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Geometry effect of irrigation storage basin on particles removal efficiency: A computational fluid dynamics study

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Abstract

Drip irrigation requires the use of high quality water to avoid emitters clogging and the wear of hydraulic pumps and sand filters. Investing in an irrigation storage basin is not only beneficial to meet crop water requirements but also to remove naturally suspended solids by sedimentation. However, the design and sizing of an irrigation storage basin is usually based only on irrigation water needs and plant area without taking into consideration that the shape and size of the basin can also have an effect on the removal efficiency. Moreover, storage volume can be achieved by different combinations of length, width and depth. The present paper studies the effect of irrigation storage basin geometry on its performance in settling down suspended sediments. The methodology adopted in this study is based on the computational fluid dynamics using ANSYS Fluent. Specific experimental results taken from the literature are used to confirm the reliability of the numerical simulations to describe the flow field. First, a parametric study is executed in order to identify the effect of each basin dimensions. Then, trap efficiency is calculated for twenty basins having the same capacity of storage and different geometries in order to select the optimal dimensions. Results show that the removal efficiency is very sensitive to basin size, especially to its depth and length. Nevertheless, for a specific capacity of storage, two different dimensionless parameters can be used to select the optimal size: the length to depth ratio and the length to width ratio. In cases, where the depth value is required due to soil type or land surface, the second ratio can be used.

Keywords: drip irrigation, irrigation storage basin, removal efficiency, computational fluid dynamics

1. Introduction

Drip irrigation is a method of irrigation with high frequency application of water in and around the root zone of plants (crop) and consists of a network of pipes with suitable emitting devices [10]. However, this irrigation method requires the use of high quality water to avoid emitters clogging, damage of hydraulic pumps and sand filters [4,13,15]. Emitters can be clogged either by suspended solids or by biofilm development inside pipes and emitters [2]. To overcome the problem, chemical treatments in conjunction with filtration equipment have been developed in order to improve the quality of irrigation water. Moreover, an important portion of sediment can be removed by gravity in a large basin, called irrigation storage basin used for preserving water. The design and sizing of this basin only requires the capacity of storage desired to meet crop water requirements without taking into consideration settling basin sizing criteria such as flow velocity, sediments proprieties and geometry parameters of the basin. Therefore, removal efficiency of this basin is insufficient to justify the construction and maintenance costs. However, more than 80% of suspended solids can be settled naturally by sedimentation [20].

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So far, many researches interested in emitters clogging study either the quality of irrigation water effect or the emitter structural design effect [7, 11, 12, 14, 21]. However, optimization of irrigation storage basin sizing in order to improve its removal efficiency has not been reported yet.

The computational fluid dynamics (CFD) approach has been used to optimize different process designs and can be used to partially replace expensive experiments. The flow in sedimentation tanks is generally turbulent and treated as a multiphase flow. Different turbulence and multiphase models have been used in the modeling of sedimentation tanks [16]. This knowledge has been particularly used to study the flow patterns and removal efficiency in settling basins for sewage water [3, 18, 19] and potable water treatment [9]. However, in the literature, there are not many works on CFD modeling of settling basins used in an irrigation network. Thus, the objective of the present paper is a three-dimensional numerical simulation of flow behavior in an irrigation storage basin using a CFD method in order to investigate the geometry effect of the basin on its removal efficiency. First, a parametric study will be performed in order to enhance the understanding of the influence of each geometry parameter separately (length, width and depth). Then, the performance of twenty basins having the same capacity of storage and different dimensions will be studied in order to find dimensionless parameters that can aid the design of irrigation storage basins.

2. Materials and methods

2.1. Physical problem

2.1.1. Irrigation basin sizing method

During extended dry seasons, irrigation basins are used to preserve water needed to irrigate crop areas during appropriate days of autonomy. The storage capacity of an irrigation basin can be expressed as follows:

$$V = \mathrm{IN} \cdot \delta \cdot A, \tag{1}$$

where V is the volume of the basin, IN is the irrigation water need, δ is the number of autonomy days, and A is the crop area. The irrigation water need is defined as a difference between the crop water need and the effective rainfall, i.e., the rainfall that is effectively used by the plants. In this study, the irrigation water need is determined for the month of July based on the following formula:

$$\mathrm{IN} = \frac{K_c \cdot K_r \cdot \mathrm{ET}_0 - P_e}{E_a}, \tag{2}$$

where ET_0 is the reference crop evapotranspiration calculated by the Penman-Monteith formula and climatic parameters, K_c is the crop coefficient, K_r is the evaporation reduction coefficient dependent on the cumulative depth of water depleted (evaporated) from the topsoil, P_e is the effective rainfall estimated by the USDA SCS method (USDA 1967), and E_a is the water application efficiency.

An irrigation basin was dimensioned in order to irrigate three hectares of citrus fruit for five days ($\delta = 5$). Technical information needed to calculate the citrus water need in Gharb region of Morocco is summarized in Table 1. The capacity of storage calculated by (1) and (2) is 750 m^3. The density of carried fluid is taken to be 998.2 $\mathrm{kg/m}^3$, the discharge is 30 m^3/h, the mass sediment flow rate is 0.081 kg/s and the sediment density is 2 000 $\mathrm{kg/m}^3$. Influent suspensions have generally a polydispersity size. In this study, the grain-size distribution is

Table 1. Technical information for the calculation of the citrus water need

K_c	K_r	ET_0 [mm/day]	P_e [mm]	E_a [%]	A [ha]
0.95	0.72	6.5	0.2	90	3

determined using the Rosin-Rammler function. The minimum diameter is taken to be 30 μm, the median is 50 μm, the maximum diameter is 100 μm and the spread parameter is 3.5.

2.1.2. Test configurations

Twenty irrigation basins having the same capacity of storage and different forms are tested to identify the optimal one in terms of removal efficiency. The specific design of an irrigation basin is shown in Fig. 1. The basin is characterized by a trapezoidal cross section. The top surface represents the free surface of the basin. In this study, we assume that the inlet and outlet are placed in the middle of the top surface. Configurations of tested geometries are presented hereafter in Table 2. On the other hand, a parametric study is performed in order to examine the effect of irrigation basin dimensions on flow patterns and the removal efficiency. First, the basin width effect is investigated in an irrigation basin of 15 m in length, 3 m in depth and its width varied from 10 to 15 m. Then, numerical simulations focused on the length are carried out in an irrigation basin of 7 m in width, 3 m in depth and its length varied from 10 to 21 m. Finally, the basin depth effect is studied in an irrigation basin of 15 m in length, 7 m in width and its depth varied from 2.5 to 5 m.

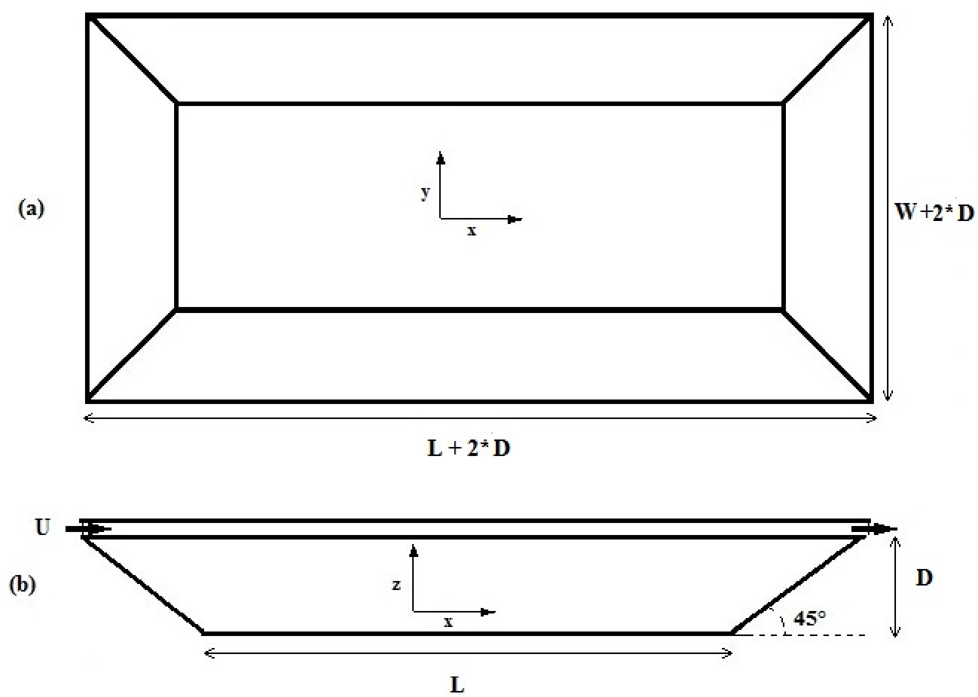

Fig. 1. Specific design of an irrigation storage basin: a) top view, b) side view

Table 2. Trap efficiency of twenty basins with different sizes

	length [m]	width [m]	depth [m]	capacity of storage [m^3]	trap efficiency η [%]
Case 1	20	14.98	2.0	750	100.00
Case 2	21	14.25	2.0	750	100.00
Case 3	24	12.37	2.0	750	100.00
Case 4	18	16.69	2.0	750	98.78
Case 5	24	8.75	2.5	750	99.80
Case 6	21	10.18	2.5	750	97.89
Case 7	18	12.03	2.5	750	96.20
Case 8	24	6.15	3.0	750	97.00
Case 9	21	7.29	3.0	750	96.00
Case 10	18	8.76	3.0	750	95.00
Case 11	15	10.72	3.0	750	90.38
Case 12	12.72	12.72	3.0	750	88.00
Case 13	12.58	9.58	3.5	750	86.93
Case 14	18	5.34	3.5	750	95.00
Case 15	15	7.86	3.5	750	92.40
Case 16	13	9.24	3.5	750	88.46
Case 17	21	4.13	3.5	750	87.00
Case 18	15	5.52	4.0	750	86.93
Case 19	12	7.29	4.0	750	87.82
Case 20	10	8.89	4.0	750	86.00

2.2. Numerical modeling

The flow behavior in an irrigation storage basin can be studied as a multiphase flow. Two different approaches are available to simulate multiphase flow: the Euler-Euler approach and the Euler-Lagrange approach. In practice, the Euler-Lagrange approach is only valid for low particle volume fractions, generally less than 10–12 % [5]. Moreover, this method provides more information on trap efficiency and particle deposition location. The irrigation water entering the basin is characterized by a low sediment volume fraction, which does not exceed 10 %, so in this study, the Lagrangian method is applied using the discrete phase model (DPM). The sediment concentration is typically small; the effect of discrete phase on the continuous phase is negligible (one way coupled). Regarding the Eulerian phase, the fluid flow is simulated by solving the Reynolds-averaged Navier-Stokes equations. The SST k–ω model is applied as a turbulence closure, since this model is better at predicting low Reynolds number flows.

ANSYS Fluent 14.0 software is used to simulate the flow behavior in the irrigation storage basin and to predict the trap efficiency of different irrigation basin geometries used in this study. The generated mesh is depicted in Fig. 2. A grid independent study was conducted for all irrigation basins tested in this study in order to ensure the accuracy of the results. The grids used in this study were composed of 950 000 to 1.25 million tetrahedral cells.

For boundary conditions, the velocity inlet is defined as a velocity magnitude of 1.5 m/s nor-

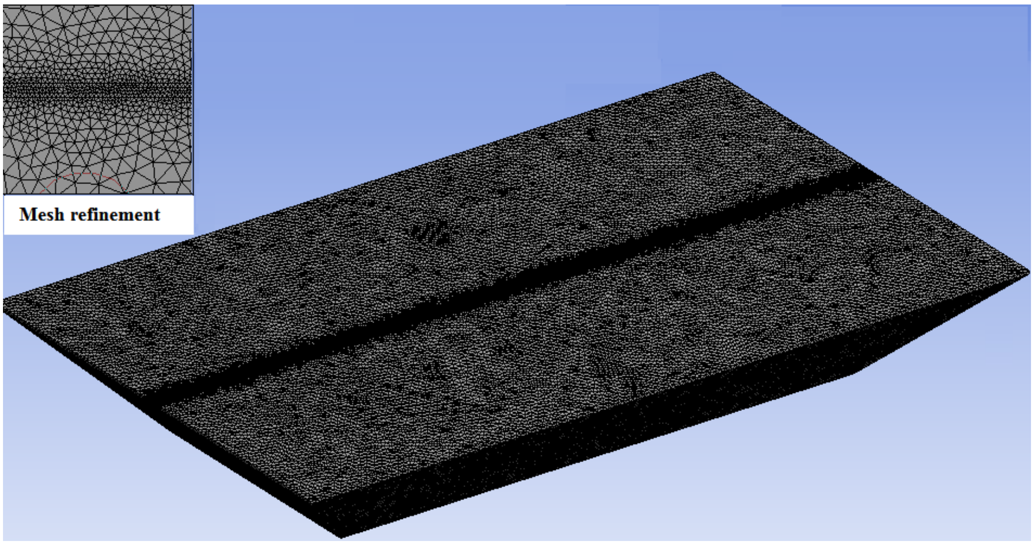

Fig. 2. Mesh used in numerical simulations

mal to the inflow boundary. The outlet face is considered as an outflow boundary. The backflow conditions for the inlet and outlet are: hydraulic diameter of 0.083 m and turbulence intensity of 3.69 %. All solid boundaries are specified as stationary with a no-slip shear condition. The free surface of the irrigation basin is characterized by zero normal gradients for all variables, so the symmetry condition is used. Other boundary conditions are prescribed when the discrete phase model is chosen: "Escape" condition for the inlet and outlet, "Trap" condition for the bottom wall, where particles will settle down, and "Reflect" condition near solid boundaries.

The CFD model is run with the PISO discretization scheme for pressure-velocity coupling, standard for the pressure and second order upwind for the momentum, turbulence kinetic energy and specific dissipation rate. As a first step, the continuous fluid phase is solved in the absence of particles. Then, particles are injected from the inlet of the basin with 10 stochastic trials. Particles are tracked without impacting the continuous phase (uncoupled calculation). The converged solution is determined when the absolute residuals normalized for all variables are under 10^{-4}. In addition, the outflow rate is calculated at each iteration and the physical convergence is reached when the change in flow rate becomes less than 1 %.

2.3. *Trap efficiency*

In the discrete phase model, the efficiency of the basin is related to the number of particles trapped at the bottom. The trap efficiency η is calculated as follows:

$$\eta = \frac{N_T}{N_I}, \tag{3}$$

where N_T is the number of particles trapped at the bottom and N_I is the the number of particles injected through the inlet.

2.4. *Model verification*

In order to examine the reliability of the ANSYS Fluent code, we assume that the flow near the inlet zone is similar to the flow in a backward facing step. Specific experimental results were compared with simulation results. This was attained by simulating the velocity measurements

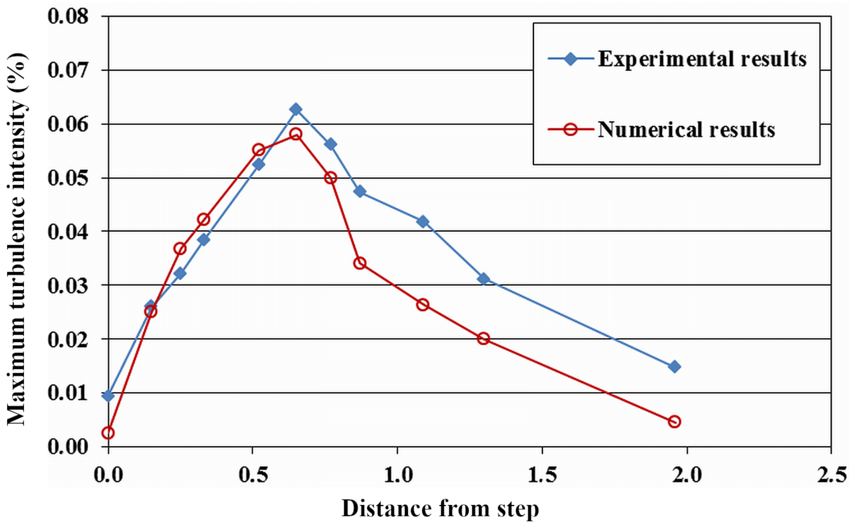

Fig. 3. Comparison of numerical and experimental [17] results

of Ruck and Makiola [17]. The velocity measurements were implemented in a backflow-facing single-step for various wall inclination angles. The comparison concerns the maximum turbulence intensity measurements of a flow with Re $= 47\,000$ and an inclined step at 45°. As shown is Fig. 3, the comparison is good.

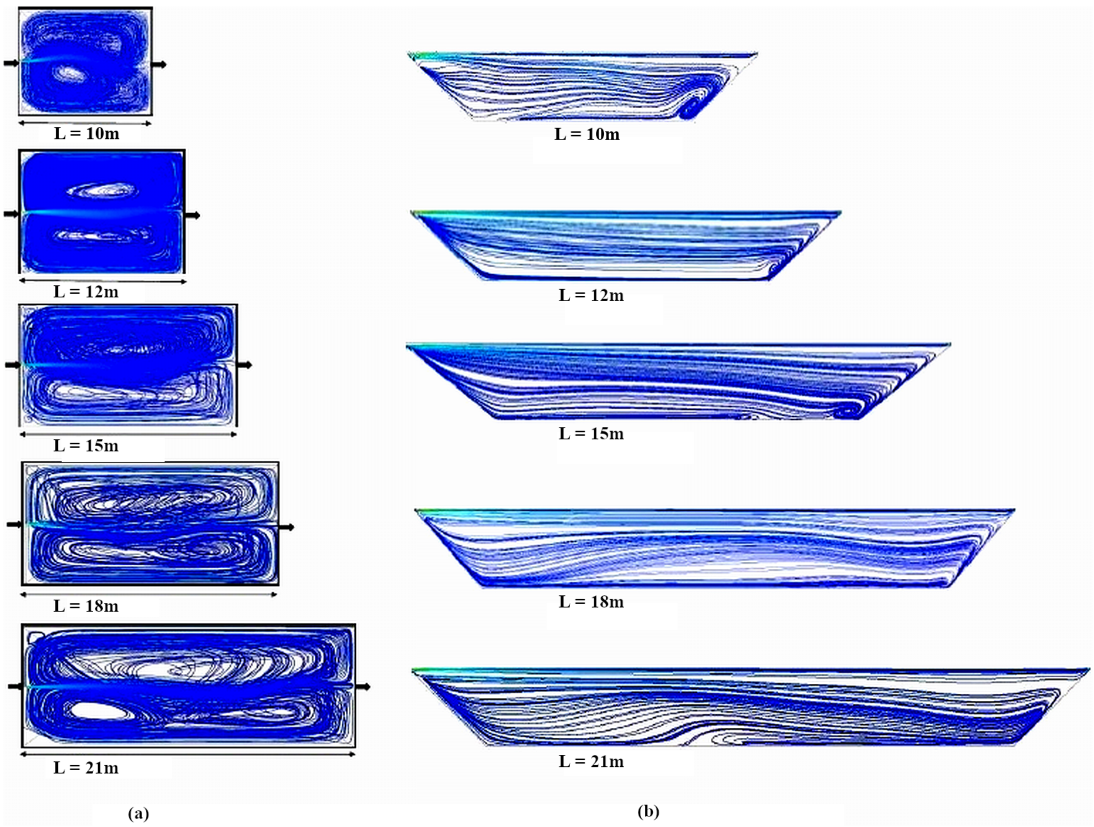

Fig. 4. Streamlines depicted in irrigation basins of different lengths: a) plan view, b) plan of the flow direction

3. Results and discussion

3.1. Effect of length on flow patterns and removal efficiency

Predicted streamlines for the irrigation storage basins are shown in Fig. 4a. When the length of the basin was less than 12 m, the flow presented a symmetric behavior; two circulation zones took place in the basin. Nonetheless, symmetry disappeared when the length was increased to 21 m; the circulation zone formed on the right side was divided into two circulation zones. This behavior is consistent with the observations of [6]. The authors showed that the symmetry of the flow pattern is transformed into asymmetry in shallow reservoirs when the length is increased. Likewise, it can be seen in Fig. 4b that the streamlines contours depicted in the flow direction were characterized by a small recirculation region located near the outlet zone. The size of this recirculation region was reduced in the longest basins and the flow became uniform which help particles to settle easily to the bottom of the basin. In the same context, it can be noted from Fig. 5 that the data show a reasonably consistent correlation between the removal efficiency and the basin length. One explanation for this behavior is that the long-circuit between the inlet and outlet gives the particles sufficient time to settle down at the bottom before leaving the basin.

3.2. Effect of width on flow patterns and removal efficiency

Fig. 6 depicts predicted streamlines. A symmetric flow pattern was observed for all geometries. Hence, the basin width did not affect the symmetry of the flow. However, the size of the recirculation region near the outlet zone was in accordance with the width, see Fig. 6b. By reducing the basin width, the size of the recirculation zone was reduced. As a result, the removal efficiency was increased in basins with reduced widths, see Fig. 7. On the other hand, it can be seen in Fig. 7 that the removal efficiency was increased by 6 % when the basin width was decreased from 15 m to 5 m. However, the width effect is not significant when the basin width is greater than 12 m.

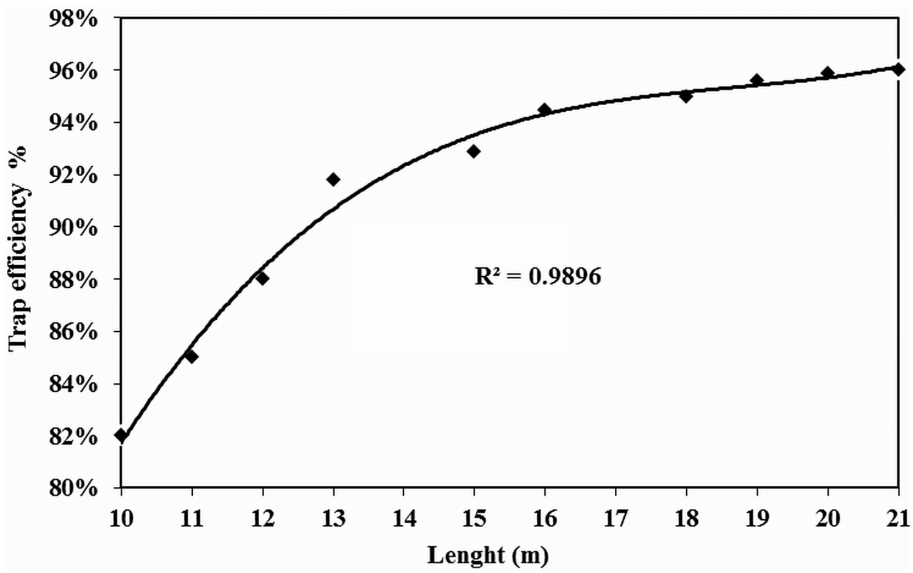

Fig. 5. Trap efficiency versus irrigation basin length

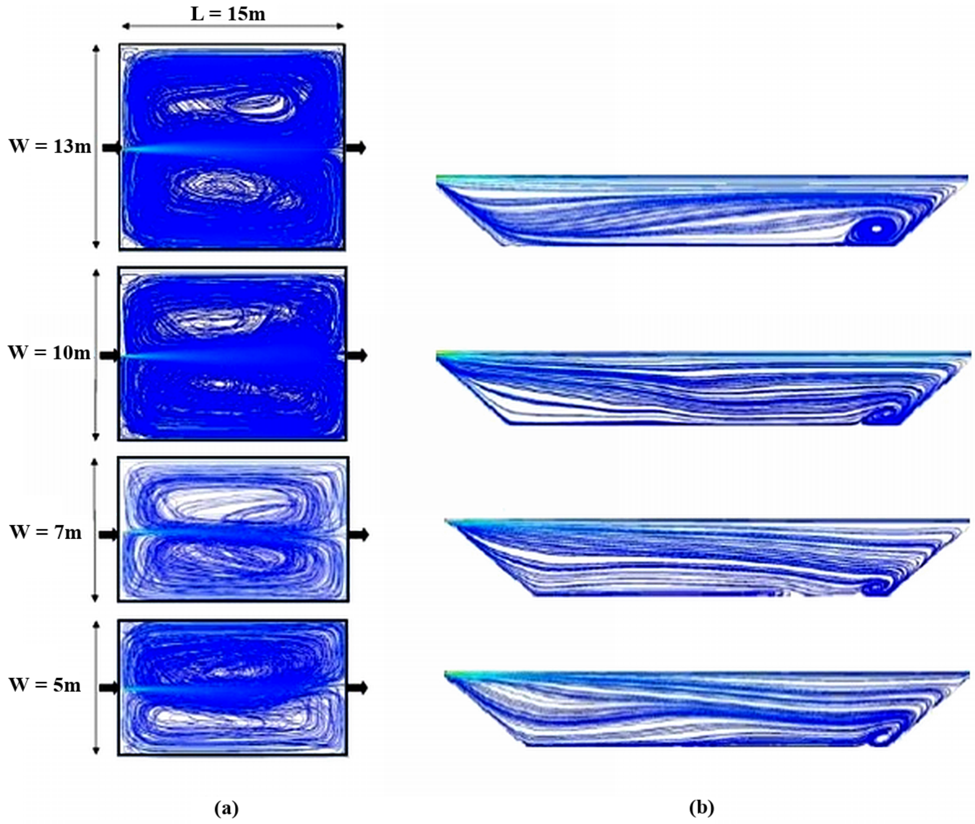

Fig. 6. Streamlines depicted in irrigation basins of different widths: a) plan view, b) plan of the flow direction

3.3. *Effect of depth on flow patterns and removal efficiency*

Streamlines contours are shown in Fig. 8. As can be seen, the flow pattern is symmetric for all tested geometries. Predicted streamlines depicted on the flow direction are illustrated in Fig. 9. It can be observed that the size of the recirculation region is minimized in basins with reduced depths. As a result, high removal efficiencies were noted, see Fig. 10. The same behavior has

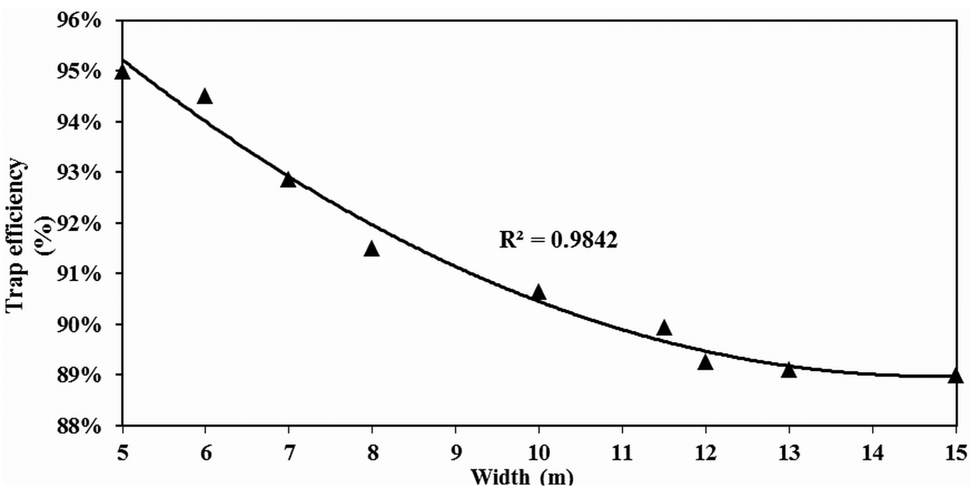

Fig. 7. Trap efficiency versus irrigation basin width

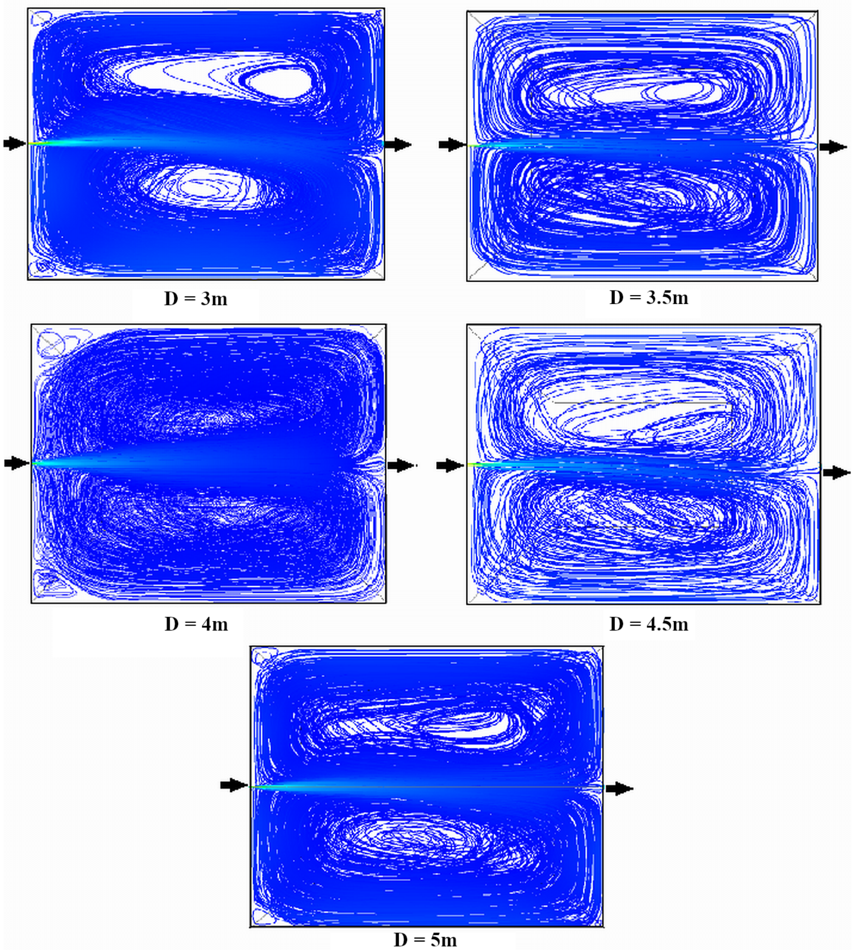

Fig. 8. Streamlines depicted in irrigation basins of different depths

been observed by [1]. The authors revealed that the recirculation zone length is related to the depth of the sedimentation basin.

The removal efficiency as a function of depth is depicted in Fig. 10. It can be noted that a reasonable correlation exists between the removal efficiency and the basin depth. Although increasing the depth by only 0.5 m may decrease the removal efficiency by more than 3 %, thus, the depth has a strong effect on the removal efficiency compared to the basin width.

3.4. Optimal design of an irrigation storage basin

Table 2 presents the results of the trap efficiency calculated for twenty basins having the same capacity of storage but different geometry. The obtained results allow us to make two remarks. First, the trap efficiency varies from 86 % to 100 %, which confirms the results of our previous parametric study, so the geometry of the basin has a significant effect on the trap efficiency. Moreover, it can be seen for the cases 4, 7, 10 and 14, which have the same value of length ($L = 18$ m), the trap efficiency for each basin is different. Similarly, it can be observed that for different basins having the same depth, the calculated trap efficiency is not the same. On the other hand, despite increasing the length between the cases 11 and 17, the trap efficiency decreased by more than 3 %. This results lead to the conclusion that we need dimensionless parameters to predict the trap efficiency of the storage irrigation basin.

Many investigations have been focused to find a relationship for the removal efficiency

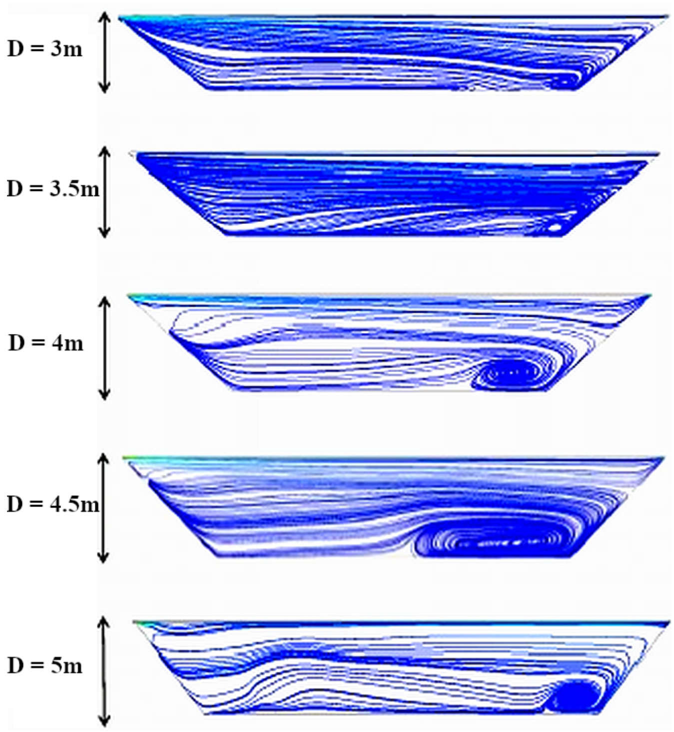

Fig. 9. Streamlines for geometries of different depths depicted in the flow direction

of settling basins. The majority of these studies have found two parameters to describe the trap efficiency. The first one is directly related to the geometry of the basin (L/D) and the second one to the flow and sediment characteristics (ω_s/u^*). In this section, the method of Garde et al. [8] has been checked in order to identify the agreement of our numerical data with the published relationship. The authors express the removal efficiency through the following exponential relation:

$$\eta = \eta_0 \left(1 - e^{-k\frac{L}{D}}\right), \tag{4}$$

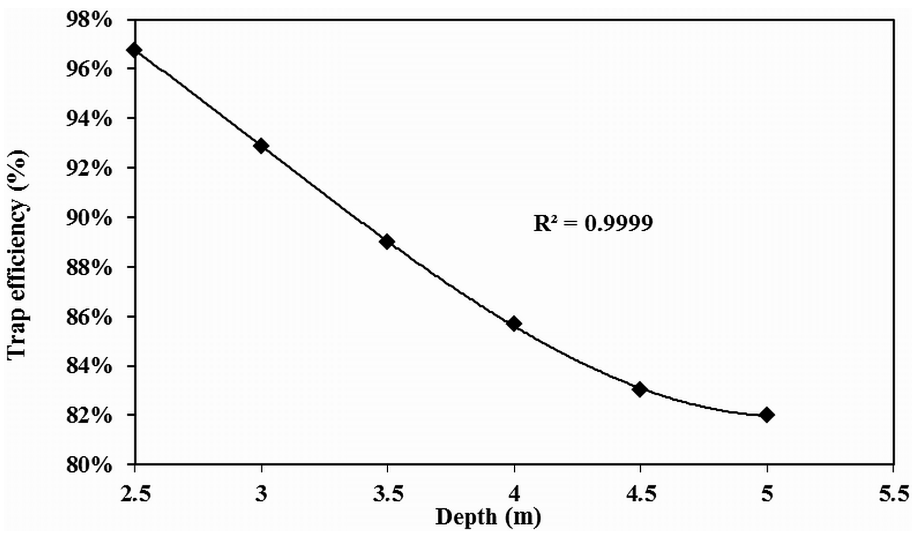

Fig. 10. Trap efficiency versus irrigation storage basin depth

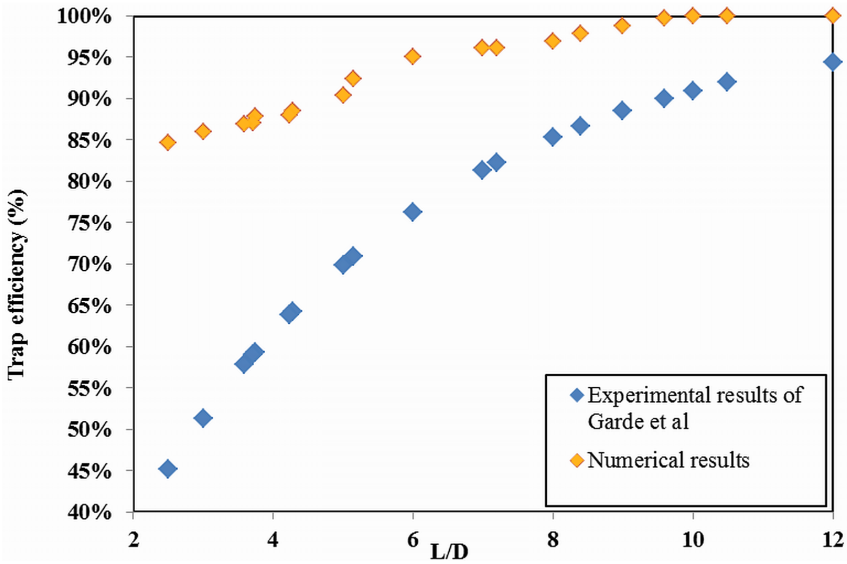

Fig. 11. Comparison of trap efficiencies versus L/D calculated through experimental data [8] and numerical results

where η_0 is the limiting efficiency obtained for a given ω_s/u^* at large values of L/D and k is a coefficient. Knowing the fall velocity of sediment particles ω_s, the Manning's roughness coefficient n and the discharge Q, one can calculate ω_s/u^*. In our case, the limiting efficiency is 100 % and ω_s/u^* is in the range of 12.31–24.86, i.e., ω_s/u^* is greater than 2.2. Then, the parameter k takes the maximum value 0.24. Using this parameter and the L/D ratio, the efficiencies were calculated using (4) and their values plotted against the numerical values in Fig. 11. As shown, the numerical and computed efficiencies have nearly similar values in the case of $L/D > 8$. This can be justified by the fact that the suspension is practically absent when the L/D is large, which gives a significant decrease in velocity and an efficiency of nearly 100 %. Moreover, it is significant to note that the trap efficiency is independent of ω_s/u^* when ω_s/u^* is much larger than 2.2. Hence, the efficiency according to this method could not be determined and a new relationship giving the trap efficiency as a function of geometric parameters is needed.

As shown in Fig. 12, the trap efficiency increases gradually with L/D. Moreover, good correlation is observed between the trap efficiency and L/D, with the R^2 coefficient value of 0.98. On the other hand, poor correlation exists between the trap efficiency and L/W, see Fig. 13. However, significant correlation can be observed when the depth value is constant, see Fig. 14. This can be explained by the fact that the depth has a strong effect compared to the width. Hence, L/D is found to govern the trap efficiency regardless of the width value. Nevertheless, L/W can be used to identify the optimal size even if the depth value is already known.

4. Conclusions

In this paper, a three-dimensional numerical model was used to simulate the dynamics and flow structure of an irrigation storage basin. The proposed numerical approach was tested and verified through experimental data. Then, twenty basins having the same capacity of storage and different geometries were evaluated in order to identify the geometry effect on trap efficiency. It was found that the trap efficiency of an irrigation storage basin is very sensitive to the geometry.

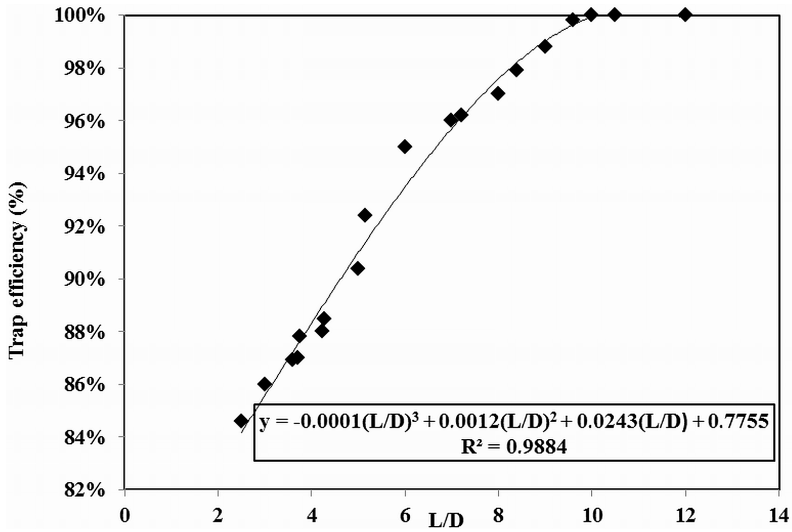

Fig. 12. Trap efficiency versus L/D

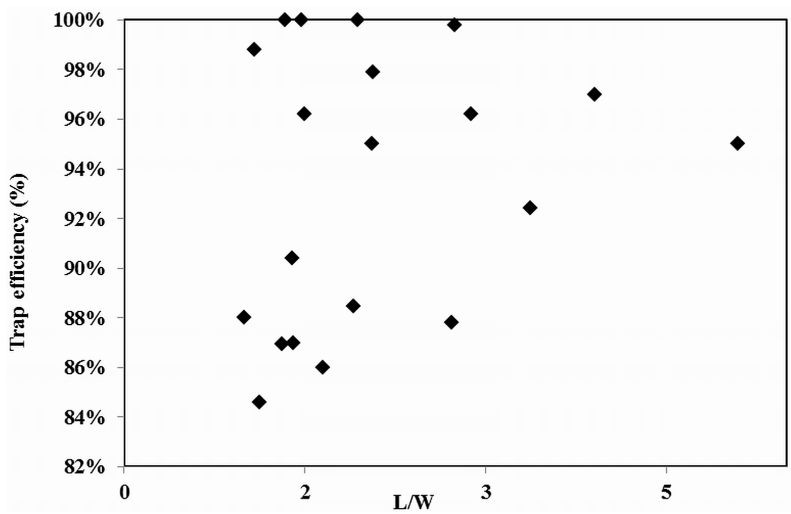

Fig. 13. Trap efficiency versus L/W

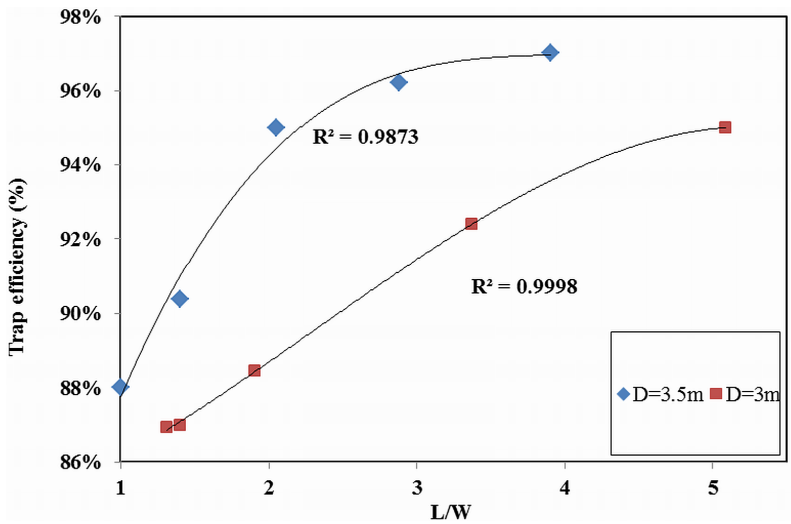

Fig. 14. Trap efficiency versus L/W for two depth values

Therefore, for a specific water irrigation need, some recommendations were proposed in this research paper to design an irrigation storage basin with the maximum trap efficiency. First, it was strongly recommended to design a group of basins having the same capacity of storage and different geometries. Then, the geometry of the basin must be chosen so that it will lead to a maximum value of the L/D ratio. Nevertheless, if the value of depth is already fixed, the length and the width should be taken in such a way that they give a maximum value of the L/W ratio.

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