

• 水利工程 •

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## 挺水植被布局对矩形浅池水体流态的影响

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**摘要:** 研究浅池水体流态水力学特性有助于优化景观池塘、湖泊和湿地等设计, 提高水体连通性, 改善流态。挺水植被与景观水体结合不仅能提高景观美学性, 而且具有改善水体连通性的作用。本文采用2维浅水数值模拟, 探索了植被覆盖变化下的水流沿中轴线槽道进入和推出矩形浅池的水体流态特性, 并进行了基于水力特性的定量分析。研究发现: 植被具有均化浅池水体流速和稳定流动的作用, 非对称流态转变为对称流态; 当植被密度 $\geq 5 \text{ m}^{-1}$ 时, 两侧分离回流区完全消失, 水体连通性最佳, 形成平推流。基于场景模拟后发现, 紧邻入口植被局部覆盖能达到浅池植被全覆盖的改善流态的效果; 进一步分析表明, 浅池流态与中轴线流速及流速梯度分布相关。表征水体流通性的流通水体占比与表征水流调整的无量纲平均流速梯度存在显著的对数相关, 提出的预测模型可用于矩形浅池类景观的水力设计。

**关键词:** 浅池流态; 挺水植被; 浅水模拟; 分离回流区; 水流连通性

**中图分类号:** TV135; P901

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浅池水体被广泛应用于如景观池塘、景观湖泊和景观湿地等景观设计中。在乡村建设、城市规划和生态修复方面, 各种类型的浅池水体扮演着至关重要的角色。例如: 池塘的风水寓意使得其在乡村形成过程中成为村民生活不可或缺的部分<sup>[1-2]</sup>; 湖泊景观在城市规划中代表高品质居住环境<sup>[3-4]</sup>; 池塘景观、湖泊景观、湿地景观是水生态环境修复的重点关注对象, 能够为不同动植物物种提供栖息地, 从而促进当地生态多样性<sup>[5-6]</sup>。然而, 在浅池几何边界和水流相互作用下, 往往会形成大面积分离回水流动, 从而出现死水区<sup>[7-8]</sup>。在死水区, 由于水体与周围水体交换效率极低, 在长时间的化学物理变化作用下, 水质往往较差。因此, 如何通过改变死水回流区尺度及形态来改善浅池水体的流通性, 是提高水质的核心思想。

当前对浅池水体流态的研究以国外居多。Dewals等<sup>[9]</sup>开展了对称型矩形浅池流动水槽模型试验, 采用平面浅水模型进行了数值模拟, 成功模拟出不稳定非对称流态发展。Camnasio等<sup>[8]</sup>基于大量浅池水槽试

验数据发现矩形水池长宽比的变化决定水流形态的变化, 并提出基于浅池长、宽及进出口槽道宽的流态识别概化模型。Peltier等<sup>[10]</sup>基于POD模态分析讨论了2维浅水模型对于矩形浅池流动的适应性, 指出2维浅水模型对浅池水流的模拟具有较好的可靠性。Sabokrouhiyeh等<sup>[11]</sup>采用2维浅水模型研究了矩形和椭圆形浅池水体流态特征, 指出后者对于流态发展比较友好。Valero等<sup>[12]</sup>基于多种紊流模型的3维URANS模态分析研究了矩形浅池流动的不稳定发展过程。Mat等<sup>[13]</sup>采用HECRAS2维浅水模型与原型水库水深流速数据进行验证, 研究了水流条件对水库水动力特性的影响。

将水生植被种植在浅池水体景观中, 能够增加浅池景观的层次感, 提升景观美学<sup>[14-15]</sup>。从水动力学角度来看, 当植被与水体相互作用时, 植被对水体施加阻力, 降低了水流经过植被区的流速。虽然形成类似于固体障碍物的区域, 然而由于植被间有空隙可以通过水流, 其扰流分离作用会大幅度降低。例如, 当水流流经有孔隙率的植被斑块, 尾流不稳定涡旋

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显著滞后于植被斑块,且水流分离效应消失。植被的存在导致植被区和相邻非植被区形成流速差剪切作用,可触发水平方向的周期性Kelvin-Helmholtz涡旋,从而提升相邻水体的交换效率。当前,浅水环境植被水流的水动力特性研究有较丰富的成果,包括淹没植被群落<sup>[16-19]</sup>、滨河植被群落<sup>[20-23]</sup>及斑块植被<sup>[24-25]</sup>。利用现有植被水流知识,可初步实现植被存在下的水体运动机制揭示、水动力参数预测及工程实践。近年来,研究发现,将植被布置在浅池水体中,可减小乃至消除大尺度环流区域。Guo等<sup>[26]</sup>发现对于植被对角线布置的人工湿地,高密度细茎灯草相比于芦蒿和西伯利亚鸢尾条件下的水体流通性更好。Sabokrouhiyeh等<sup>[11]</sup>采用浅水数值模拟结果分析了均匀分布的全池挺水植被对不同几何形态浅池(湿地)流态的影响,发现当植被密度达到一定条件时,浅池水体连通性达到最佳,形成平推流。

由以上可知,水生植被与浅池水体的结合可以改善流态,提升水体连通性。然而,对于景观水体,全池分布的挺水植被可能因遮挡水体视野,影响景观美学。从设计角度出发,景观水体设计时,局部点缀植被能营造独特的层次美感<sup>[27-29]</sup>。为此,将探讨如何利用局部聚集的植被斑块来改善浅池水体流态。首先,建立可模拟挺水植被效应的浅池浅水数值模型,通过比较矩形浅池水槽试验与数值模拟的特征流速剖面,验证数值模型的可靠性。随后,开展不同挺水植被格局的浅池水体流动数值模拟,探索挺水植被格局变化的浅池水体流态发展特性。

## 1 研究方法

### 1.1 浅池流态特征

矩形浅池水体流态特征如图1所示。

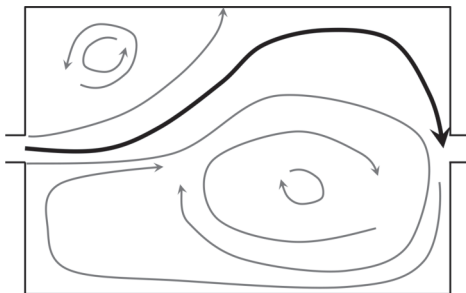


图1 矩形浅池水体流态特征

Fig. 1 Flow pattern characteristics in a rectangular shallow pool

由图1可知:对于对称矩形浅池,当水流沿中轴线从浅池上游进入、下游流出,受浅池几何形态控制,水流在两侧发生分离;又受流动不稳定性影响,形成两个非对称分离回水区,两回水区之间主流区保持流动连通性。随着浅池长宽比( $L/B$ )及孔口比( $b/B$ )

的变化,分离回流区的尺寸会相应调整<sup>[8]</sup>。显然,回水区占比越低,浅池的流动性即流态越好。因此,浅池水体连通性可采用流动水体面积 $A_{cnt}$ 与浅池面积 $A$ 之比 $A_r$ 表征:

$$A_r = A_{cnt}/A = A_{cnt}/(BL) \quad (1)$$

### 1.2 数值模拟方法

由文献<sup>[9,11]</sup>可知,采用浅水方程可以较好地捕捉浅池水流中的分离回流和稳定涡旋水动力学特征,因此采用2维浅水动力学模型Nays2DH对浅池水流运动进行模拟研究。同时,该模型能够很好模拟植被对水流的阻力效应<sup>[30-31]</sup>。

采用水深平均2维水动力学模型对浅池水体流动进行模拟,其数学控制方程描述如下。

连续方程:

$$\frac{\partial h}{\partial t} + \frac{\partial(hU)}{\partial x} + \frac{\partial(hV)}{\partial y} = 0 \quad (2)$$

动量方程:

$$\frac{\partial(hU)}{\partial t} + \frac{\partial(hU^2)}{\partial x} + \frac{\partial(hUV)}{\partial y} = -gh \frac{\partial \eta}{\partial x} + T_x - \frac{\tau_{bx}}{\rho} + \frac{F_x}{\rho} \quad (3)$$

$$\frac{\partial(hV)}{\partial t} + \frac{\partial(hUV)}{\partial x} + \frac{\partial(hV^2)}{\partial y} = -gh \frac{\partial \eta}{\partial y} + T_y - \frac{\tau_{by}}{\rho} + \frac{F_y}{\rho} \quad (4)$$

其中,

$$\begin{cases} T_x = \frac{\partial}{\partial x} \left( \nu_t h \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left( \nu_t h \frac{\partial U}{\partial y} \right), \\ T_y = \frac{\partial}{\partial x} \left( \nu_t h \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left( \nu_t h \frac{\partial V}{\partial y} \right) \end{cases} \quad (5)$$

$$\begin{cases} \tau_{bx} = \rho C_f U \sqrt{U^2 + V^2}, \\ \tau_{by} = \rho C_f V \sqrt{U^2 + V^2} \end{cases} \quad (6)$$

$$\begin{cases} F_x = \frac{1}{2} \rho C_d a h_v U \sqrt{U^2 + V^2}, \\ F_y = \frac{1}{2} \rho C_d a h_v V \sqrt{U^2 + V^2} \end{cases} \quad (7)$$

式(2)~(7)中: $h$ 为水深; $h_v$ 为植被淹没高度(挺水植被 $h_v=h$ ); $\rho$ 为水的密度; $t$ 为时间; $U$ 、 $V$ 为水深平均流速; $g$ 为重力加速度; $\eta$ 为水面高程; $\tau_{bx}$ 、 $\tau_{by}$ 为床面切应力; $C_f$ 为床面阻力系数,由曼宁阻力系数 $n$ 和水深表示,即 $C_f=gn^2/h^{1/3}$ ; $F_x$ 、 $F_y$ 为植被拖曳力; $C_d$ 为拖曳力系数; $a$ 为植被密度; $\nu_t$ 为涡流系数,采用 $k$ - $\varepsilon$ 模型求解:

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (8)$$

$$\begin{aligned} \frac{\partial hk}{\partial t} + U \frac{\partial hk}{\partial x} + V \frac{\partial hk}{\partial y} &= \frac{\partial}{\partial x} \left( \nu_t h \frac{\partial k}{\partial x} \right) + \\ &+ \frac{\partial}{\partial y} \left( \nu_t h \frac{\partial k}{\partial y} \right) + (P_h + P_{kv} - \varepsilon)h \end{aligned} \quad (9)$$

$$\frac{\partial h\varepsilon}{\partial t} + U \frac{\partial h\varepsilon}{\partial x} + V \frac{\partial h\varepsilon}{\partial y} = \frac{\partial}{\partial x} \left( \frac{\nu_t}{\sigma_\varepsilon} h \frac{\partial \varepsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\nu_t}{\sigma_\varepsilon} h \frac{\partial \varepsilon}{\partial y} \right) + \left( C_{1\varepsilon} \frac{\varepsilon}{k} P_h + P_{\varepsilon v} - C_{2\varepsilon} \frac{\varepsilon^2}{k} \right) h \quad (10)$$

其中,

$$P_h = \nu_t \left[ 2 \left( \frac{\partial U}{\partial x} \right)^2 + 2 \left( \frac{\partial V}{\partial y} \right)^2 + \left( \frac{\partial U}{\partial y} \right)^2 + \left( \frac{\partial V}{\partial x} \right)^2 + 2 \frac{\partial U}{\partial y} \cdot \frac{\partial V}{\partial x} \right] \quad (11)$$

$$P_{kv} = C_f^{-1/2} \frac{U_*^3}{h} \quad (12)$$

$$P_{\varepsilon v} = C_{\varepsilon\beta} C_\varepsilon C_\mu^{-1/2} C_f^{-3/4} \frac{U_*^4}{h} \quad (13)$$

式(8)~(13)中:  $C_{1\varepsilon}=1.44$ ,  $C_{2\varepsilon}=1.92$ ,  $\sigma_k=1.0$ ,  $\sigma_\varepsilon=1.3$ ,  $C_\mu=0.09$ ,  $C_{\varepsilon\beta}=3.6$  和  $C_\varepsilon=1.3$  为模型经验参数;  $U_* = \sqrt{\tau_b/\rho}$  为摩阻流速; 根据Nezu和Nakagawa提出的经验公式,  $k=2.07U_*^2$ ,  $\varepsilon=C_\varepsilon k^{3/2}/l$ ,  $C_\varepsilon$  为 0.17,  $l$  为涡流长度尺度, 与水深有关。

通常可采用两种方法计算植被对水流的阻力效应: 一是将植被视为固体边界, 网格在植被表面生成, 然而由于植被杆径较小, 导致网格尺寸非常小, 因此当植被聚集成群落/斑块时, 网格数量极为庞大, 计算效率极低; 二是将植被群落/斑块影响区域视为多孔介质整体, 此时植被型的多孔介质对水流产生拖

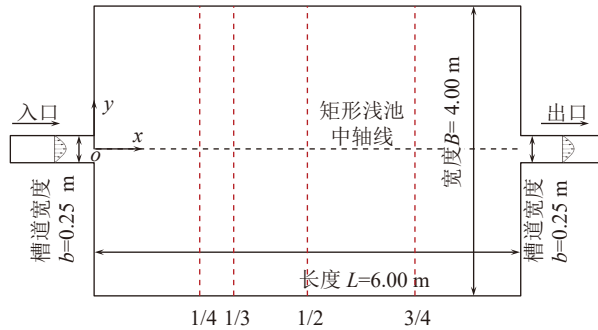
曳力, 即植被阻力, 植被阻力与植被密度呈正比例关系(式(7)), 该多孔介质或植被拖曳力方法对网格质量要求不高, 计算效率高, 被广泛应用于基于浅水方程的植被水动力学和水沙动力学模拟。本文数学模型将植被考虑为一种多孔介质, 植被作用于水流的阻力采用拖曳力法进行模拟, 将拖曳力考虑为源汇项(式(7)的  $F_x$  和  $F_y$ ), 起到调整动量通量平衡的作用。

为求解水流运动方程, 在进水口处, 将流量指定为入流边界条件, 将其均匀地转换为槽道断面的纵向速度剖面, 横向速度为 0。在出水口处, 指定水深作为流出边界条件。在侧壁处, 流速、湍流动能和耗散率均采用无滑移条件。采用有限差分法对结构网格上的控制方程进行离散化。采用 3 次插值伪粒子法作为 3 阶数值格式, 可得显式数值解。

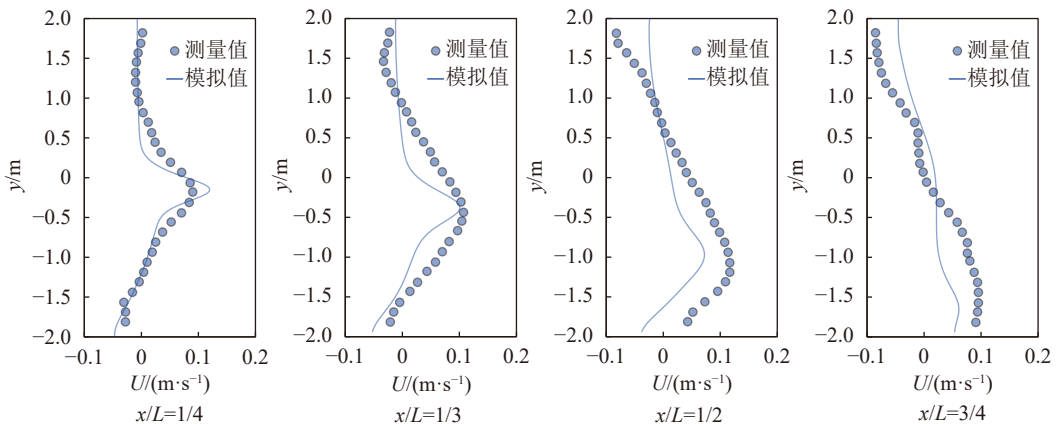
## 2 结果与讨论

### 2.1 模型验证

为开展不同植被分布情景下的矩形浅池流态模拟, 对浅水数值模型进行验证, 用于验证的试验数据来自 Dewals 等<sup>[9]</sup> 试验的矩形浅池水槽试验, 结果如图 2 所示。



(a) 矩形浅池几何形态布置与验证流速剖面位置



(b) 不同位置流速剖面测量值与模拟值对比

图 2 数值模型验证

Fig. 2 Validation of numerical model

矩形浅池物理模型采用长 $L$ 为6.00 m,宽 $B$ 为4.00 m的矩形水槽进行模拟(图2(a));水槽底部水平,材质为光滑PVC塑料板,曼宁系数 $n=0.02$ ,入口和出口沿中轴线分别位于矩形浅池两侧,槽道长度为1.00 m,宽度为0.25 m。采用沿轴线方向不同位置的横向流速测量值进行验证,具体选取 $x=1.5$ 、2.0、3.0和4.5 m,对应 $x/L=1/4$ 、 $1/3$ 、 $1/2$ 和 $3/4$ 。在模型设置方面,分别适当将入口和出口延长至2.00 m,以确保边界效应不影响浅池水流运动。经网格敏感性测试,发现流向和横向网格宽度大小分别为 $dx=0.01L$ 和 $dy=0.015B$ ,流场收敛且流态达到稳定。

图2(b)为数值模拟与测量的对比结果。从图2(b)可看出,本文模型在矩形浅池沿流向不同位置的流速剖面模拟结果较为可靠。模拟流速分布正确反映了矩形浅池流动的不稳定性特征,即水流从入口进入,主流逐渐与中轴线偏重合( $x/L=1/4\sim 1/3$ )到逐渐偏离中轴线( $y=0$ ),并发展到浅池的一侧( $x/L=1/2\sim$

$3/4$ ),成功反映出长宽比一定条件下矩形浅池水流流态不稳定发展的水动力学现象。同时,大多数流速剖面模拟误差较小,如: $x/L=1/4$ 、 $1/3$ 和 $4/3$ ,剖面流速平均误差为5.1%~8.9%;仅当 $x/L=1/2$ 时,剖面最大流速模拟值明显小于预测值,平均误差约为15.3%。由此可知,本文模型在定性和定量方面均具有较大可靠性,可用于不同工况的模拟预测。

## 2.2 挺水植被格局流态模拟

为研究植被分布对浅池流态的影响,开展不同场景的植被覆盖的浅池水流数值模拟,浅池为模型验证水槽。本文采用了5种植被覆盖情景,如图3所示。

从图3可知,对于全域完全覆盖情景,通过模拟植被密度变化的流态演化来探究最优流态(即平推流)的临界植被密度;然后,保持临界植被密度探索植被覆盖度变化下的流态演化规律,建立预测模型,为利用植被改善浅池流态提出建议。

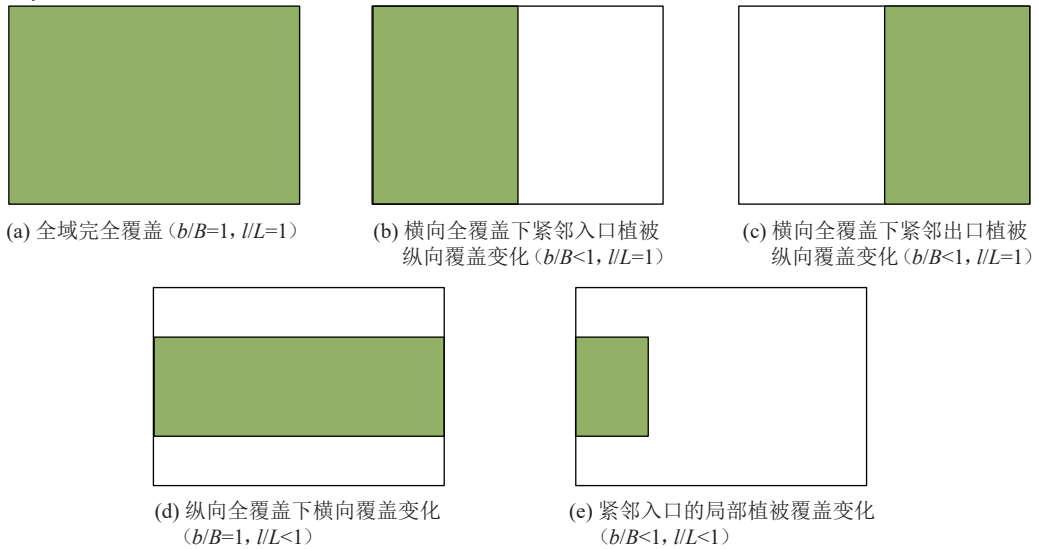


图3 挺水植被分布模拟场景

Fig. 3 Emergent vegetation layout scenarios in the rectangular shallow pool for numerical modeling

### 2.2.1 植被密度影响

当浅池完全覆盖挺水植被时,植被密度是影响水流流态演化的关键要素。Sabokrouhiyeh等<sup>[11]</sup>通过浅水模型发现当植被密度高于 $1.50\text{ m}^{-1}$ 时,矩形浅池回流区消失。图4为挺水植被密度变化下的矩形浅池流态演化。由图4可知,无植被时( $a=0$ ),矩形浅池流态呈现不稳定状态,主流偏离中轴线附着一侧壁面,形成一对非对称分离回流区,回流区面积比约为83.2%。从流速云图和矢量上看,主流流速大,且沿程衰减减小,形成流速较大的主流通道。

植被分布于浅池时,浅池流速大幅降低,流态发生显著变化。当植被密度较小时,即植被密度

$a=0.25\text{ m}^{-1}$ (植被杆径为0.005 m,每平方米50株),尽管回流区存在,但是流态逐渐形成稳定解,即主流沿中轴线分布,两侧分离回流区呈对称分布。随植被密度增大,分离回流区面积逐渐减小,浅池水流连通性大幅提升。当植被密度 $a>4.00\text{ m}^{-1}$ 时,两侧分离回流区几乎完全消失,该植被密度明显高于Sabokrouhiyeh等<sup>[11]</sup>提出的 $a=1.50\text{ m}^{-1}$ ;通过与该研究对比发现,当 $a>1.50\text{ m}^{-1}$ 时,流通性变化虽然较小,仍然随着植被的密度增大而增大。因此,当 $a\geq 5.00\text{ m}^{-1}$ 时,分离回流区完全消失,植被生长在浅池流态塑造上起着稳定流动的作用,未出现不稳定解。

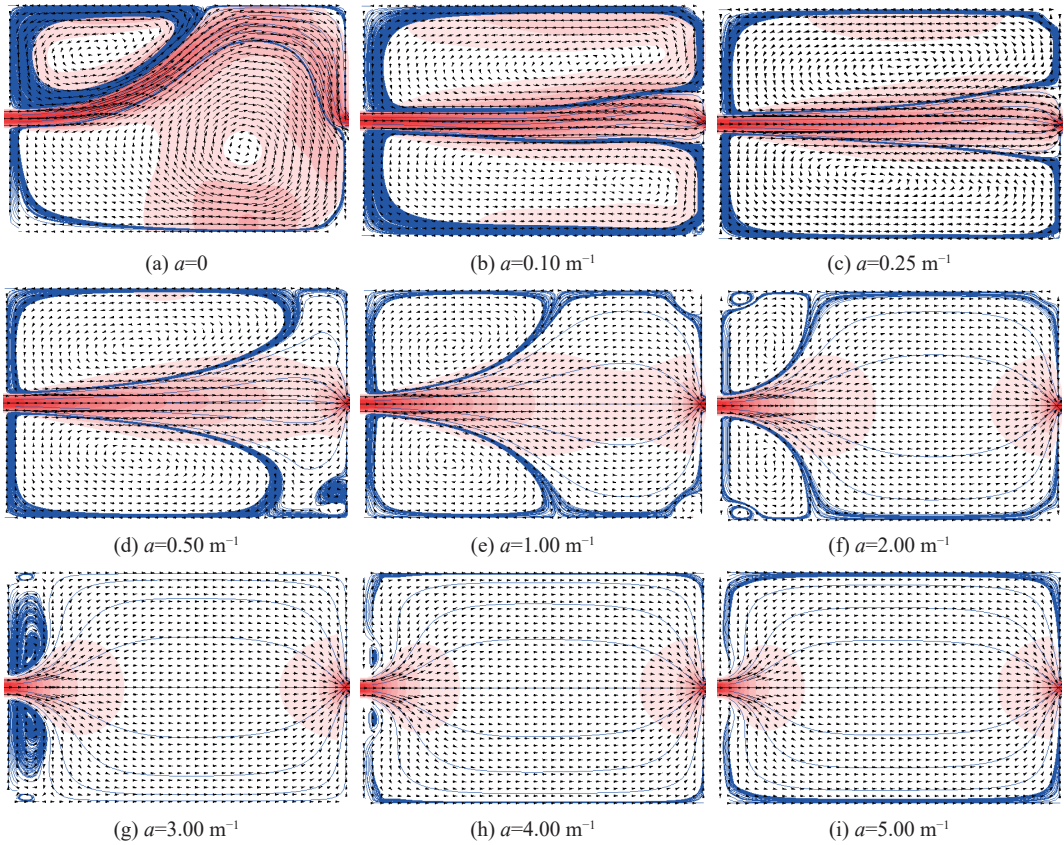


图 4 矩形浅池全覆盖挺水植被不同密度下流态演化

Fig. 4 Flow pattern evolution in the rectangular shallow pool fully covered by emergent vegetation of different density

### 2.2.2 植被覆盖度的影响

浅池流态受到挺水植被覆盖度的影响如图5所示。图5中,绿色虚线范围代表植被区域,\*代表植被紧邻出口覆盖场景,下同。首先对紧邻入口覆盖场景进行分析(图5(a)~(f))。当覆盖度为0时,浅池流态呈现非稳定结构,含有非对称分离回流区。随着植被覆盖度的降低,流态开始发生变化。当维持植被密度 $a=5.00\text{ m}^{-1}$ 时,全覆盖条件下无分离回流区产生,流态为平推流。当覆盖度降低至 $l/L=1/8$ 时,矩形浅池入口两个边角形成两个较小且尺度相近的对称分离回流区。随着覆盖度进一步降低,流态的对称性和稳定性开始被破坏。当覆盖度达到 $l/L=1/16$ 时,主流向一侧(上侧)发展并附着,下分离回流区面积略大于上回流区。最终当植被完全消失时,下回流区完全发展至出口,同时挤压浅池另一半区域,形成非对称分离回流区非稳定流态。通过比较 $l/L=1/16$ 和 $l/L=0$ 主流特征可以发现,后者主流流速显著低于前者,后者的横向梯度较大,这也是导致非稳定流态的原因。

保持紧邻出口植被覆盖,从入口端逐渐降低覆盖度,模拟矩形浅池流态的发展(图5(g)~(i))。当

植被覆盖度不为0时,矩形浅池两侧产生了沿中心轴对称的主要分离回流区和边角次要回流区。随着植被覆盖度的减小,主次分离回流区面积同步增大。并且,因前区覆盖度变化形成的主次两组分离回流区流态与之前的流态存在明显不同,当植被密度变化或植被覆盖度沿后区减少时,仅形成一组对称或非对称分离回流区。后区植被覆盖时,即使较大流速水流从入口槽道以射流形态进入矩形浅池,分离回流区仍保持对称分布,表明植被对于分离回流结构具有稳定作用。

保持植被纵向覆盖度和植被密度不变( $a=5.00\text{ m}^{-1}$ ),研究了横向覆盖度变化的流态演化,结果如图6所示。图6(a)~(c)为纵向覆盖度 $l/L=1$ ,图6(d)~(f)为纵向覆盖度 $l/L=1/4$ 。由图6可以发现,矩形浅池流态不随纵向覆盖度场景不同而发生明显变化,这表明植被紧邻入口的局部分布能有效起到改善浅池流态的作用。当横向覆盖度减小为 $b/B=1/2$ (图6(a)),流态基本维持平推流状态,仅在浅池出口端两个边角形成了两个较小的分离回流区。这主要是由于沿边壁形成了两条流速较大的主流带,触发了边角流动分离,与植被横向完全覆盖情景的

流动在机制上存在较大差异。然而,当纵向覆盖度为 $l/L=1/4$ 时(图6(d)),出口端分离流态基本消失。其原因在于植被的纵向缩短造成主流带在后区流速降低,呈现主流带不连续性。当 $b/B=3/8$ 时,随着前区主流带流速增大,在边角两侧形成了一对

分离回流区,并随横向覆盖度的进一步减小,分离回流区尺寸亦出现成长趋势。基于上述分析可以推断:当水流进入浅池,在局部植被流速均化作用下,水流分离程度显著降低,从而使水流连通性提升。

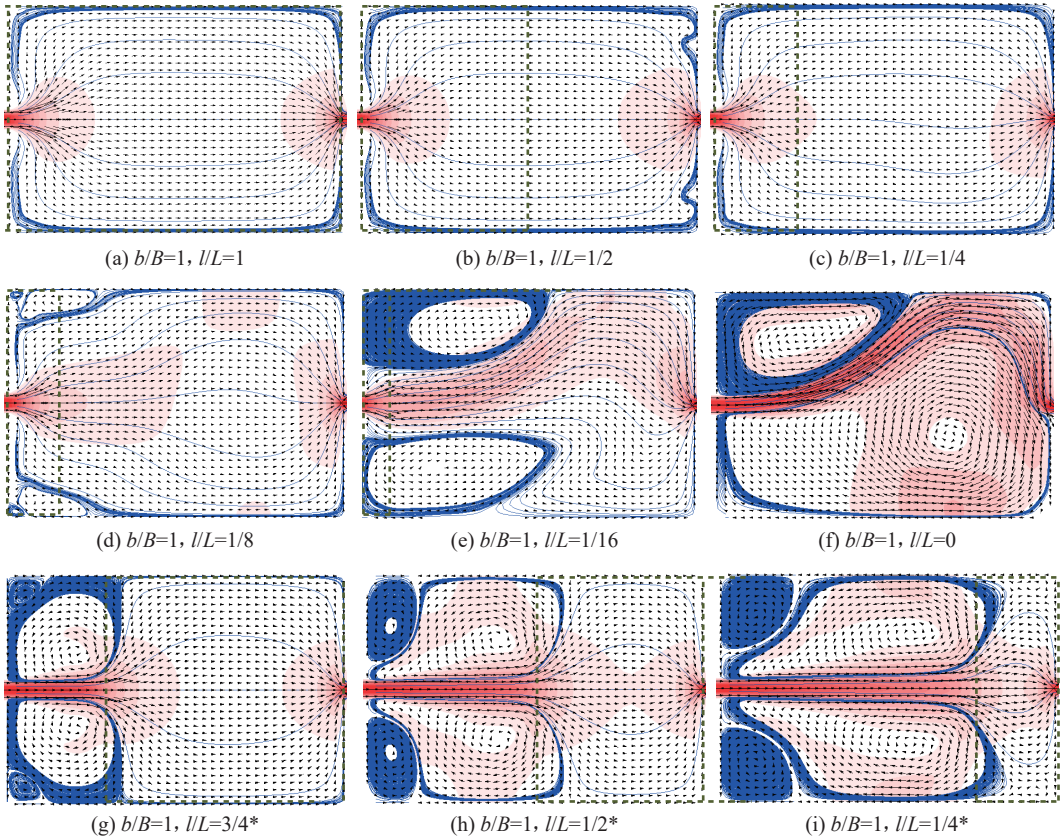


图5 单一密度下( $a=5.00\text{ m}^{-1}$ )矩形浅池植被覆盖度沿纵轴向变化的流态演化

Fig. 5 Flow pattern evolution in the rectangular shallow pool with the longitudinal variation of emergent vegetation coverage under  $a=5.00\text{ m}^{-1}$

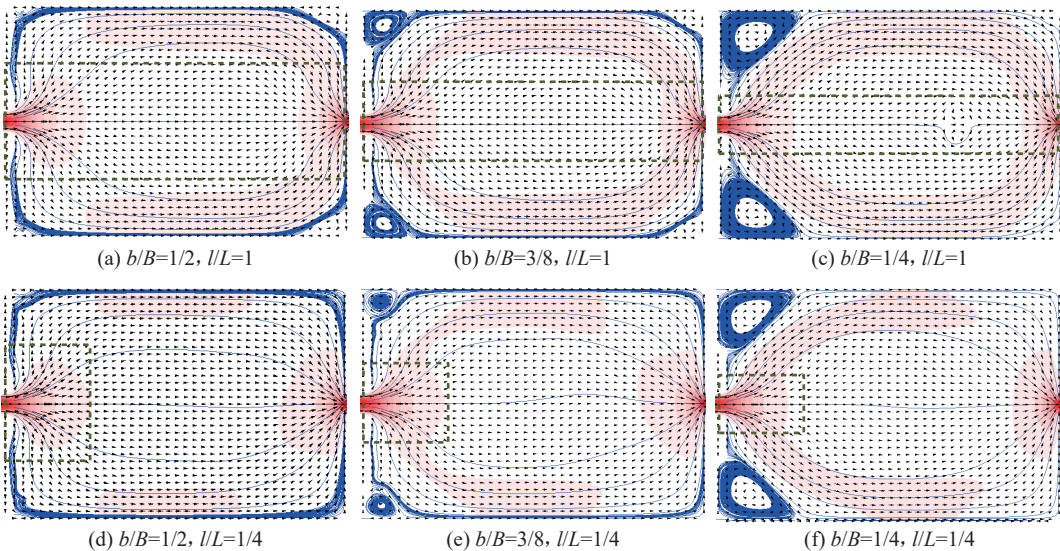


图6 单一密度下( $a=5.00\text{ m}^{-1}$ )矩形浅池植被覆盖度沿横向变化的流态演化

Fig. 6 Flow pattern evolution in the rectangular shallow pool with the transverse variation of emergent vegetation coverage under  $a=5.00\text{ m}^{-1}$

### 2.3 流速分布与水流连通性

由矩形浅池植被分布变化时的流态响应结果分析可知,浅池植被覆盖主要通过降低入口出口轴线流速,使全池流速更加均匀。随着流速的均化,分离回流区逐渐缩小,在一定条件下回流区完全消失,形成平推流,即连通面积与浅池面积之比为 $A_f=1$ (式(1)),此时,水流连通性达到最佳。图7为植被分布变化条件下的中轴线流速分布与流速梯度沿程变化。由图7可知,全覆盖情况下(图7(a)),随着植被密度的增大,

流速沿程迅速降低,在较短的距离里达到平衡,同时流速梯度(绝对值)随之由靠近入口处的较大值沿程迅速调整为0附近。当 $a$ 为 $2.00\sim 5.00\text{ m}^{-1}$ 时,流速及流速梯度曲线较为接近,水流分离回流区呈现逐渐缩小至消失的趋势,表明植被密度改善流态是一个渐变的过程,不存在突变现象。然而,当植被密度 $a=0$ 时,中轴线流速也呈现出快速降低调整态势,这是两侧分离回流区不稳定发展导致的结果;但对主流弯曲轴线进行分析后可知,沿程流速仍呈现逐渐降低趋势。

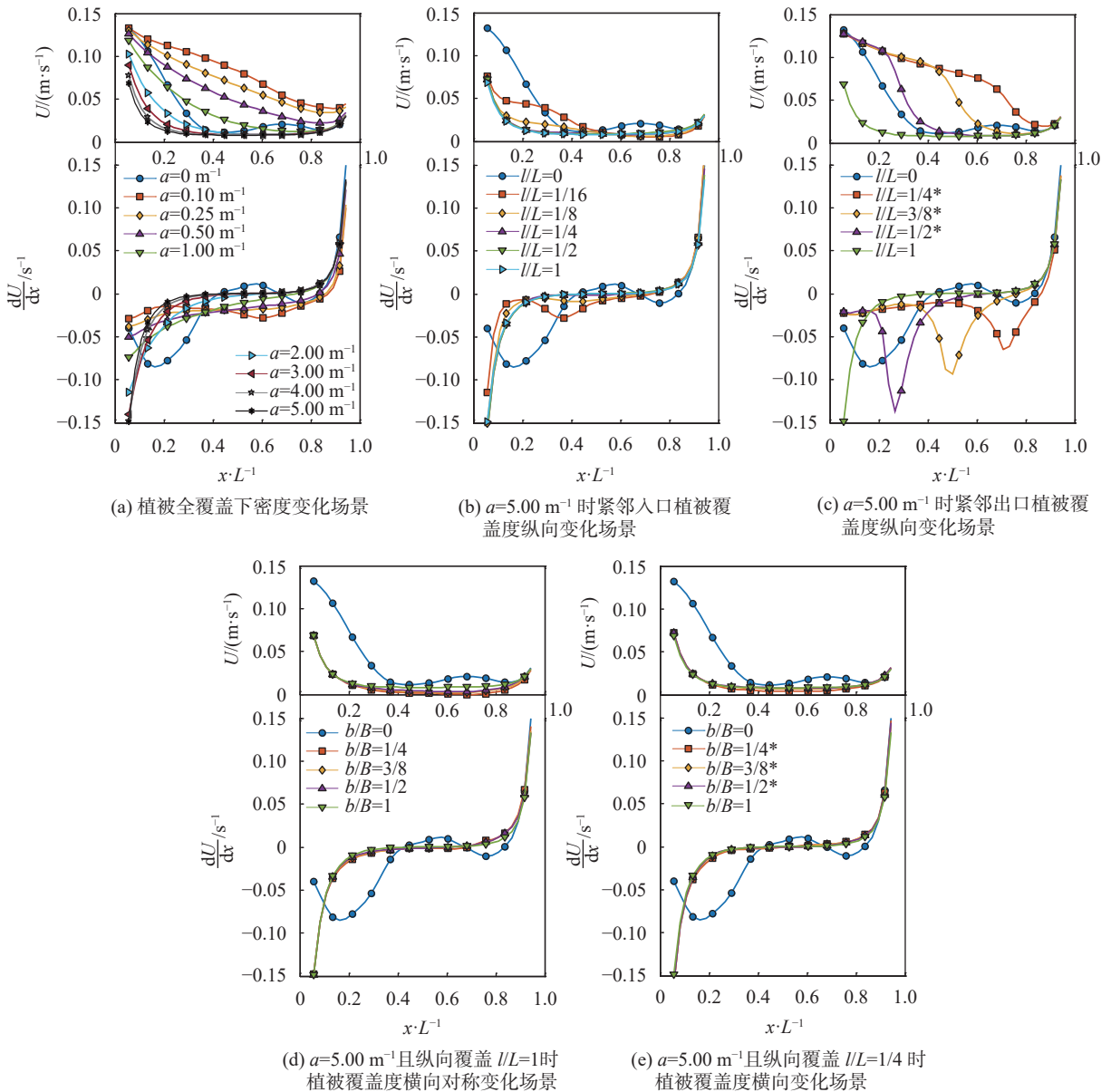


图7 不同植被覆盖场景浅池中轴线纵向流速 $U$ 与流速梯度 $dU/dx$ 沿程变化

Fig. 7 Distribution of longitudinal velocity  $U$  and velocity gradient  $dU/dx$  along the middle axis

保持植被密度不变( $a=5.00\text{ m}^{-1}$ ),对于紧邻入口植被覆盖场景(图7(b)、(d)、(e)),流速和流速梯度沿程变化呈现一定的相似性。当 $l/L\geq 1/4$ 时,流速及其梯度的曲线几乎不随覆盖度的变化而变化,这是由

于水流在较长植被作用下,经过充分调整达到了平衡状态,而植被沿轴向加大覆盖对流速无显著影响,这与水流在滨河植被内部调整的机理和规律保持一致<sup>[20,32]</sup>。同时,植被覆盖的横向变化对轴向流速及梯

度沿程分布无显著影响,但是植被覆盖度在横向上减小,在浅池两个边角会产生分离回流区(图6(c)、(f)),表明流速在中轴线上的调整不是流态完全发展为平推流的充分条件。而对于紧邻出口覆盖场景(图7(c)),随植被覆盖度的减小,流速由刚开始缓慢降低转变为植被区内的快速调整,相应地,流速梯度(绝对值)由非植被区(水池前区)的较小值(接近0)转变为植被区的先增大再减小的过程。前区非植被区接近于0的流速梯度可以解释为何浅池流态始终存在分离回流区,而后区植被区的流速快速降低或流速梯度负向增大很好地说明了对称分布分离回流区的发展。

通过分析可以发现,分离回流区大小与水体进入浅池后的流速调整相关,当流速快速调整均化时,分离回流区面积减小,连通水体占比增加,一定条件下增加至100%,即平推流。因此,可定义连通水体与矩形浅池面积比 $A_r$ 表征水体的连通性,分析 $A_r$ 与流速梯度的相关性。水体进入浅池在植被作用下的流速调整区,流速平均梯度为 $\Delta U/L_a$ ,其中, $\Delta U$ 为调整区的流速差, $L_a$ 为调整区的长度。利用浅池平均流速 $U_m=Q/(hB)$ 与长度 $L$ 进行无量纲化,即可得到描述浅池水流调整的特征变量 $(\Delta U U_m^{-1})/(L_a L^{-1})$ 。由图8可知:当浅池含植被覆盖时, $A_r$ 与 $(\Delta U U_m^{-1})/(L_a L^{-1})$ 存在较好的相关性;不含植被覆盖的场景,结果则明显偏离该模型。该模型可以用于矩形浅池水体连通性的量化预测,可用于矩形浅池如公园水池、城市湖泊及湿地等景观水力设计。

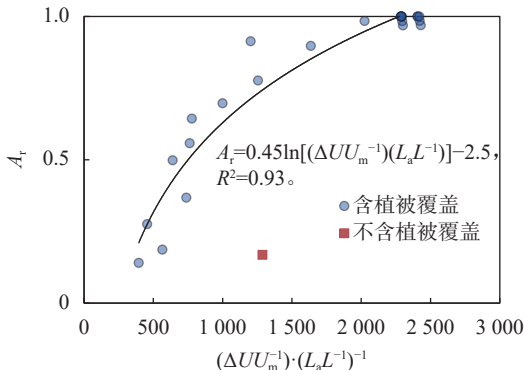


图8 水流连通面积占比 $A_r$ 与浅池中轴线无量纲平均流速梯度 $(\Delta U U_m^{-1})/(L_a L^{-1})$ 的关系

Fig. 8 Dependency of water connectivity area  $A_r$  proportion on dimensionless mean velocity gradient  $(\Delta U U_m^{-1})/(L_a L^{-1})$  for the middle transect

### 3 结论

浅池水体如池塘、湖泊和湿地,由于其几何边界特征的特殊性,具有独特的水力学特性。通过合理的设计,能够改善浅池水体的流态,降低分离回流的面

积,提高水体的连通性。本文充分利用了植被均化流速,起到稳定浅池水体运动的作用,采用2维浅水数值模拟,探索了植被分布变化下的矩形浅池水体流态特性,主要结论如下:

1) 基于水槽试验流速剖面验证,2维浅水模型能可靠地模拟浅池水体流动,成功模拟出主流附着于一侧边墙、两侧非对称发展的分离回流区的流态。

2) 植被具有均化浅池水体流速、稳定流动的作用。模拟结果表明植被存在使水流从非对称流态发展为对称流态;并且,随着植被密度的增大,两侧对称分离回流区面积逐渐减小,当密度为 $a=5.00 \text{ m}^{-1}$ 时,回流区完全消失,形成平推流。

3) 进一步分析植被空间覆盖变化的流态发现,一定植被密度条件下( $a=5.00 \text{ m}^{-1}$ ),将植被设置为紧邻入口局部覆盖,可实现基于局部植被覆盖下的最佳流态,即回流区消失。

4) 通过分析水体流通性表征参数即流通水体面积占比 $A_r$ 与表征水流调整的无量纲平均流速梯度 $(\Delta U U_m^{-1})/(L_a L^{-1})$ 之间的关系,发现两者存在显著的对数相关性( $R^2=93\%$ ),可采用对数模型进行描述,可用于矩形浅池类景观的水力设计。

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## Influence of Emergent Vegetation Layout on Flow Pattern in a Rectangular Shallow Basin

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### Abstract:

**Objective** Shallow basins, varying in natural and artificial forms, are prevalent in urban and rural areas. They play critical roles in ecology, water resource management, environmental protection, and enhancing landscape aesthetics. For instance, wetlands and ponds become hubs for fish, plants, and plankton; reservoirs store water for agricultural irrigation, drinking, and industrial uses; constructed wetlands and ponds facilitate the removal of pollutants and harmful chemicals; and landscape ponds and lakes, adorned with vegetation, increase the real estate value. Prior research has extensively debated shallow basins' functions and influencing factors from these perspectives, employing methods such as field investigations, aerial remote sensing, physical experiments, large-scale modeling, and surveys. Despite achievements in addressing individual perspectives, a comprehensive, systematic study covering multiple aspects remains lacking. The hydrodynamics within a shallow basin dictate its efficiency in treatment, water exchange rate, and the ratio of stagnant water areas. Hence, numerous strategies have been employed to enhance the hydraulic performance of shallow basins. Altering the aspect ratio, for example, can adjust the stagnant water ratio, enhancing or impairing the basin's hydraulic function. Elliptical basins are recognized for their superior hydraulic performance over rectangular ones. In addition, aquatic vegetation, whether emergent or submerged, is acknowledged to enhance the hydraulic performance of shallow basins by equalizing flow velocity as water spreads laterally upon entering the basin. From the landscape design perspective, strategically interspersing aquatic vegetation is believed to elevate the aesthetic appeal of the basin and its vegetation. However, a detailed quantitative analysis of the impact of vegetation's spatial distribution remains unexplored, leaving room for optimizing vegetation layout for hydraulic efficiency and landscape beauty.

**Methods** This study focuses on how various spatial arrangements of emergent aquatic vegetation affect the hydraulic performance of shallow basins, aiming to identify an optimal vegetation design. The basin shape is limited to a rectangle with a fixed width-to-length ratio (width: 4 m and length: 6 m), and the dimensions of inlet and outlet were standardized. The depth-averaged Reynolds Averaged Navier–Stokes equations with the  $k-\varepsilon$  turbulence model are applied to simulate water movement within the shallow basin. Experimental data from existing literature, specifically velocity distributions, are initially utilized for model validation. In addition, the study examines the independence of results from grid size to ensure modeling consistency. Based on the validation of the velocity profile from flume tests, the two-dimensional shallow water model can reliably simulate flow within shallow pools and successfully capture the flow patterns of circulations where the main stream adheres to one sidewall while developing asymmetrically on both sides. Incorporating a vegetation drag term into the momentum equations allows the simulation of flow dynamics influenced by emergent vegetation.

**Results and Discussions** In order to examine the impact of vegetation's spatial distribution on flow patterns within a shallow basin, five vegetation distribution scenarios are conceptualized: 1) complete coverage, 2) lateral full coverage with variable longitudinal partial coverage downstream of the inlet (LFVLPI), 3) lateral full coverage with variable longitudinal coverage downstream of the outlet (LFVLPO), 4) longitudinal full coverage with variable symmetrical lateral partial coverage (LFVSLP), and 5) localized vegetation coverage near the inlet. In the case of complete coverage, the influence of vegetation density is assessed to identify the threshold at which a plug flow pattern (or absence of dead water zones) emerges. The findings indicated a transition from bare to vegetated conditions, where an asymmetrical flow pattern featuring two distinct circulation sizes (or dead water zones) evolves into a symmetrical flow pattern with similar circulations. As vegetation density reaches a threshold of  $5 \text{ m}^{-1}$ , circulations vanish, yielding a plug flow pattern. This density threshold surpasses those reported in previous studies. Upon reaching this

critical vegetation density, the impact of various spatial distributions of vegetation, with constant density, on flow patterns is explored. For LFVLP, reducing the vegetation coverage ratio from full coverage does not alter the plug pattern until the ratio diminishes to 1/8, at which point small circulations appear near the basin's inlet. In contrast, with LFVLP, circulations persist, characterized by a pair of large cells and a pair of small corner cells. For LFVSLP, only small corner circulations form. As lateral coverage lessens, these corner cells scarcely enlarge until vegetation is absent. The minimal local vegetation coverage necessary for establishing a plug flow pattern occurs when the lateral coverage ratio is 1/2 and the longitudinal ratio is 1/4. Further analysis of the center-axis longitudinal velocity and its gradient along the basin's length is conducted to indicate the formation of the plug flow pattern in response to hydraulic adjustments due to the introduction of vegetation. The evolution of circulation zones is closely linked to the rate of longitudinal velocity adjustment upon water entering the basin. A rapid local decrease in velocity leads to a swift global homogenization, significantly reducing the velocity shear or adverse pressure gradient between the center and surrounding zones. Consequently, introducing vegetation can eliminate flow circulations or dead water zones if it causes a rapid velocity decrease in the area following the inlet. In addition, examining the relationship between the proportion of the circulating water body area  $A_r$  and the dimensionless mean velocity gradient  $(\Delta U U_m^{-1})/(L_a L^{-1})$ , which demonstrates flow adjustment, revealed a significant logarithmic correlation between the two metrics ( $R^2=93\%$ ).

**Conclusions** The results demonstrate that emergent vegetation can be applied to suppress flow circulation in shallow basins, which improves shallow basin flow pattern. Its mechanism is identified that the porous vegetation can effectively uniformize the flow velocity transversely after the flow enters into the basin. The spatial distribution of the vegetation and its density in combination play a significant role. A logarithmic model  $A_r=0.45\ln[(\Delta U U_m^{-1})/(L_a L^{-1})]-2.5$  is found to offer guidance for the hydraulic design of rectangular shallow basins with selective vegetation distribution.

**Key words:** shallow basin flow pattern; emergent vegetation; shallow water simulation; flow circulation area; water connectivity efficiency

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