Asummaryofseveralfuturedirections arenowoutlined.

1.2 Numericalsimulationofvegetatedflow

1.3 Numericalsimulationisapowertooltoinvestigatetheflowstructureunderdifferentsituations[89-90]. In our previous work, an LES modelwas established to explore local blockage of artificialvegetationpatchesinrectangularopenchannelspartiallycoveredbyarigidcylindricalvegetationarray[25], where the influence of turbulent structures onmomentumtransferalongthevegetationperipherywas studied. Results show thatthe LES agree wellwiththeexperimentalresultslendingconfidencein the LES model for vegetated flow. Lu and Dai[91-93]adopted an LES model with flexible vegetation, wherethedeflectedheightofflexiblevegetationwasconsidered in the model and a Runge-Kutta schemewas combined with the operator splitting algorithm tosolve the governing equations. Scalar transport wasalso simulated using Eulerian and Lagrangian models.Resultsshowedthattheverticalmixingandthe diffusion of scalar concentration can be enhanced byflexiblevegetation.Themodelcanquantitativelypredictthedecreasingtrendofconcentrationdistribution along the flow direction with increase invegetationdensity.

1.4 Interactionbetweenvegetation,pollutanttrans-portand sedimentsinflow

To represent the impact of vegetation in wetlandson pollutant transport, previous LES work focused onverticalbuoyancyjetinjectingcross-flowforrigidvegetation.Theexistenceofvegetationelementsreduce the velocity of the channel, thus significantlyincreasingthepenetrationheightandthedilutionofthejet.Thevortexlengthscorrespondingtothe dominant frequencies at different positions in the flowcan be studied by means of spectral analysis. Fromanother perspective, the vegetation in wetland, openchannelor lakes affects thelongitudinaldispersion,thelateraldiffusionandthe velocitydistribution,thustheflowregioncanbedivided intoseverallayers/zonesaccordingtothecharacteristicsoftheturbulentstructure.

Future investigations of sediments will use therandom displacement model (RDM)[94] that offers apowerfultooltosimulateparticletransportinvegetated flows. Concentrations are represented by alargenumberofindependentparticlestomodelmaterialtransportintheflow.ComparedtotheEulerianmethod(EM)thatfocusesonconcentrationat the whole region, the RDM in the Lagrangian modehasseveraladvantages[95].Firstly,withRDM,the motionandthepositionofparticlesaredirectlydisplayed, while with the EM, only the positions withcrowdedparticlesareshown.Secondly,thescaleof the source in the EM is always much smaller than thespatial resolution, which makes the representation ofthe source difficult, but the RDM does not have suchshortcomings.Thirdly,theRDMhasahighcomputationalefficiencybyfocusing ontheregionwith more particles. Last but not least, with the RDM,we do not have the artificial dispersion because thesteep concentration gradient has no effect on the RDM.Weplantoconductnewflumeexperimentswhereparticles are introduced andtheirdispersion/capturebyvegetationanalyzedtotestRDMandEMpredictions.

1.5 Applicationforecologicalenvironmentrecons-truction

Ecologicalenvironmentreconstruction,alsocalled phytoremediation, can be applied based on thetheory of hydrodynamics for flow through vegetation.As previously noted, phytoremediation refers to theadoptionofvegetation/plantswithcoexistingmicrobialsystemstoremovepollutantsandrestoreecological function. It is shown that pollutants in soilorwatercanbepurifiedbymeansofabsorption,volatilization,rootfiltration,degradationandstabi-lization of vegetation. The function of vegetation inecologicalreconstructioncanbesummarizedasfollows: (1) purification by absorption and enrichmentof aquatic vegetation, (2) sedimentation and filtrationof aquatic plants, and (3) inhibition of aquatic plantsonalgae.

Future flumeexperiments aimedat developingtheoriesforphytoremediationwillfocuson :(1)optimal plant morphology and density to be used inecologicalrestoration,(2)theeffectsofcombiningdifferentaquaticplantsandtheiroptimalconfigurationfor pollutantpurificationbasedonmerginghydrodynamicsandbiochemistryofvegetatedflow,(3)harvestingand subsequenttreatmentofaquaticplantstoavoidsecondarypollution. These planned flume experiments will assistinecologicalrestorationofmovingwaterbodies, whereplantsplay akey role.

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