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模擬水道中水生植物抗流機制之種間差異研究

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摘　要

本研究係從水工模型出發，比較不同物種之水生植物在抗流反應方面的種間差異。在水芹菜的研究中，發現在面對較高流速沖刷時，其生長速度趨緩，莖芽組織變得矮小且柔軟，以增加植物的抗流彈性，此外，其平均根長變短，錨定能力降低，根、莖與芽的生物量也隨之下降。

鑑於適性植物種類可能是多元化的組成，因此本研究另針對不同的水生植物：台灣原生種—柳葉水蓑衣為材料，探討其面對不同流速之抗流機制的種間變化。結果顯示流速增加時，其生長速度、乾鮮重、直徑降低，但是與水芹菜反應不同的是水蓑衣在面對較高流速的環境，其平均根長變長，株高也較高。本研究之成果除可進一步確認適性植生種類或先驅植物種外，亦可瞭解植物在生態工程上可扮演的角色與極限，未來可做為河道植生工程之設計依據。

關鍵詞：抗流機制、模擬水道、水生植物、生態工程

ABSTRACT

The present study is carried out in a simulated channel for examining how different aquatic macrophytes respond to different channel flow velocities in terms of changes in their flow resistance mechanisms. Preliminary research of the planting material *Oenanthe javanica* DC. (water celery) showed that when facing higher flow velocity, the growth rate of water celery became slow and plant shoots were shorter and softer to increase plant flexibility. Root length and root anchorage decreased. Root, stem, and shoot were also found to reduce their biomass.

It is significant for the following stage to examine the interspecific differences in flow resistance mechanisms among different planting materials since suitable streambank vegetation might include a variety of plants. The native species *Hygrophila salicifolia* (Vahl) Nee. was chosen as the next planting material. Experimental data show that the growth rate, dry weight, fresh weight, diameter of this planting material decreased as flow velocities increased. However, the average roots length, average height of *Hygrophila salicifolia* (Vahl) Nee. became higher when facing higher flow velocity. This is different to water celery. This research is anticipated to verify the suitable planting materials or precursors for riverbanks and, additionally, to clarify the roles and limitations of applying aquatic macrophytes in ecological engineering.

Keywords：Flow resistance; simulated channel; aquatic macrophytes; ecological engineering.

Ⅰ、研究動機與目的

本研究係延續過去兩年的實驗，從水工模型出發，比較不同物種之水生植物在抗流反應方面的種間差異。根據過去兩年的實驗，發現以水芹菜為材料的實驗中，因應不同流速，確實在植物生理上產生不同的反應機制，在面對較高流速沖刷時，單株栽植之水芹菜之生長速度、莖芽組織、根長、地上莖葉與地下根系的生物量等均產生不同的變化。當改變水芹菜的配置方式時，在總株數不改變的條件下，簇群栽植模式的水芹菜較單株者有較強的抗流能力，雖然其在株高、根長與平均綠葉數方面之差異並不如單植者明顯，但是平均單位面積之維管束數量在高流速之實驗組仍高於低流速之控制組，呈現與單植者相同的結果，亦即水芹菜在面臨較高流速時，確實以減少莖芽之斷面積但是增加維管束密度的方式作為生理機制的調整。

鑑於適性植物種類可能是多元化的組成，因此本次研究係針對不同的水生植物，以台灣原生種—柳葉水蓑衣為實驗材料，探討其面對不同流速之抗流機制變化，以與水芹菜比較是否在抗流機制上呈現種間差異。預期研究成果除可進一步確認適性植生種類或先驅植物種外，亦可瞭解植物在生態工程上可扮演的角色與極限，未來可做為河道植生工程之設計依據。

II、文獻回顧

2.1 國外對於植物抗流之相關研究

研究發現，在河道抗流與河道植生覆蓋比例間存在非線性的關係。雖然學者很早即提出抗流平均值包括岩屑碎石與水中植物，認為水生植物主宰了其盤據的水道之水力（hydraulic），但對植被於河道的抗流作用之相關研究卻很少見。因此，非常缺乏對於植生河川流速之模式研究，特別是植生自由分佈的河道（Green, 2004）。許多的實證研究是在模擬流場中以塑膠葉片或沉水性植物進行流速測試，少有操作於自然河道或者先行試種水生植物，再以不同流速之水流測試植物之生理反應機制者（Green, 2004; Järvelä, 2004）。

雖然對於植被影響河岸之研究已陸續有文獻發表，例如：Simon and Collison 提出河岸植被對河岸的穩定性有機械與水力兩種影響，有的改善河岸穩定性，有的卻相反（Simon and Collison, 2002），Greenway 提出植物將其根錨定土壤中以支撐植物的地上部，因此對土壤基質產生強化作用（Greenway, 1987）；一些研究也發現，植被的根系型態也對河道之沖蝕作用有影響（Anderson *et al*., 2004）。但是植物是如何影響河道抗力？其機制為何？卻仍有很大的研究空間。Lewis 提出河道抗力係由兩種因素組成：經由摩擦力產生的能量損失與河道內流速的變化作用（Lewis, 1997），後者在植被河道中特別明顯，植物莖的尺寸形成的抗力會導致植株內的低速與植株外的高速這種大幅度的流速變化，不同莖葉尺寸將形成不同的流速。

歷來的研究已證明植被的存在確實影響河流的流速，利用植物做為河岸緩衝帶的相關研究包括 Dabney 等人提出的論點，認為緩衝帶可降低沖蝕、攔截沉澱物，以及經由緩慢逕流移除污染物質，即使緩衝帶小於 1m 寬也能攔截許多沉澱物（Dabney, 2006）。

研究同時發現，淡水水生植物在流動水流中遭遇潛在的阻力時，必須在形態上加以適應以避免機械性的傷害與連根拔起。部分物種自短莖上長出小而硬的簇葉狀（rosette），以便抵抗強的阻力與加強裸露湖岸的力量。其他物種則遺傳了流線型的長線狀葉與莖。大部分的物種無關乎生長的形式，會形成很具彈性的枝芽以讓其順著水流並降低直接暴露於水流的表面積（Sand-Jensen, 2003）。

從國外相關研究中可以得知，對於植物在抗流上的研究已開始受到重視，但因為侷限

於開放河道複雜的不可確定因素，研究仍多以實驗室操作為主，而且不乏以塑膠葉片為實驗材料者，實驗的方式則多以模擬河道中植被如何影響流速為重點，對於從植物生理例如植物解剖學的角度探討植物因應流速變化的生理反應機制，如莖葉分歧、維管束之變化等之研究尚很罕見，也從未就配置模式差異或不同物種產生的抗流機制做相關研究，因此可預見此領域的研究價值。

2.2 國內相關研究

2.2.1 植生對邊坡穩定性的相關研究

關於植生對邊坡生態穩定性的研究，國內拱祥生、林宏達曾利用植生材料的特性，結合不飽和土壤理論，進行邊坡生態工法穩定機制的探討，以釐清植生對邊坡穩定性的影響。其提出植生根系的強度及錨定至岩層中的厚度，為邊坡植生工程的重點，而草本植物的高地表覆蓋率是防止邊坡沖蝕的重要因素；木本植物的高根系強度及土壤含根比則是抑制邊坡淺層崩塌的有效方法。（拱祥生、林宏達，2003）。林信輝等（2005）九芎植生木樁之生長與根系力學之研究，針對九芎植生木樁之生長特性與根力進行研究，探討不同生長地點與處理方式之萌芽樁成活率；吳瑞賢的研究團隊則利用根系力學模式，計算百喜草的植根對土壤強度之增量，並建立分析模型（陳秀婷等，2006）；另外尚有吳正雄（1990）針對植生根力與坡面穩定關係之研究、游新旺等（2006）提出「根力模式對含根土壤剪力強度評估之影響」，以及朱榮華等(2005)對於「根系變形模式與含根土壤剪力強度之研究」等，均是針對植物根系對土壤強度影響之研究，至於植物如何因應流速變化而產生抗流反應的相關研究則闕如。

2.2.2 國內關於生態渠道之研究

國內關於生態渠道之研究包括楊紹洋等（2006）針對植生護岸和粗糙渠床之渠槽試驗，以人造草皮模擬護岸植生，分析渠道在不同植物種類和高度時的水理特性；林鎮洋等（2006）以實驗水槽養殖指標魚種，嘗試建立本土性的水理參數（如雷諾數與福祿數等），據以模擬變遷的水域生態環境，以預測溪流完工後的生態環境變化趨勢。呂珍謀等（2008）針對河道植生群型態對水流之影響的研究，嘗試建立一水流通過植生群之水深平均二維水理模式，並探討植生群型態對水理特性之影響。但在其研究中植物本身的抗流機制未被考量，而研究以竹子模擬植株，亦無法代表一般植物之生理與型態特性。

根據本研究團隊第一階段之研究，水芹菜在面對較大的流速變化時，其反應機制為降低株高、根長，採收後計算株高與根長之比值，實驗組 CD 槽比值要大於控制組 AB，意謂流速增加會抑制植物根部的生長速度，水芹菜用以避免機械傷害的反應機制乃是降低植株的高度與直徑，以便有較彈性柔軟的莖部對抗拖曳力，至於其根部變短，推測乃是為使植株降低錨定作用，以便有機會尋找更適當的生長環境(陳湘媛等，2008)。由於柳葉水蓑衣與水芹菜同為溼地植物，前者更是台灣原生物種，針對不同物種面對流速變化的環境，是否有相同或相異的反應機制？則是本次研究擬釐清的課題。

III、實驗設備與研究方法

3.1 採土原則

由於研究係以河川砂石為植物栽培介質，以更能模擬實際河道之環境，因此選定苗栗縣南庄鄉蓬萊溪中上游段為採土樣區，實驗土壤與水芹菜實驗之土壤來源相同，至於土壤採土原則如下：

1、未經過人為整治過之天然河川或經整治但已植生穩定之河川。
2、人員車輛可及性高的地點。
3、採土周圍有植栽及生物生長，未受污染之土壤。
4、採取約 10cm 厚的表層土壤。
5、過大的石塊及多餘的水份於採土前事先排除。

3.2 蓬來溪環境資料

蓬萊溪是中港溪的上游重要支流之一，位於苗栗縣南庄鄉蓬萊村，因屬上游河段，河岸植被樹木茂密，河中大石林立，以前蓬萊溪因清澈的河水、豐富的魚蝦，每至假日吸引眾多遊客至此戲水烤肉，因此造成河川污染，加上因網捕、毒魚而破壞河川生態（資料來源：台灣河川復育網站），因此近年來推動封溪護漁運動，希望能夠回復當地的生態資源。

3.3 植物選種

3.3.1 植物材料選種依據：

1、為配合水槽尺寸，植物材料尺寸需低於30 cm。
2、植物生長勢強、易於繁殖、多年生草本、分佈範圍廣。
3、屬本土或馴化種，對本土生態環境無威脅性。
4、低人工維護，天然之環境可自然生長。
5、根系需有良好之固土定砂能力。

3.3.2 植栽選定

柳葉水蓑衣：爵床科(Acanthaceae) 學名：*Hygrophila salicifolia (Vahl)*

1、植物分佈：全台灣溼地均可見。

2、植物生理特性：一年或多年生草本，高可達 80 cm，莖略為木質化，方形，有稜溝。葉對生，寬線形或倒披針形，長 3~8cm，寬0.7~1.5 cm，有柄，，近全緣，雙面略覆軟毛。花腋生，淡紫色唇型；可以扦插法無性繁殖（黃增泉等，1978；台北植物園資訊網，2010）。

3.4 實驗設備

3.4.1 實驗水道模型設備

1、水槽：1cm 厚可調式壓克力水槽兩組，長200cm，寬 30cm，高 40cm。
2、變頻馬達 2 具。
3、植栽槽木箱，長 90cm，寬 29cm，高 5cm，板厚 1cm，以樹脂與鐵釘膠著固定。
4、三尺長 40w 雙管植物燈兩盞。
5、定時器 Timer，(設定照光時間 6:30am~17:30pm)。
6、溫度計。
7、水槽平均坡度設定在 2%以下，屬於緩流型河岸之坡度。

3.4.2 實驗操作

3.4.2.1 植物栽種計劃

1、於栽種前每株水蓑衣扦插芽先於電子秤秤得其鮮重，再測量個別水蓑衣之株高、直徑、與綠葉數。
2、每組植栽槽種植 3 株一簇共 48 株水蓑衣，採品字型種植，初期兩槽固定相同流速，讓水蓑衣生長勢穩定後調整實驗組流速。
3、植栽槽覆土深度 4cm。

3.4.2.2 實驗採收

1、採收後測量個別水蓑衣之高度及根長、最高綠芽之直徑、全株鮮重。
2、於攝氏 105℃、24 小時烘乾後測其實驗後總乾重。
3、烘乾後將地上部與根部分開，量測地上部乾重與根部之乾重。

IV、結果與討論

前期研究中水芹菜之實驗從 2006 年 9 月進行至 2008 年 8 月，歷時兩年，有三次實驗成功紀錄，至於本次研究的水蓑衣實驗期間則是從 2009 年 8 月至 2010 年 6 月，於實驗後第 43 周實驗組對照組之成活率相差超過10%以上時結束並採收，實驗期間曾感染介殼蟲害，以無毒農藥「葉潔 Globrite(Potassium salts of fatty acids 49%）」1/50 濃度噴灑控制。

4.1 不同流速下水生植物之生長速度比較

在水芹菜實驗中，三次實驗在實驗前平均綠葉數的差距均在 3.0%以內，而採收後均呈現實驗組平均綠葉數低於控制組平均綠葉數的結果，說明流速會抑制水芹菜綠芽之生長（表 1）。

至於水蓑衣的實驗，因採取扦插方式栽植，所有的扦插芽均無根，並將其大部分的葉片剪除以降低蒸散。起初兩組之平均綠葉數均在 1.0 以下，在實驗組平均流速低於 16.0 cm/s 時，其平均綠葉數略高於控制組，當實驗組平均流速提高至 16.0 cm/s 以上後，其綠葉數量急遽降低，成活率也快速下降，顯示逐漸接近水蓑衣的流速耐受極限（圖 1），同時也說明水蓑衣與水芹菜的生長均會受到流速之影響。

表 1. 水芹菜三組實驗前後平均綠葉數之變化比較
（資料來源：陳湘媛，2010）

Changes in quantity of green leaves	Control group		Experiment group	
	before exp.	after exp.	before exp.	after e
Experiment I	2.92	4.86	3.00	3.33
Experiment II	4.62	6.48	4.67	5.68
Experiment III-1	3.60	6.61	3.85	6.76
Experiment III-2	1.63	8.73	1.61	7.09

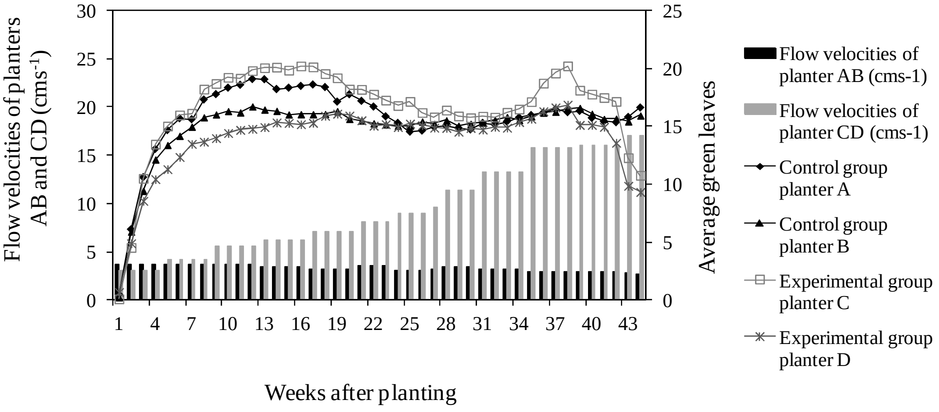

圖 1 水蓑衣於不同流速下之平均綠葉數變化

4.2 不同流速下水生植物生物量之變化

在水芹菜的實驗中，雖然在初始實驗時將鮮重差距控制在 10%以下，但在採收後控制組之總鮮重均高於實驗組（圖 2），實驗一之流速差異性大，反應在乾鮮重上的差異性尤其明顯。至於在水蓑衣的實驗最初，控制組 AB 與實驗組 CD 總鮮重相差在 1.0%以下，實驗結束後總鮮重之差距卻達到 56.0%，也是呈現實驗組低於控制組之現象，當計算平均鮮重時，控制組亦高於實驗組 9.0%（表 2），與水芹菜實驗的結果一致，說明流速對水生植物生物量之影響。

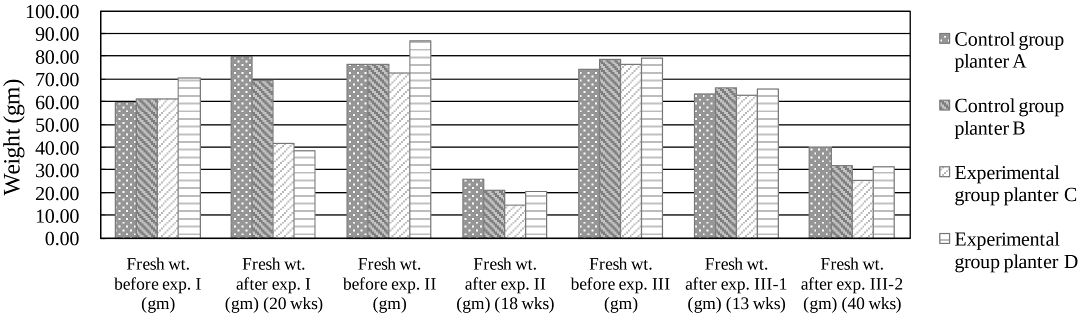

圖 2. 三組水芹菜實驗前後總鮮重比較表（資料來源：陳湘媛，2010）

表 2.實驗前後水蓑衣之鮮重變化

	Fresh wt. before Exp.	Fresh wt. after Exp. (gm)	Average fresh wt. of Exp.
Control group	237.51	348.92	3.88
Experimental group	236.00	223.63	3.56

當以攝氏 105℃，24 小時烘乾後，水芹菜控制組的總乾重均高於實驗組（圖 3），與總鮮重之變化趨勢相同。而在水蓑衣的實驗中，採收後測得控制組 AB 總乾重為 58.73 gm，實驗組總乾重為 35.23 gm，控制組之總乾重約高於實驗組 66.7%，當比較平均乾重時，控制組的平均乾重僅較實驗組高 16.4%。如將乾重分為地上部的芽重與地下部的根重時，控制組 AB 之平均芽重較實驗組高 18.4%，但平均根重卻是實驗組的 95%，顯示水蓑衣在面對較高流速環境時，其地上部莖葉生長速度會降低，但是地下根部的生長速度與生物量卻會增加，與水芹菜面對高流速環境時同時降低地上部與地下部之生物量的反應不同（表 3、圖 3）。

4.3 不同流速下水生植物之型態變化比較

4.3.1 不同流速下之株高變化

在水芹菜實驗中，實驗組在平均株高上要較控制組低矮(圖 4)，實驗 III 中雖然實驗組略高於控制組 7.0%，但是株高平均值均低於實驗之初始值，表示流速對水芹菜之株高確有影響。而在水蓑衣的實驗中，栽植之初水蓑衣係以扦插法種植，實驗前控制組 AB 平均株高較實驗組 CD 的平均株高要高 8.8%;實驗 43 週後控制組 AB 平均株高卻是實驗組 CD 的 99.0%，實驗後在株高的增加率方面也是實驗組較控制組高（表 4），與水芹菜實驗之結果不同。

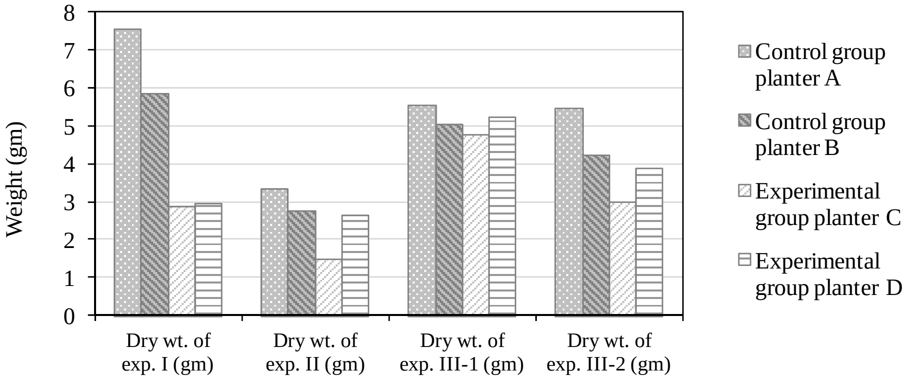

圖 3. 水芹菜三組實驗總乾重比較圖

表 3. 實驗前後水蓑衣之乾重變化

	Dry wt. after Exp.	Dry wt. of shoots after Exp.	Dry wt. of roots after Exp.	Average dry wt. after Exp.	Average dry wt. of shoots after Exp.	Average dry wt. of roots after Exp.
Control group	58.73	54.62	4.11	0.65	0.61	0.05
Experimental group	35.23	32.25	2.97	0.56	0.51	0.05

（資料來源：陳湘媛，2010）

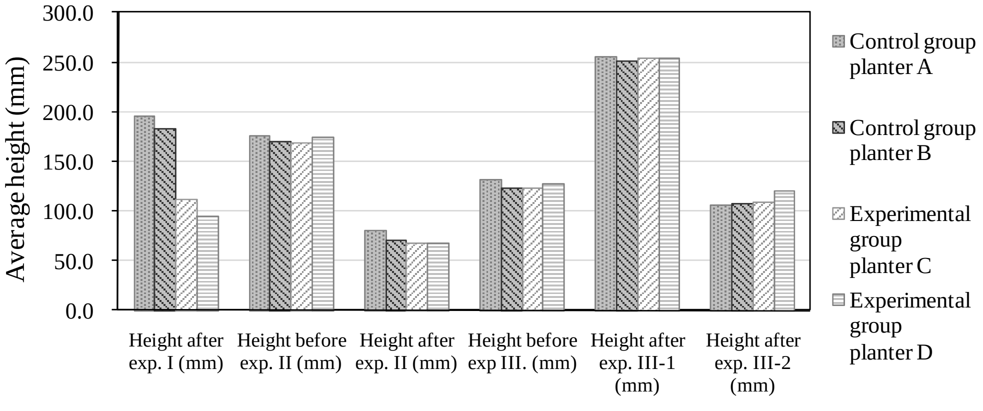

圖 4. 水芹菜三組實驗前後平均株高比較（資料來源：陳湘媛，2010）

表 4 水蓑衣於不同流速下之株高變化

	Height before exp. (mm)	Height after exp. (mm)	Percentage of increasing (%)
planter A	138.8	306.8	121.0
planter B	137.0	289.3	111.2
planter C	130.6	321.7	146.3
planter D	122.9	280.2	128.0

4.3.2 不同流速下之直徑變化

在水芹菜實驗中，無論單植或簇群栽植方式，實驗組之平均直徑均低於控制組（圖 5），顯示水芹菜以降低直徑的方式，讓植株本身與水流接觸的面積減少，以避免受到高流速的機械性傷害。而在水蓑衣的實驗中，實驗前控制組的平均直徑為實驗組之 96.4%，控制組低於實驗組 3.6%，實驗後控制組之平均直徑則較實驗組高 1.7%，雖然變化趨勢與水芹菜相似，但不如水芹菜明顯（表 5）。

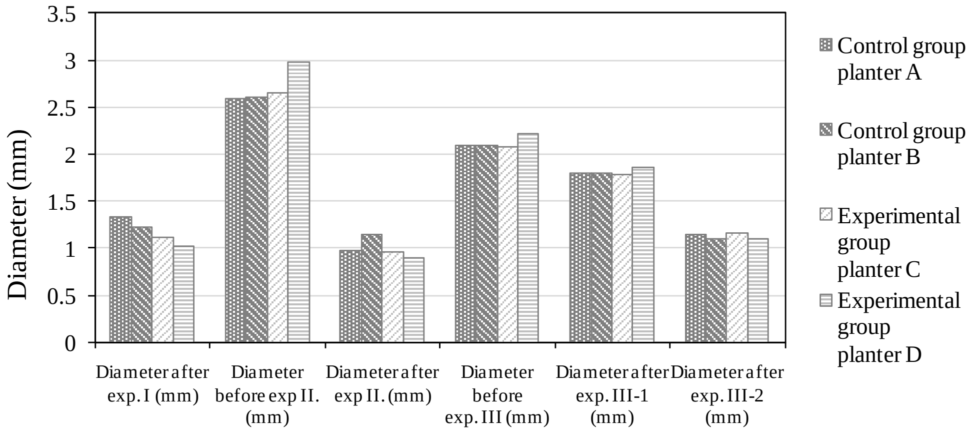

圖 5. 水芹菜三組實驗前後平均直徑比較

表 5.水蓑衣實驗前後平均直徑比較

	Diameter before exp. II	Diameter after exp. II
planter A	4.48	1.84
planter B	4.38	1.74
planter C	4.48	1.64
planter D	4.71	1.88

4.3.3 不同流速下根長之變化

在水芹菜實驗中，實驗組之平均根長均低於控制組，顯示水芹菜面臨高流速之惡劣環境，以降低根長的方式離開原來的生長地區，讓自己有機會尋求更佳的生存環境（表 6），但是在水蓑衣的實驗中，因採扦插法栽植，實驗前均無根，實驗後則發現實驗組的平均根長大於控制組，與水芹菜的反應不同，卻與先前乾鮮重量測時實驗組平均根重大於控制組的結果相符合（表 7）。

表 6.水芹菜實驗前後平均根長比較

	Root length before exp. II (mm)	Root length after exp. II (mm)	Root length before exp. III (mm)	Root length after exp. III-2 (mm)
Control group planter A	26.4	30.4	42.0	45.4
Control group planter B	28.7	22.5	39.8	49.0
Experimental group planter C	24.6	19.1	45.1	41.7
Experimental group planter D	23.3	20.0	40.5	44.6

表 7. 水蓑衣實驗前後平均根長比較

	Average root length after exp. II
planter A	252.84
planter B	191.27
planter C	274.57
planter D	272.18

4.3.4 不同流速下水平莖之數量變化

在水芹菜實驗中，部分水芹菜之葉片會由挺立生長變為水平（水平葉之認定以葉柄斜角大於 45° 者為限），經由統計分析，水芹菜控制組的平均水平葉數量低於實驗組；而在水蓑衣的實驗中，實驗組的植栽形成水平莖型態的平均數量亦高於控制組（表 8），而且呈現流速越高傾向水平生長的趨勢越明

顯，由於水平葉數量增加可以使植株更具流線型，以降低被水流沖斷的危險，因此從水芹菜與水蓑衣的實驗中證實植物確實會以改變自己的型態例如以水平化的方式，來增加植株對較高流速的耐受度。

表 8. 水蓑衣水平莖之數量變化

	parallel stems after exp.	Average parallel stems after exp.
planter A	46	1.02
planter B	36	0.80
planter C	45	1.50
planter D	30	0.91

V、結論與建議

本研究主要在了解不同水生植物在面對流速變化時的各種生理反應，以確定適生物種。在前期水芹菜的研究中，發現在面對較高流速沖刷時，水芹菜的生長速度趨緩，莖芽組織變得矮小且柔軟，以增加植物的抗流彈性，此外，其平均根長變短，錨定能力降低，流速越高平均乾鮮重越低，而為了提高對流速的耐受度，水芹菜也透過水平莖葉的形成，讓植株本身具有流線型，可降低植株被水流沖斷的危險。

在水蓑衣的實驗中，水蓑衣在面對流速變化時的部分反應與水芹菜相同，例如：生長速度受到抑制、平均乾鮮重降低、直徑較小、水平莖增加等，其中在水平莖增加方面，根據 Manz 與 Westhoff 之研究，植物可能透過增加芽的長度以增加本身的彈性，或者因增加芽的厚度而降低其個體之彈性（Manz and Westhoff, 1988），然而在本研究中卻發現，水生植物也可能透過水平莖葉之形成，讓其植株具有流線形狀，在流速增加時可以有較大的抗流能力，同時避免植株被水流沖斷。

除了以上相同的反應外，水蓑衣也有部分生理反應與水芹菜不同，例如：實驗組之平均株高大於控制組、根長較長、根部之乾鮮重較大等，顯示水芹菜以降低根長的方式讓植株有機會在錨定降低的情形下，較容易離開高流速的不良環境而尋得更適合繁殖的環境。此一現象與 Puijalon 在 2005 年的研究相符，Puijalon 發現有些水生植物在面臨較高流速時會在型態上改變，例如降低錨定的強度，以便增加其散佈的能力（Puijalon *et al.*, 2005）。然而在水蓑衣的實驗中，其面對較高流速的反應卻是加強根長的錨定作用，所以實驗採收後量測到的根部乾鮮重均是實驗組高於控制組。至於實驗後平均株高大於控制組的原因，初步推斷由於水蓑衣莖部有木質化現象，莖部必須長高變細才能水平化與呈現流線型狀。相較於水芹菜而言，水蓑衣在固土作用下似乎要較水芹菜表現更佳。

本研究因以模擬水道實驗，未來將以初步結果應用於實際河川環境中，用以確定水生植物的抗流模式，並推廣於生態工程的應用中。

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ORIGINAL ARTICLE

Flow Resistance Adaptation of Aquatic Macrophytes Under Different Flow Velocities

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Abstract

Many studies have demonstrated that plants have the ability to affect flow velocity, and plant materials have been investigated for their potential to be used as a buffer zone to prevent riverbank erosion. However, relatively few studies have investigated the effects of plant characteristics on flow conditions. In this study, an artificial channel was constructed to (1) investigate the nature of the morphological changes undergone by aquatic *Oenanthe javanica* DC (water celery) macrophytes in response to different channel flow velocities and (2) identify the tolerance limit of aquatic macrophytes under different flow velocity conditions. Results show that the morphology of *Oenanthe javanica* DC exhibits the following variations under different flow velocities: as flow velocities increase, growth rate slows and plant shoots become shorter and softer, thereby increasing plant flexibility. These variations were accompanied by a decrease in root length and root anchorage capacity. In response to different flow velocities, a nonlinear relationship in growth rate between total new green leaves and yellow leaves was also observed. The number of vascular bundles in new shoots was found to decrease in a flowing water environment, compared with the number of vascular bundles in terrestrial environments. The average density of vascular bundles, however, was found to increase as flow velocity increased, most likely to provide a compensatory structural support mechanism. Results of this research identified a suitable range of flow velocity for water celery as 0.05–0.30 m s^{-1}, which is approximately equal to the average flow velocity of dredged rivers in Taiwan. Because of its abundant growth in Taiwan and its ability to adapt to the range of velocity conditions found in Taiwan's dredged rivers, water celery was found to be an appropriate planting material for intertidal zones and reservoir bank protection.

Key words: flow resistance adaptation; flow velocity; aquatic macrophyte; artificial channel; ecological engineering

Introduction

Recent studies in Taiwan have investigated the use of ecological engineering methods to mitigate the impact of disasters, such as landslides and floods (Kuo, 2006; Wu and Feng, 2006). These studies, which have demonstrated that plants can affect flow velocities and prevent riverbank erosion (Greenway, 1987; Simon and Collison, 2002; Simon *et al.*, 2006; Wynn and Mostaghimi, 2006), show that aquatic macrophytes are frequently the dominant factor influencing flow conditions within the channels they occupy. Flow velocity has been demonstrated to affect plant stem/leaf scales and vegetation density as well as plant length, stiffness, and diameter (Manz and Westhoff, 1988; Green, 2005). However, the effects of vegetation on flow resistance are still not fully understood (Järvelä, 2004; Green, 2005). Most empirical studies of the effects of vegetation have been conducted in artificial channels using plastic leaves or submerged vegetation, and they have focused on hydraulic effects, such as drag and vegetation configurations (Sand-Jensen, 2003; Järvelä, 2004). The remaining studies have focused on types of riverbank, materials, and construction methods used for riverbank protection, slope stabilization, erosion control, or development of methods to increase the survival rate of selected plant species (Elliott, 1998, 2004; Anderson *et al.*, 2004).

Submerged plants have also been found to affect flow velocities. Plants can be utilized as buffers to reduce erosion, trap sediment, and remove contaminants by slowing runoff, increasing infiltration, and facilitating contaminant uptake and subsequent transformation (Dabney *et al.*, 2006; Wynn and Mostaghimi, 2006). Riparian vegetation has both mechanical and hydrological effects on streambank stability; some of its effects improve bank stability and others reduce

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bank stability; the latter results in an increase in the flood stage (Simon and Collison, 2002; Rhee *et al.*, 2008). In open-channel hydraulics, aquatic plants typically cause changes in flow resistance as well as changes in the retardance coefficient (Rhee *et al.*, 2008; Chen *et al.*, 2009) by anchoring their roots into channel soil to support the aboveground portion of a plant (Greenway, 1987). Variation in root type (root depth and density) can also affect channel erosion (Anderson *et al.*, 2004).

Relatively few field-monitoring studies have verified the effects of vegetation on channel and flow velocities or investigated the morphological adaptation of plants to flow conditions (Watson, 1987; Asaeda *et al.*, 2005; Green, 2005). Moreover, few studies have tested the tolerance limit of aquatic macrophytes under different flow velocities, examined aquatic macrophytes' modification of their physical characteristics to adapt to flow velocities, or investigated the effects of those changes on channel flows.

The present study utilizes an artificial channel to assess the ability of aquatic macrophytes to resist various flow velocities. The primary aim of this study was to determine whether local aquatic macrophytes are suitable for riverbank protection projects by examining how they respond to different channel flow velocities, which is measured by observed changes in their form and structure. Additional goals were to determine the growth rate and biomass of the macrophytes, morphological variations in their stems and roots, their tolerance limits, and their erosion resistance response under various flow velocities. The final purpose of this study was to determine aquatic macrophytes' range of application in ecological engineering and design.

Materials and Methods

Simulated plant environment selection

Natural riverbanks can be classified by environment, topography, and slope, all of which affect flow rate. Taiwan has three different flow environments for aquatic macrophytes: rapid flow, moderate flow, and slow flow.

1. Rapid flow: Slope exceeds 4%; only a few emerging plants can survive in this flow, which is always found in upstream sections.
2. Moderate flow: Slope is 2%–4%; this environment, which is suitable for emerging plants, can be seen in all midstream sections and some upstream sections of Taiwan's western rivers.
3. Slow flow: Slope is <2%; this environment, which is suitable for most aquatic macrophytes, can be found in all downstream sections of Taiwan's western rivers (EPA, 1995; WRA, 2008).

Tatun Creek was chosen as the channel for this experiment, because it was dredged using ecological engineering methods and was well populated with plants at 2 years after its construction. The average slope of Tatun Creek is <2%; thus, it represents a typical slow flow environment suitable for most aquatic macrophytes. Culture media used in this experiment were also extracted from Tatun Creek. The site chosen for soil collection was covered with native plants such as *Miscanthus floridulus (Labill.)* Warb. ex Schum (Japanese silvergrass) and invasive species such as *Bidens pilosa*. Dragonfly nymphs were also found under gravel in the river.

The results of grain size analysis indicate that 90% of particles were >0.15 mm in diameter and their silt content was less than 15%. According to the soil texture classification method of the United States Department of Agriculture, the texture of culture media from Tatun Creek was of the "sandy type," which has an exceptionally low water-holding capacity and also the same texture as the soil typically found in Taiwan's rivers.

Artificial channel construction

Factors affecting flow resistance include the size and structural characteristics of plants, their location in a channel, and local flow conditions (Green, 2005). Channel structure and hydrology also contribute to setting flow velocity. For the purpose of this study, an artificial channel was designed to incorporate all of the factors listed above. Artificial double channels (200 cm long, 30 cm wide, and 40 cm deep) were constructed of 1-cm-thick transparent acrylic panels. The channels' other components consisted of two adjustable water pumps, four planters, and two 200-L water tanks. The planters were made of 1-cm-thick wooden panels (90 cm long, 29 cm wide, and 5 cm deep). Lighting was supplied by four 40-watt plant lights, each 100 cm long, which were illuminated from 06:30 to 17:30, with an average luminance of 843 Lux. A control group and experimental group were subjected to the same environmental conditions with variation in flow rates (Fig. 1). All experiments were conducted at room temperature.

The main factors contributing to total channel resistance, according to the Cowan equation, are channel materials, surface irregularities, variations in the channel cross-section, obstructions, vegetation, and channel meandering (Green, 2005). The Manning's roughness coefficient in this experiment is between 0.025 and 0.054.

Choice of plant species

Differences in plant structure, such as stem and leaf morphology, have been demonstrated to affect flow rate (Sculthorpe, 1967; Sand-Jensen, 2003). Plant materials chosen for this study were required to meet the following criteria:

1. Plant species must be native aquatic macrophytes or domestic species that pose no threat to native species.
2. Plants must be shorter than 30 cm in height (the acrylic channel was 30 cm in height).
3. Plants must be easy to cultivate.
4. Plants must be perennial herbs with thread-like rootlets, whose growth rate is easy to compare and whose soil stability is easy to assess.
5. Plants must exhibit widespread growth in Taiwan.
6. Plants must have a short lifecycle.

Oenanthe javanica (Blume) DC (water celery) was selected because it grows in ditches, ponds, paddy fields, and other wet locations at low-to-medium altitudes all over Taiwan. It also fulfills all of the other conditions for species choice (Huang *et al.*, 1998).

Experimental procedure

Three experimental trials were completed between November 2006 and August 2008. A total of 48 water celery

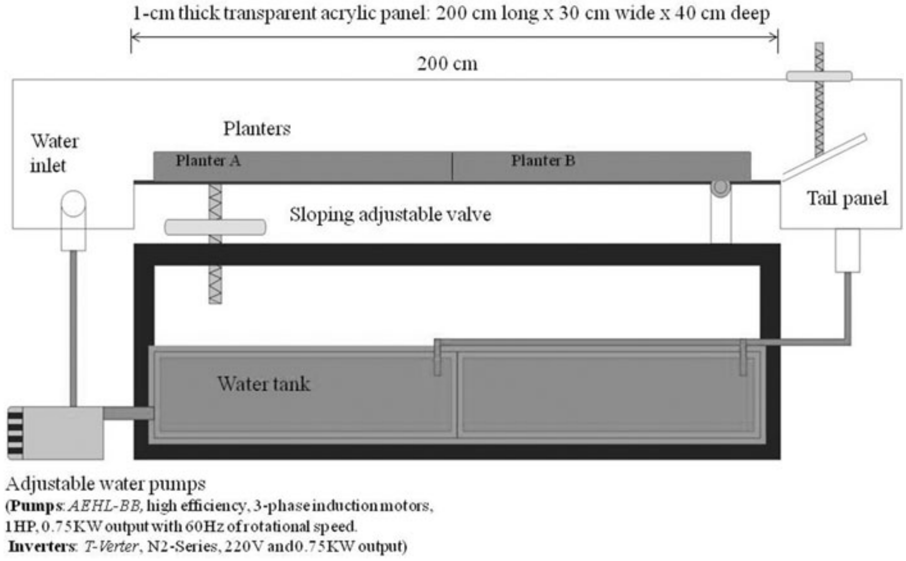

FIG. 1. Layout of an artificial channel.

plants were planted 6 cm apart in each of the four planters. All flow rates were controlled via the rotational speed of adjustable water pumps. At the beginning of the experimental trial period, the flow rates of both groups were nearly the same. Subsequently, the rotational speed of the water pump in the control group was kept constant, but the rotational speed of the water pump in the experimental group was increased by increments of 0.2–2.0 Hz once every 4 weeks (Table 1). Variation of rotational speeds was introduced to investigate the flow resistance adaptation of water celery over a range of flow rates. All three experiments were conducted over an 18-week period and were terminated when the difference in survival rate between the two groups exceeded 10%.

An initial experiment was conducted to identify the flow velocity tolerance limit of water celery to assess its compatibility with average flow velocities of dredged rivers in Taiwan, which are 0.02–0.60 m s^{-1} (Dago Stream, 0.05–0.13 ms^{-1}; Fungaue River, 0.02–0.52 m s^{-1}) (Lin, 2003; Lin *et al.*, 2005),

Step I. For the control group and the experimental group, the following measurements were obtained: culture media properties, plant weights, root lengths, channel slope, water depths, flow velocities, water qualities, pH values, and lighting duration. Water celery plants took 3–4 weeks to establish stability in the planters, so channel flow velocities were kept constant during the first 4 weeks for both the control and experimental groups and increased thereafter for the experimental group once every 4 weeks.

Step II. The number of green leaves, yellow leaves, horizontal leaves, epicormic shoots, and stolon shoots was recorded every week. Additionally, height, root length, diameter, fresh weight, and total dry weight measurements were recorded for each plant after harvesting.

Step III. Original stems and green leaves were harvested from the plants in Experiment III-1, and only new shoots were left uncut at week 13. The purpose of Step III was to observe the difference in morphology between new shoots and original terrestrial shoots.

Plant tissue sectioning

Paraffin method. After harvesting, the plant material was analyzed for vascular bundles using the paraffin method, a slicing technique for preserving fresh plant tissue. Plant sections were obtained to compare physical anatomical changes in the structure of water celery plants under different flow velocity conditions. The paraffin method procedure is outlined below:

TABLE 1. DIFFERENT EXPERIMENTAL CONDITIONS

	Experiment I	*Experiment II*	*Experiment III-1*	*Experiment III-2*
Flow velocities in the control group (m s^{-1})	0.06–0.08	0.05–0.06	0.10–0.11	0.10–0.13
Flow velocities in the experimental group (m s^{-1})	0.05–0.35	0.08–0.10	0.10–0.17	0.17–0.24
Flow velocity adjusting range	Rising the rotational speed by 1.0 Hz every 4 weeks (equivalent to a velocity increase of 0.04–0.05 m s^{-1}).	Rising the rotational speed by 0.20 Hz every 4 weeks (approximately equivalent to a velocity increase of 0.01 m s^{-1}).	Rising the rotational speed by 1.0 Hz every 4 weeks (equivalent to a velocity increase of 0.01–0.04 m s^{-1}).	Rising the rotational speed by 2.0 Hz every 4 weeks (equivalent to a velocity increase of 0.01–0.05 m s^{-1}).

Fixation → dehydration → infiltration of paraffin → embedding → slicing with rotary microtome → adhesion on slide → drying out → staining → mounting with Entellen (Tsai, 2000).

Freehand sectioning

Freehand sectioning, the simplest slicing technique for observing fresh plant tissue, was employed as the second analytical method. The thickest stem was chosen for each water celery plant and then fresh stems were sectioned and temporarily fixed with 5 mL formalin, 5 mL glacial acetic acid, and 90 mL of 50%–70% alcohol (FAA) (Tsai, 2000). The resulting sections were analyzed, and the number of vascular bundles in each section was recorded.

Results and Discussion

Each experiment was conducted over a period of 18–40 weeks. In Experiment I, 20 weeks after planting, the survival rate of the experimental group declined to 75%, whereas the survival rate of the control group was 95%. Suitable flow velocities were estimated to be 0.05–0.30 m s^{-1}.

By the second week of Experiment II, >80% of shoots had been eaten by *Spodoptera litura* Fabicius. After application of a pesticide, new shoots sprouted during week 5.

Growth rate variation under different flow velocity conditions

At the start of Experiment I, the total number of green leaves in the control group (planters A and B) was only 2.8% less than the number of green leaves in the experimental group (planters C and D). When flow velocity was increased to 0.30 m s^{-1}, the total number of leaves in the experimental group increased continuously, and the plant growth rate was higher than that of the control group. However, when flow velocity was increased to 0.35 m s^{-1} in the experimental group, the total number of new green leaves that sprouted after planting began to decline, whereas the number of yellow leaves increased and remained higher than the number of yellow leaves in the control group. After harvesting, the total number of yellow leaves in the experimental group was 35.1% higher than in the control group (Table 2). When flow velocity was fixed for the control group, the difference between the total number of green and yellow leaves in planters A and B continued to increase (Fig. 2). When flow velocity was increased once every 4 weeks in the experimental group, the difference between the total number of green and yellow leaves in planters C and D began to decrease at velocities exceeding 0.30 m s^{-1} (Fig. 3). These results indicate that suitable flow velocities for water celery are in the range of 0.05–0.30 m s^{-1}.

In Experiments II and III, the difference between the total number of new green leaves and yellow leaves not only in planters C and D but also in A and B continued to increase, because flow velocities in the experimental groups were kept under the endurable limit. Growth rates in planters C and D remained lower than those in the control groups, and the total number of new green leaves in the control groups was higher than in the experimental groups. All three results indicate that flow velocities affect the growth rate of water celery.

Biomass variation under different flow velocity conditions

At the start of Experiment I, the total fresh weight of plants in the control and experimental groups was 120.26 and 131.36 g, respectively. At week 20, the total fresh weight of plants in the control group was 148.70 and 80.03 g in the experimental group; thus, the total fresh weight of plants in the experimental group comprised only 53.8% of the control group weight. After harvesting and drying for 26 h at 100°C, the dry weight of plants in the control group was 13.42 and 5.82 g in the experimental group (Table 3).

In Experiments II and III, no distinct differences were found in biomass between the two groups at flow velocities of <0.17 m s^{-1}. After harvesting, both the fresh and dry weights of plants in the experimental group were lower than those in the control group (Table 3). All three experiments demonstrate variation of biomass under different flow velocities.

Growth rate and biomass reduction results are consistent with the results obtained in previous studies of plants exposed to increasing flow or waves; the plants generally present growth modifications and morphological changes such as height and density reduction as well as a decrease in biomass production (Idestam-Almquist and Kautsky, 1995; Coops and Van der Velde, 1996; Puijalon and Bornette, 2004; Puijalon *et al.*, 2005).

Morphological variation under different flow velocity conditions

Mechanical constraints limit plant survival and growth in environments with flowing water, because hydraulic force

TABLE 2. CHANGES IN NUMBER OF GREEN AND YELLOW LEAVES

	Control group			*Experimental group*		
Changes in green/yellow leaves	*Total green leaves before experiment*	*Total new green leaves after experiment*	*Total yellow leaves after experiment*	*Total green leaves before experiment*	*Total new green leaves after experiment*	*Total yellow leaves after experiment*
Experiment I	280	720	541	288	689	731
Experiment II	443	702	625	448	577	574
Experiment III-1	345	629	340	369	630	350
Experiment III-2	—	1,010	657	—	862	623

Experiment I: Flow velocities were 0.06–0.08 m s^{-1} in planter AB and 0.05–0.35 m s^{-1} in planter CD. Experiment II: Flow velocities were 0.05–0.06 m s^{-1} in planter AB and 0.08–0.10 m s^{-1} in planter CD. Experiment III-1: Flow velocities were 0.10–0.11 m s^{-1} in planter AB and 0.10–0.17 m s^{-1} in planter CD. Experiment III-2: Flow velocities were 0.10–0.13 m s^{-1} in planter AB and 0.17–0.24 m s^{-1} in planter CD.

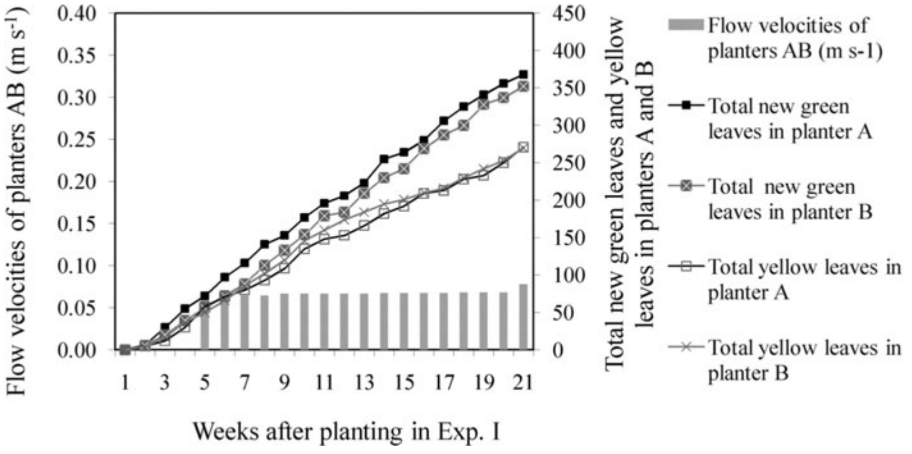

FIG. 2. Difference between total new green leaves and yellow leaves in the control group of planters A and B for Experiment I: When flow velocity was controlled under $0.08\,\mathrm{m\,s^{-1}}$, difference between total green/yellow leaves of planters A and B continued increasing. Total number of new green leaves was the total new leaves that sprouted after planting.

generally dislodges or breaks plants (Schutten and Davy, 2000). A flowing water environment can also trigger morphological adaptations; for example, some species, such as *Eichhornia crassipes* and *Pistia stratiotes*, develop a rosette of small, stiff leaves from a short stem, which can resist strong drag and accelerational forces on wave-exposed lakeshores. Other species, such as *Vallisneria natans* and *Sparganium*, develop a streamlined morphology of long linear leaves or stems in response to higher flow velocities (Sculthorpe, 1967; Sand-Jensen, 2003). Most species develop very flexible shoots, which allows them to bend and twist in flowing water, and reduces the surface area directly exposed to current flow (Koehl, 1984; Sand-Jensen, 2003).

In Experiments I and II, average plant height after harvesting in the experimental groups was less than in the control groups. For the fast flow velocity condition in Experiment I, average plant height in the experimental group was 54.3% of the control group plant height. The average diameter of stems in the experimental group was 84% of the control group diameter (Table 3).

Experiment II results show the plant height to be inversely related to flow velocity. The difference between the two groups was only 11% in Experiment II (not as large as in Experiment I), and the average length of roots in the experimental group was 73.8% of the average control group length (Table 3).

The results of Experiment III were similar to those of Experiment I: as flow velocities for the experimental group had been increased gradually to just under $0.24\,\mathrm{m\,s^{-1}}$, a rate that does not exceed the endurable limit, no distinct differences were found between the two groups with respect to epicormic shoots or dwarfish shoots. However, the average plant height in the control group was 6.5% lower than in the experimental group, a finding that is not consistent with the results of Experiments I and II (Table 3). Comparison of the final average plant height with the average plant height at the start of the experiments shows that average heights were lower after the experiment for both groups. However, average root lengths in the experimental groups were shorter than root lengths in the control groups, which is consistent with the results of Experiment II (Table 3).

All three experiments show that water celery plants decrease their height and root length under high flow velocity conditions. After harvesting, the ratio of plant height to root length in the experimental group was higher than in the control group (Table 4). Flow velocity hindered the overall growth rate of the water celery plants, which affected the plant root length considerably more than the plant height. It was also found that a decrease in the plant root length reduces the use of root anchorage as a mechanism for creating a more favorable propagation environment. Similar results were obtained by Puijalon *et al.* (2005); aquatic plant species

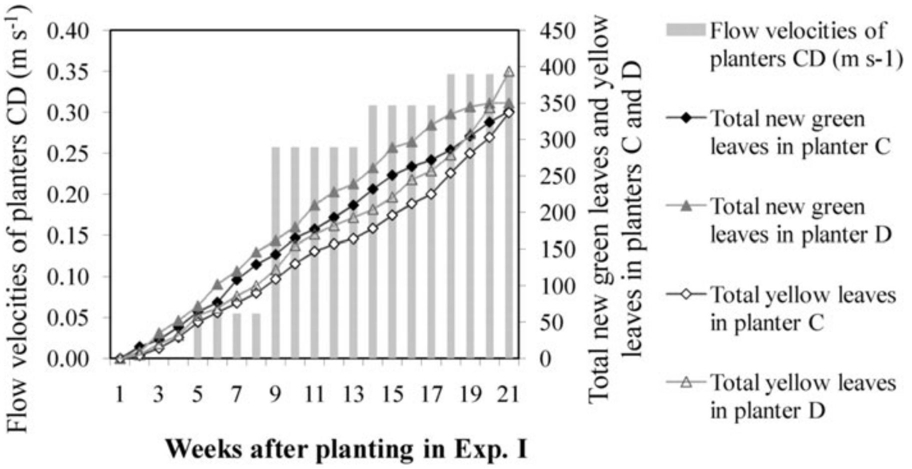

FIG. 3. Difference between total new green leaves and yellow leaves in experimental group of planters C and D for Experiment I: When flow velocity was adjusted higher every 4 weeks in experimental group, difference between the total green/yellow leaves of planters C and D decreased when the velocity exceeded $0.30\,\mathrm{m\,s^{-1}}$.

Table 3. Morphological Variations Before and After Experiments

		Before experiment				After experiment			
		Control group		Experimental group		Control group		Experimental group	
		Planter A	Planter B	Planter C	Planter D	Planter A	Planter B	Planter C	Planter D
Experiment I	Plant height (mm)	—	—	—	—	195.5 ± 58.9	183.0 ± 63.0	111.1 ± 64.4	94.5 ± 61.7
	Diameter (mm)	—	—	—	—	1.33 ± 0.27	1.23 ± 0.30	1.11 ± 0.32	1.03 ± 0.26
	Average leaf number	2.69 ± 0.80	3.15 ± 0.97	3.04 ± 1.05	2.96 ± 0.97	4.89 ± 1.52	4.83 ± 1.48	3.47 ± 1.07	3.19 ± 1.10
	Total fresh weight (g)	59.27	60.99	60.92	70.44	79.52	69.18	41.45	38.58
	Average fresh weight (g)	1.14 ± 0.12	1.17 ± 0.28	1.17 ± 0.20	1.35 ± 0.25	1.73 ± 0.07	1.50 ± 0.07	0.94 ± 0.06	1.07 ± 0.05
	Total dry mass (g)	—	—	—	—	7.55	5.87	2.86	2.96
Experiment II	Plant height (mm)	175.3 ± 33.3	169.3 ± 32.8	168.5 ± 32.0	173.7 ± 30.2	80.4 ± 35.7	70.0 ± 32.6	67.6 ± 25.5	67.3 ± 35.1
	Root length (mm)	26.4 ± 10.2	28.7 ± 16.9	24.6 ± 12.2	23.3 ± 9.6	30.4 ± 16.3	22.5 ± 10.1	19.1 ± 10.7	20.0 ± 8.3
	Diameter (mm)	2.59 ± 0.36	2.60 ± 0.49	2.65 ± 0.47	2.98 ± 0.60	0.97 ± 0.39	1.14 ± 0.62	0.97 ± 0.44	0.90 ± 0.44
	Average leaf number	4.77 ± 1.42	4.46 ± 1.47	4.19 ± 1.57	4.69 ± 1.48	7.36 ± 4.18	5.60 ± 3.34	5.10 ± 3.04	6.27 ± 4.21
	Total fresh weight (g)	76.44	76.21	72.41	86.61	25.69	21.12	14.18	20.32
	Average fresh weight (g)	1.59 ± 0.20	1.59 ± 0.10	1.51 ± 0.42	1.80 ± 0.19	0.57 ± 0.12	0.53 ± 0.21	0.35 ± 0.07	0.48 ± 0.15
	Total dry mass (g)	—	—	—	—	3.34	2.75	1.48	2.65
Experiment III-1	Plant height (mm)	131.9 ± 36.0	123.3 ± 31.6	123.0 ± 32.8	127.5 ± 39.4	255.2 ± 116.0	251.5 ± 135.4	253.2 ± 135.0	253.4 ± 135.5
	Root length (mm)	42.0 ± 15.1	39.8 ± 14.6	45.1 ± 19.0	40.5 ± 16.3	—	—	—	—
	Diameter (mm)	2.10 ± 0.27	2.09 ± 0.32	2.08 ± 0.40	2.22 ± 0.42	1.80 ± 0.36	1.80 ± 0.45	1.79 ± 0.33	1.86 ± 0.45
	Average leaf number	3.65 ± 1.06	3.54 ± 0.94	3.75 ± 0.93	3.94 ± 0.98	6.75 ± 3.28	6.46 ± 2.48	6.79 ± 2.34	6.73 ± 2.44
	Total fresh weight (g)	74.18	78.39	76.34	79.33	63.13	66.11	62.86	65.41
	Average fresh weight (g)	1.55 ± 0.61	1.63 ± 0.66	1.59 ± 0.73	1.65 ± 0.76	1.32 ± 0.78	1.38 ± 0.95	1.34 ± 0.76	1.39 ± 0.94
	Total dry mass (g)	—	—	—	—	5.56	5.03	4.76	5.25
Experiment III-2	Plant height (mm)	—	—	—	—	106.5 ± 65.1	107.6 ± 49.6	108.7 ± 45.9	120.3 ± 52.3
	Root length (mm)	—	—	—	—	45.4 ± 29.5	49.0 ± 25.6	41.7 ± 30.4	44.6 ± 25.2
	Diameter (mm)	—	—	—	—	1.15 ± 0.33	1.10 ± 0.21	1.17 ± 0.22	1.10 ± 0.27
	Average leaf number	1.69 ± 2.68	1.56 ± 2.11	1.58 ± 2.22	1.63 ± 1.93	9.71 ± 5.35	7.75 ± 4.49	6.45 ± 3.31	7.73 ± 4.08
	Total fresh weight (g)	—	—	—	—	39.91	31.65	25.01	31.20
	Average fresh weight (g)	—	—	—	—	1.14 ± 1.02	0.99 ± 0.73	0.86 ± 0.63	1.04 ± 0.72
	Total dry mass (g)	—	—	—	—	5.46	4.24	2.99	3.88

Table 4. Ratio of Average Plant Height to Root Length

	Height/root length before experiment II	*Height/root length after experiment II*	*Height/root length before experiment III*	*Height/root length after experiment III*
Control group	6.3	2.9	3.1	2.3
Experimental group	7.2	3.5	2.9	2.7

were found to undergo morphological changes, which decreased their anchorage strength, thereby increasing their spreading ability in high flow velocity conditions (Puijalon *et al.*, 2005).

The results presented above demonstrate variation in the morphological characteristics of aquatic macrophytes, such as plant height and root length, under different flow velocity conditions. Water celery avoids mechanical stresses under drag forces at high flow velocities by reducing height and diameter, thereby forming relatively softer and more flexible shoots. This is consistent with the results of previous studies of macrophytic freshwater plants, in which they were found to morphologically adapt to prevent mechanical damage and uprooting when exposed to substantial drag forces in flowing water (Coops and Van der Velde, 1996; Sand-Jensen, 2003). In contrast, differences in the number of epicormic and dwarfish shoots between the control and experimental groups were not as obvious, because flow velocities had been increased incrementally.

Change in plant tissue sections under different flow velocity conditions

Section analyses show that the average height of new shoots in experimental specimens was lower than that of terrestrial plants and that experimental specimens contained fewer vascular bundles than terrestrial water celery. Terrestrial water celery also presented larger stem diameters and more vascular bundles than water celery that had been planted in water (terrestrial specimens, >5 vascular bundles; water specimens, <5 vascular bundles) (Fig. 4).

Greater stem thickness in the control groups than in the experimental groups was also observed (Fig. 5). However, data analysis shows that, although average diameter and stem thickness decreased as flow velocity increased, the average ratio of vascular bundles to square millimeter of stem sectional area increased as flow velocity increased (Fig. 6), most likely as a compensatory structural support mechanism. The water celery plants adapted to changing conditions in the flowing water environments via alterations in stem thickness and vascular bundle density.

Formation of algal mats to protect topsoil

During the three experiments, algal mats, including *Anabaena azollae*, *Oscillatoria Formosa Bory*, and *Navicula* sp., began to form at week 6 after planting. In Experiment III, *Chroococcus* sp. grew in the control group planters A and B at week 24 after planting, in which the flow rate had been controlled at 0.10–0.13 m s^{-1}. This kind of algal mat forms in high-temperature environments with low oxygen levels. All of the algal mats mentioned protect topsoil, especially from silt erosion. The water celery in planters provided algal mats with an opportunity to attach without being flushed away by flowing water. In this study, algal mats formed more slowly in the experimental group than in the control group. When plants died or were exposed to high flow velocities, the attached algal mats broke away, reducing topsoil protection.

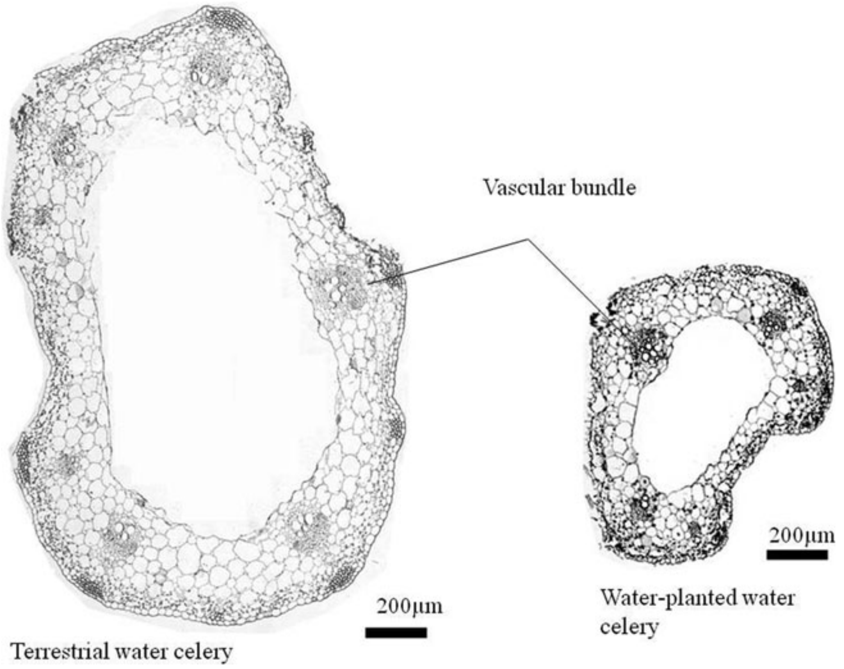

FIG. 4. Comparison of plant tissue sections from terrestrial and water-planted water celery: Terrestrial water celery had larger diameter and more vascular bundles than that of water-planted water celery.

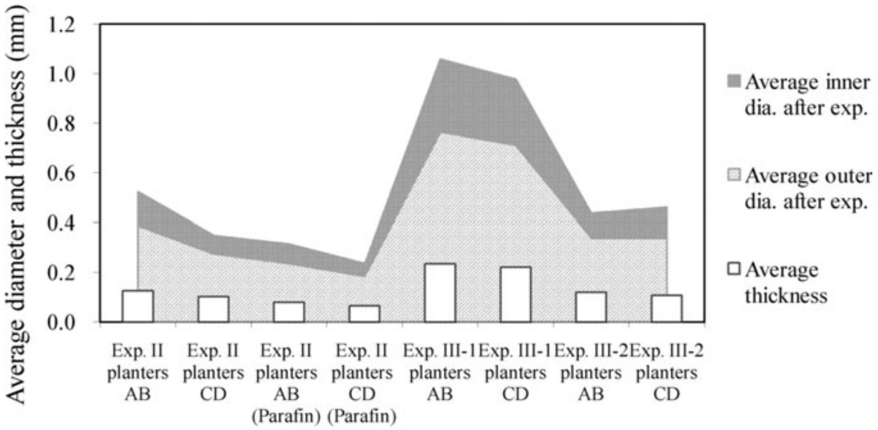

FIG. 5. Plant section variations in the three experiments: Stem thickness was thicker for the control groups than for the experimental groups.

Tolerance limit of water celery to flow velocities

The three experimental trials also served to determine the flow velocity tolerance limit of water celery. In Experiment I, the number of green leaves in the experimental group increased at flow velocities of $<0.30\,\mathrm{m\ s^{-1}}$, and growth rate declined after flow rate had been increased to $>0.30\,\mathrm{m\ s^{-1}}$. Survival rate decreased to <75% at a flow velocity of $0.35\,\mathrm{m\ s^{-1}}$. Calculation of the total number of green and yellow leaves in planters C and D at various flow velocities showed that the difference between the number of green and yellow leaves decreased when velocity exceeded $0.30\,\mathrm{m\ s^{-1}}$. The total number of new green leaves and yellow leaves in the experimental group also displayed a nonlinear relationship over a range of flow velocities (Fig. 7).

In Experiment II, <80% of green shoots had been eaten by *Spodoptera litura* Fabicius, so the total number of yellow leaves initially exceeded the number of new green leaves (Fig. 8). However, the number of green leaves in the experimental group continued to increase until harvesting at week 18 after planting, because flow velocities had been consistently maintained at a level below the tolerance limit of water celery.

In Experiment III, the number of green leaves in the experimental group continuously increased during the two stages. The difference between the total number of new green leaves and yellow leaves in planters C and D increased at velocities of $<0.30\,\mathrm{m\ s^{-1}}$. Nonlinear regression relationships were found between flow velocities and the number of new green leaves and yellow leaves, which is consistent with the results of Experiments I and II (Figs. 9 and 10).

Conclusion

This research demonstrates that the way in which water celery avoids mechanical stresses when encountering drag forces at higher flow velocities is to reduce both plant height and stem diameter, thereby forming softer and more flexible shoots. Such morphological adaptations to reduce root length also serve to reduce root anchorage strength, which increases plants' spreading ability at high flow velocities.

The plant section data from Experiments II and III show that the number of vascular bundles in new shoots was lower in flowing water environments than in terrestrial environments. However, subsequent data analysis of Experiments I–III revealed that although the total number of vascular bundles per stem decreased under high flow velocity conditions, the density of vessels per unit area increased. Plants undergo this kind of adaptation to avoid breakage or mechanical injury. At high flow velocities, aquatic macrophytes, such as *Oenanthe javanica* (Blume) DC, adapt to produce fewer vascular bundles per stem and a higher vascular bundle density per unit area to compensate for the structure lost in reduction of stem diameter, thereby reducing the likelihood of damage due to breakage. It must be noted here that morphological adaptation triggers may include factors other than flow velocity. To investigate this possibility, future experiments will vary other environmental conditions or planting methods, such as hydrology and cluster patterns.

The suitable flow rate range for water celery was determined to be $0.05–0.30\,\mathrm{m\ s^{-1}}$, which is approximately equal to most average flow velocities of dredged rivers in Taiwan.

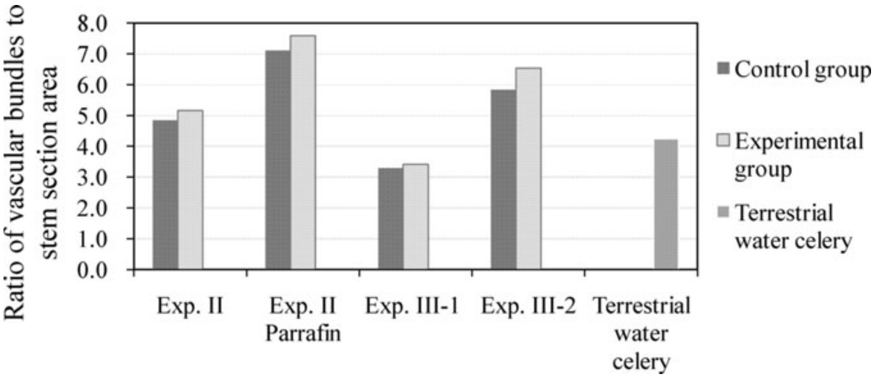

FIG. 6. Ratio of vascular bundles to stem section area: Average ratio of vascular bundles to square millimeter of stem section area increased as flow velocity increased.

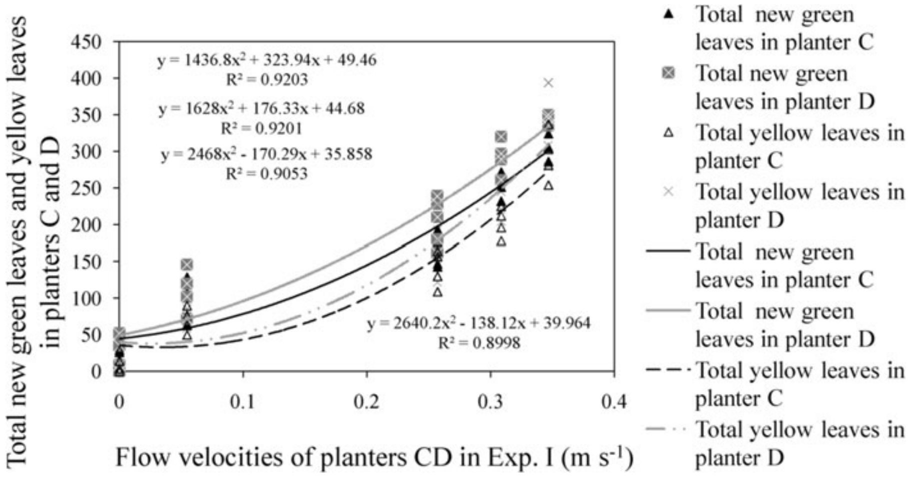

FIG. 7. Relationship between total new green leaves and yellow leaves and flow velocities in experimental groups of Experiment I: Difference between total new green leaves and yellow leaves in planters C and D decreased as velocity exceeded 0.30 m s^{-1}.

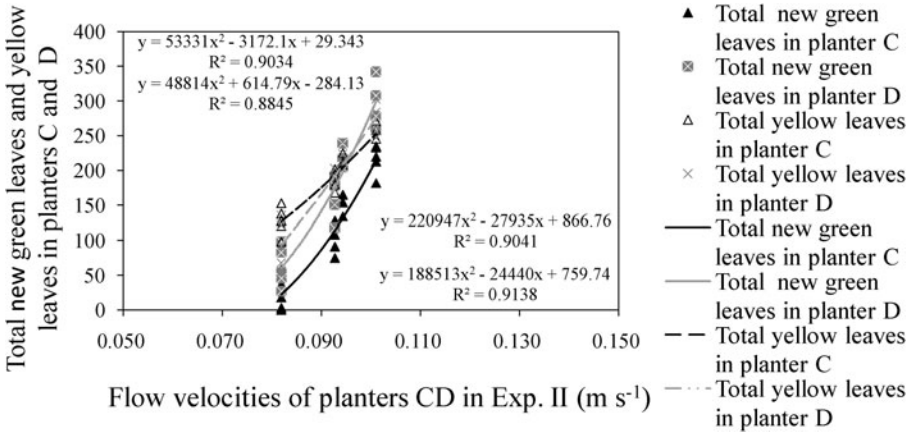

FIG. 8. Relationship between total new green leaves/yellow leaves and flow velocities in experimental groups of Experiment II (first 2 weeks were not included): Flow velocities were under tolerance limit of water celery in this trial. Green leaves in the experimental group kept increasing until harvested at 18 weeks after planting.

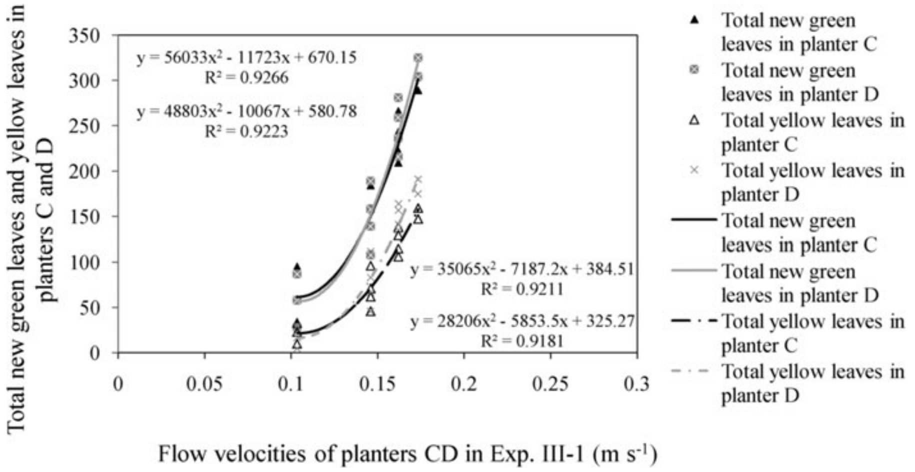

FIG. 9. Relationship between total new green leaves/yellow leaves and flow velocities in experimental groups of Experiment III-1: In Experiment III-1, the green leaves in experimental group increased during the first stage with flow velocities below than 0.20 m s^{-1}.

Water celery, a wet land plant with the advantages of easy cultivation and the ability to protect topsoil, has been found to be an appropriate planting material for intertidal zones and reservoir bank protection. As suitable streambank vegetation may include a variety of plants, future studies can examine the flow resistance mechanisms of clustered water celery and other plants, to further investigate the feasibility of applying aquatic macrophytes to ecological engineering.

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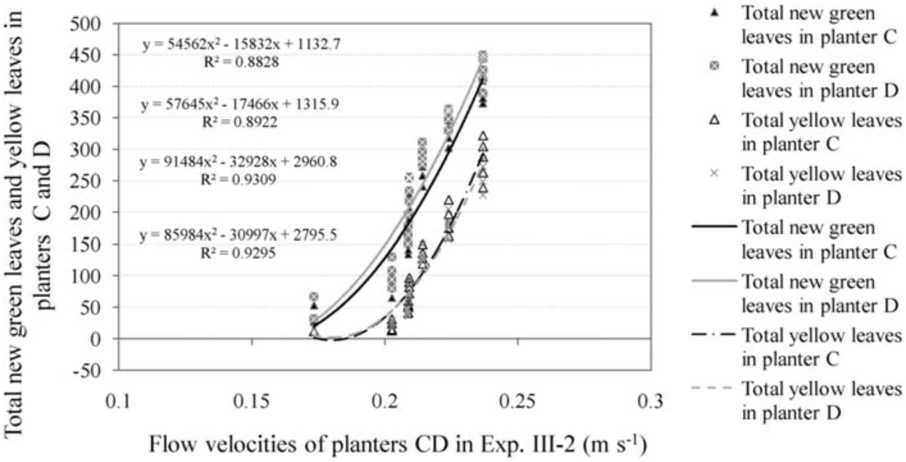

FIG. 10. Relationship between the total new green leaves/yellow leaves and flow velocities in the experimental groups of Experiment III-2: In the second stage, as the flow rates were under tolerant flow rate of 0.30 m s^{-1}, the green leaves in both planters C and D continued to increase.

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Author Disclosure Statement

No competing financial interests exist.

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行政院國家科學委員會補助國內專家學者出席國際學術會議報告

100 年 8 月 26 日

附件三

報告人姓名	陳湘媛	服務機構及職稱	中華大學 景觀建築學系助理教授
時間 會議 地點	20110821 中國北京林業大學	本會核定補助文號	台會綜二字第 1000049212 號
會議名稱	(中文) 2011 海峽兩岸綠色行政與生態文明交流研討會 (英文)		
發表論文題目	(中文) 生態社區之規劃理念與執行經驗 (英文) Planning Concept of Eco-community and Implementation experience in Taiwan.		

報告內容應包括下列各項：

一、參加會議經過

為促進兩岸在綠色營建與行政的經驗交流，彰化師範大學於 2005 年起與北京林業大學開始合作舉辦海峽兩岸綠色行政與生態文明交流研討會，今年由北京林業大學主辦，邀請國內各大學與業界菁英參加，共計台灣參加的大學共有 12 所，業界代表六位，本人亦榮獲邀請，以過去五年帶領學生協助社區與小學進行環境改造的經驗，與對岸相關學術團體交流。

二、與會心得

本次的研討會議程非常緊湊，林業大學的經濟管理學院副院長溫應利教授以「大陸生態保育的發展現狀與趨勢」開場，從巨觀的角度說明近年大陸在生態保育方面所做的努力與國家政策，李鐵錚教授從歷史的縱向面著眼，向大家說明「中國生態文明」，國內學者則是從管理的角度探討「台灣與大陸企業綠色管理發展現況」，以及綠色供應鍊與環境績效。由於研討會的學者背景多元，讓本人的視野能夠從生態設計的面向延伸至環境的經營與管理，受益匪淺！

三、考察參觀活動(無是項活動者省略)

研討會後主辦單位安排有北京市區導覽、頤和園與天津北戴河濕地與植物園參觀，讓首次到北京的我們對園林、濕地與植栽示範園區的經營有初步的概念。

四、建議

在參與此次研討會與相關活動後，發現兩岸在環境經營策略上大方向相同，但細節則各有擅長，大陸因為幅員廣闊，在環境設計上雖然不如台灣精緻，但其對環境生態的積極態度卻讓常流於口號階段的我們自嘆不如，而近年來兩岸聯繫越來越密切，希望政府部門能夠放寬兩地學生交流的管道，讓年輕學生有機會從彼此的經驗中互相學習。

五、攜回資料名稱及內容

研討會論文集（個人收存）

六、其他

無

國科會補助計畫衍生研發成果推廣資料表

日期:2011/10/13

國科會補助計畫	計畫名稱: 模擬水道中水生植物抗流機制之種間差異研究
	計畫主持人: 陳湘媛
	計畫編號: 99-2410-H-216-009- 學門領域: 景觀學

無研發成果推廣資料

99 年度專題研究計畫研究成果彙整表

計畫主持人：陳湘媛	**計畫編號：**99-2410-H-216-009-
計畫名稱：模擬水道中水生植物抗流機制之種間差異研究	

成果項目			量化			單位	備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）
			實際已達成數（被接受或已發表）	預期總達成數(含實際已達成數)	本計畫實際貢獻百分比		
國內	論文著作	期刊論文	0	0	100%	篇	
		研究報告/技術報告	0	0	100%		
		研討會論文	1	1	100%		第十九屆水利研討會
		專書	0	0	100%		
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（本國籍）	碩士生	1	1	30%	人次	兼任助理
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
國外	論文著作	期刊論文	1	1	100%	篇	Shiang-Yuarn Chen, Jen-Yang Lin (2011) Flow resistance adaptation of aquatic macrophytes under different flow velocities. Environmental engineering science, Vol. 28, No. 5, pp. 373-383. (SCI/EI, IF: 1.111).
		研究報告/技術報告	0	0	100%		
		研討會論文	1	1	100%		Shiang-Yuarn Chen, Jen-Yang Lin (2010/7) Morphological Adaptation of Aquatic Macrophytes in

							Response to Different Flow Velocities. 5th International Conference on Environmental Science and Technology (2010 ICEST). Houston, Texas, USA.
		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（外國籍）	碩士生	0	0	100%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)		無					

🟥	**成果項目**	**量化**	**名稱或內容性質簡述**
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標

□未達成目標（請說明，以100字為限）

□實驗失敗

□因故實驗中斷

□其他原因

說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：■已發表 □未發表之文稿 □撰寫中 □無

專利：□已獲得 □申請中 ■無

技轉：□已技轉 □洽談中 ■無

其他：（以100字為限）

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以500字為限）

本研究係從水工模型出發，比較不同物種之水生植物在抗流反應方面的種間差異。在水芹菜的研究中，發現在面對較高流速沖刷時，其生長速度趨緩，莖芽組織變得矮小且柔軟，以增加植物的抗流彈性，此外，其平均根長變短，錨定能力降低，根、莖與芽的生物量也隨之下降。

鑑於適性植物種類可能是多元化的組成，因此本研究另針對不同的水生植物：台灣原生種—柳葉水蓑衣為材料，探討其面對不同流速之抗流機制的種間變化。結果顯示流速增加時，其生長速度、乾鮮重、直徑降低，但是與水芹菜反應不同的是水蓑衣在面對較高流速的環境，其平均根長變長，株高也較高。本研究之成果除可進一步確認適性植生種類或先驅植物種外，亦可瞭解植物在生態工程上可扮演的角色與極限，未來可做為河道植生工程之設計依據。