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ADVANCES IN THE DESIGN OF SHALLOW WATER PUMPING SYSTEM FOR MOBILE USE AT THE CENTRAL REGION OF ARGENTINA

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Abstract. *According to the "Food and Agriculture Organization (FAO)," the world will require in the coming decades an increase in agricultural production to meet the food needs of the population, and this will depend heavily on water use. One of the problems of agricultural production in the central region of Argentina, Córdoba, is the poor temporal distribution of rainfalls and her shortage. In the plan submitted by the "Instituto Nacional del Agua", appears a relevant subject how the problem of deteriorating irrigation systems, whose use efficient is a multidimensional problem and therefore a complex research topic. In this paper presents the progress made in the development of the irrigation pumping system that allows boosting shallow surface water (≤ 40 cm) from rivers, lakes and canals. So it is vital achieve a geometry in pump inlet allowing the particle entrainment minimum since the submerged surface. Making it necessary adequately describe the flow before the inlet to the impeller. The system is lightweight, easy to transport and variable geometry to adapt to different terrain profiles. It could also be used as a system for rapid action in affected areas by flooding problems. This article will show in detail different geometries of the admission of the pumping system with their streamlines respective, which was studied using techniques modern of "Computational Fluid Dynamics (CFD)" to solve the equations that govern a viscous incompressible steady two-dimensional flow.*

Keywords: *Irrigation, CFD, Córdoba*

1. INTRODUCTION

The increasing demand for food worldwide, presents for Argentina the opportunity to become one of the leading suppliers of grains and meats. According to the "Food and Agriculture Organization (FAO)," the world will require a significant increase over the coming decades, of agricultural production to meet the food needs of the population; and increasing production will depend largely of use of water, and in this regard, does an attention call on the diminishing availability of this resource for future use in irrigation (FAO, 2002).

A study by the World Bank (WB), believes that Argentina has a great potential to increase the area under irrigation. Total water storage capacity is about 160 km^3 (World Bank, 2006). The potential irrigated area is 6.3 million hectares, of which 2.5 million could have irrigation throughout the year. There are currently 1.75 million hectares under full irrigation and with favorable economic conditions, could add 750,000 hectares.

One of the problems of agricultural production in the south central region of the state of Córdoba is the poor temporal distribution of rainfall and the occurrence of shortage of the same. The complementary irrigation is an available practice that can bridge this adversity and stabilize yields of field crops characteristic of the region. The area under sprinkler irrigation in the country is far below the total cultivated area that can be irrigated, and while it grew at a considerable rate until 2000, is now stabilized. (Salinas *et al*., 2006).

The state of Cordoba has a good potential for irrigation defined by the large area of suitable land, which coincide with areas where groundwater is possible to obtain in sufficient quantity and quality, complemented with significant sources of surface water.

The sustainability in the time of this system depends on the rational use of water resources (aquifers) and also the soil and crops management. There are aspects that are not known about the performance and the underground aquifers recharge that are used and the magnitude of the danger of salinization soil when it incorporated water with some salt. Therefore, the correct application of this technology is conditioned by the availability of quality water and enough flow rates, in combination with apt soils, that justify with good yield the investments implementation, operation and maintenance that technology require (Agencia Córdoba Ambiente – INTA, 2006).

The importance of technological contribution to primary production in the state of Córdoba is remarkable. There may be mentioned, for example, some indicators of Córdoba and in particular of the Río Cuarto Department (where is located the Universidad Nacional de Río Cuarto). Data from the "Sistema Integrado de Información Agropecuaria del

Ministerio de Agricultura, Ganadería y Pesca de la Nación" (SIIA, 2011) and the "Unidad Provincial del Sistema Integrado de Información Agropecuaria del Ministerio de Agricultura, Ganadería y Alimentos de la provincia de Córdoba" (UPSIIA, 2009):

- First national peanuts producer and first at the departmental level.
- Second national soybean producer and third at the departmental level.
- Second national corn producer and first at the departmental level.
- Third national wheat producer and eighth at the departmental level.
- The Río Cuarto Department is the first in importance in Cordoba in number of cattle head.
- Cordoba is the third largest exporter nationwide.
- Córdoba regarding processing capacity: 100% of peanuts and milk production, 40% of the production of beef cattle, 30% of soya production and 10% of corn production.

In our country and according to the strategic plan 2005 - 2008, presented by the "Instituto Nacional del Agua" (INA, 2005) under the "Subsecretaría de Recursos Hídricos de la Nación" (SSRH) among current relevant thematic issues appears the existence of a deterioration of the irrigation systems. According to what is stated in this report, irrigation, which accounts for 70% of water withdrawals for different uses, has efficiencies of use lower at 40%.

Today pressurized irrigation systems are a viable alternative for water efficiency, since it has been found that with their employment is possible to increase productivity by increasing yields.

In the pumping of groundwater is common the use of submersible pumps normally known to as deep-well pumps designed primarily for applications important heights and relatively low flow rates (Turton, 1995). There is not specific designs for pumping of surface water. There only, devices with adaptations of the pumps mentioned before, that requires the use of generators to generate the energy they need. This means more capital investment, because not used available power plants by the farmer.

This paper aims to develop a pumping system for irrigation, that allows boosting shallow water, either from rivers or lakes and even channels. When the water comes from a shallow surface source (≤ 40 cm), and its use for agricultural purposes is not continuous, as in the case of having to supply water only in specific periods of crop growth, the principle of optimal design is the of portable pumping equipment and modulars. The system must be easy to transport and variable geometry to adapt to different terrain profiles and lightweight. At the same time must be able to adapt to different power plants (tractors) that are available in rural areas.

Given the conservation of the environment, does not arise any intervention to watercourses that involving modifying the topography, so the design of the pumping system must overcome problems related to shallow rivers of the south zone to the Córdoba state.

By its nature, an additional advantage of the proposed system is that, was although designed for use in irrigation, it could be also used as a fast-acting system for pumping water in affected areas by flooding problems.

2. MODELING PRE-FILTER SUCTION PIPE INTAKE

2.1 Mathematical equations

2.1.1 Conservation of mass: the equation of continuity

The continuity equation in differential compact form, for a simple compressible fluid is:

$$\frac{\partial \rho}{\partial t} + \underset{\sim}{\nabla}\left(\rho \underset{\sim}{v}\right) = 0 \qquad (1)$$

where ρ is the density of fluid, t the time and $\underset{\sim}{v}$ the velocity field. This equation is valid for any point of the fluid domain. In this vector form the equation is still quite general and can readily be converted to other than cartesian coordinate systems. If the flow is steady, $\partial\rho/\partial t \approx 0$, and all properties are functions of position only.

A special case which affords great simplification is incompressible flow, where the density changes are negligible. Then $\partial\rho/\partial t \approx 0$ regardless of whether the flow is steady or unsteady, and the density can be slipped out of the divergence in Eq. (1) and divided out. Further, we consider two-dimensional incompressible plane, thus $\partial/\partial z=0$.

In a cartesian coordinate systems, Eq. (1) reduces to:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (2)$$

where u and v are the scalar components of the velocity field. This is valid for steady or unsteady incompressible flow (White, 1998).

2.1.2 Conservation of momentum: the Navier-Stokes equations

The basic differential momentum equation for an infinitesimal element, also is

$$\rho \frac{D\underset{\sim}{\mathrm{v}}}{Dt} = -\underset{\sim}{\nabla} p + \rho \underset{\sim}{\mathrm{F}} + \nabla \cdot \tau_{ij} \tag{3}$$

where the term on the left is the product of the density and acceleration, the first term on the right represents the pressure forces per unit volume, the second term are volume forces per unit volume and the last term are the viscous forces per unit volume, in which τ_{ij} is the viscous-stress tensor acting on the element.

For a Newtonian fluid, the viscous stresses are proportional to the element strain rates and the coefficient of viscosity. Therefore, the differential momentum equation for a Newtonian fluid with constant density and viscosity

$$\begin{aligned} \rho \frac{du}{dt} &= -\frac{\partial p}{\partial x} + \rho \mathrm{F}_x + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \\ \rho \frac{dv}{dt} &= -\frac{\partial p}{\partial y} + \rho \mathrm{F}_y + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \\ \rho \frac{dw}{dt} &= -\frac{\partial p}{\partial z} + \rho \mathrm{F}_z + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \end{aligned} \tag{4}$$

where p is the pressure, F_x, F_y and F_z are the scalar components of the volume forces and μ is the fluid viscosity coefficient.

These are the Navier-Stokes equations. They are second-order nonlinear partial differential equations, and have four unknowns: p, u, v, and w (White, 1998).

2.1.3 Frictionless flow: The Bernoulli equation

A useful theoretical equation for computing the relation between pressure, velocity, and altitude in a steady flow of a nearly inviscid, nearly incompressible fluid with negligible heat transfer is the Bernoulli equation.

$$\frac{p_1}{\rho} + \frac{1}{2} V_1^2 + g z_1 = \frac{p_2}{\rho} + \frac{1}{2} V_2^2 + g z_2 = \text{const} \tag{5}$$

where p_1 is the pressure in point 1 on the streamline, p_2 is the pressure in point 2 on the streamline, V_1 is the magnitude velocity flow in point 1 on the streamline, V_2 is the magnitude velocity flow in point 2 on the streamline, z_1 and z_2 are altitude in point 1 and 2 on the streamline, respectively (White, 1998).

2.1.4 Sediment transport: Incipient motion

Incipient motion is important in the study of sediment transport, channel degradation, and stable channel design. Due to the stochastic nature of sediment movement along a fluvial bed, it is difficult to define precisely at what flow condition a sediment particle will begin to move. There is no single criterion that indicates the conditions under which sediment transport starts.

Most incipient motion criteria are derived from either a shear stress or a velocity approach. One of the most prominent and widely used incipient motion criteria is the Shields diagram (1936) based on shear stress. Shields assumed that the factors in the determination of incipient motion are the shear stress, τ, the difference in density between sediment and fluid $\rho_s - \rho_f$, the diameter of the particle d, the kinematic viscosity ν, and the gravitational acceleration g. These five quantities can be grouped into two dimensionless quantities, namely,

$$d \frac{\left(\tau_c / \rho_f\right)^{1/2}}{\nu} = \frac{dU_*}{\nu} \tag{6}$$

$$\frac{\tau_c}{d\left(\rho_s-\rho_f\right)g}=\frac{\tau_c}{d\gamma\left[\left(\rho_s/\rho_f\right)-1\right]} \tag{7}$$

where ρ_s and ρ_f are densities of sediment and fluid, respectively, γ is specific weight of water, U_* is shear velocity, and τ_c is critical shear stress at initial motion. The relationship between these two parameters is then determined experimentally. The experimental results obtained by Shields and other investigators at incipient motion, were represented in a graphs called Shields diagram for initiation of motion. The graphs contain a curve that delimits the particle move. At points above the curve, the particle will move. At points below the curve, the flow is unable to move the particle (Vanoni, 1975).

2.2 Results

2.2.1 Couette Flow between a Fixed Plate

To check the computational code, previously was resolved the flow due to pressure gradient between two fixed plates (Couette flow). The solution is mathematically exact for an incompressible fluid.

The application of Eq. (2) gives as result $\partial u/\partial x=0$, so $u = u(y)$ only. Replacing $u = u(y)$ into the x-component of Eq. (4), the analytical solution of two-dimensional (x, y) flow in a channel due to pressure gradient, is

$$u=-\frac{dp}{dx}\frac{h^2}{2\mu}\left(1-\frac{y^2}{h^2}\right) \tag{8}$$

where h is the half of the separation distance between parallel plates.

Was considered two-dimensional incompressible plane ($\partial/\partial z=0$) viscous flow between parallel plates, as shown in Fig. 1. We assume that the plates are very wide and very long, so that the flow is essentially axial, $u\neq0$ but $v = w = 0$. The effect of gravity is negligible. Both plates are fixed, but the pressure varies in the x direction only.

The fixed plate model that was used have a separation distance between parallel plates of 100 mm between them circulates a fully developed water flow in steady state with pressure gradient of $16\text{x}10^{-3}$ Pa/m. The boundary conditions are in y=0, u=0 and in y=100 mm, u=0, and was shown in Fig. 1.

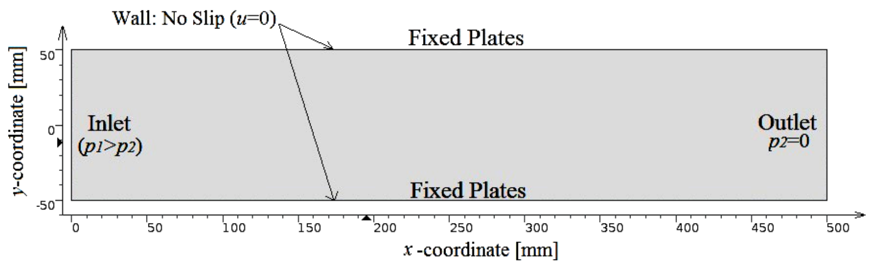

Figure 1. Incompressible viscous flow between parallel plates fixed.

The model is discretized with a structured mesh type, calibrated for fluid dynamics, composed by 6444 quadrilateral elements, with a size of 2.79 mm by 2.78 mm.

Figure 2 shown graphs of the velocity profiles for both cases and Fig. 3 shown graphs of the square error and absolute error between the theoretical velocity profile and the simulation model.

Experiments show that laminar flow between stationary parallel plates becomes turbulent for Reynolds numbers greater than approximately 1400. Consequently, the Reynolds number should be checked to ensure a valid solution (Fox, *et al.*, 2004). In the theoretical model, the Reynolds number is equal to 825 and in the simulation model is equal to 830.

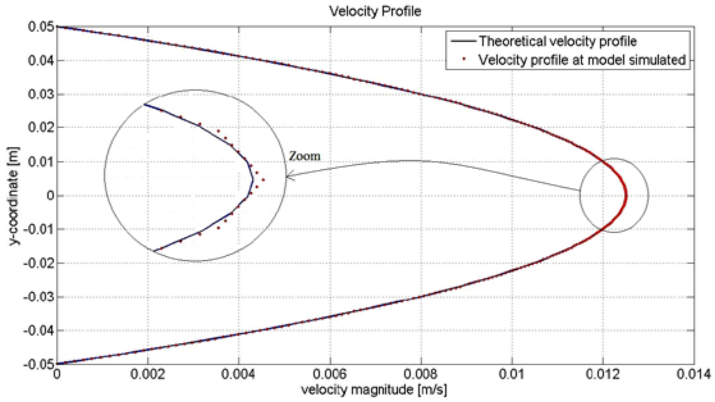

Figure 2. Comparison of velocity profiles for fully developed laminar flow between infinite parallel plates.

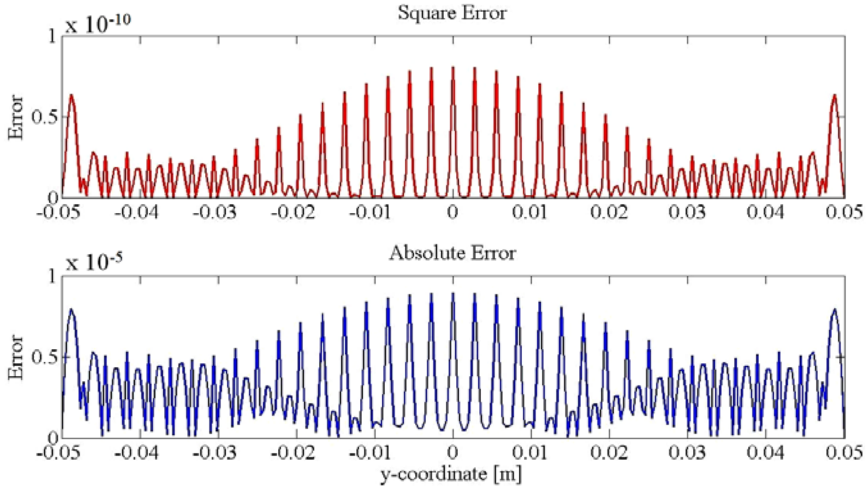

Figure 3. Square error and absolute error between the theoretical velocity profile and the simulation model.

2.2.2 Two-dimensional numerical modeling of the pre-filter

This paper presents a two-dimensional numerical modeling of the pre-filter vacuum suction pipe of a pumping system to drive shallow surface water for irrigation from rivers, lakes and canals. This filter will be equipped with wire mesh to prevent suction of foreign bodies and large enough particles that can damage equipment, but for the simulation was not included the latter to simplify the model geometry.

The designed system will be applied to the supplementary irrigation of vegetable crops in the central region of the province of Córdoba, Argentina. Therefore morphometric and hydrological information on a channel belonging to the upper basin of the river bed, Rio Cuarto department, was used in the simulation (Degiovanni, *et al.*, 2013).

The model was implemented and analyzed by finite element method using appropriate software for physical and engineering applications. This computational code solves Eq. (2) and (4). Model configuration is shown in Fig. 4.

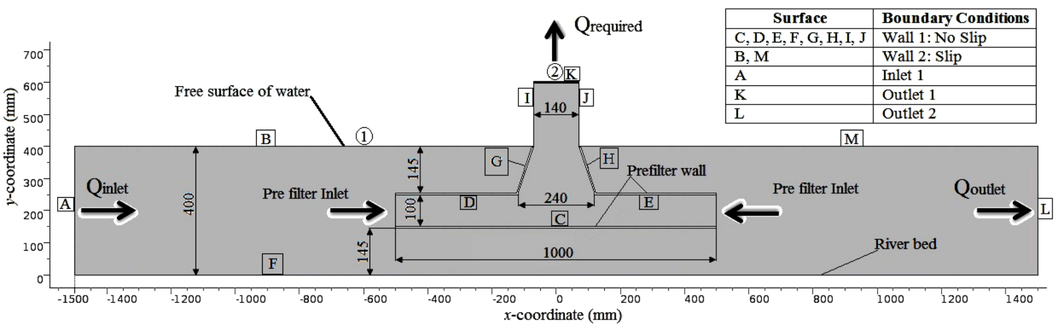

Figure 4. Model configuration, pre-filter geometrical dimensions and boundary conditions.

In this model it is considered a stretch of 3000 mm length of a shallow channel (400 mm), and zero slope, where the water is flowing from left to right. In the channel is submerged pre-filter suction pumping system, whose three-dimensional shape is cylindrical, diameter 1000 mm and height 100 mm, although the two-dimensional model can only see a rectangular cross-section thereof. Its shape and dimensions were proposed with the intention of decreasing the flow velocity in his entrance and thus reduce the drag of the channel bed particles toward the suction pipe. Perpendicular to the channel can be seen the first portion of the suction pipe coupled to pre-filter; whose internal diameter is 140 mm.

The aim of this first job was to find the approximate geometry must have the pre-filter from the analysis of the fluid velocity field and the shear stresses in the river bed taking as a starting point the proposed geometry.

The analysis of a numerical code used to solve the equations that model the flow of a fluid, is incomplete without a description of the boundary conditions. They describe the interaction of the fluid with the "world" outside the domain of analysis, specifying the value of the primitive variables and / or their gradients on the edge of the domain.

The value of the input speed is the same that average speed of the river during drought season, taken in station Nº 10 of the river (Degiovanni, et al., 2013). The value of the output speed of the pre-filter (and input to the suction pipe) has been calculated by applying Eq. (5) in a streamline between points 1 and 2 shown in Fig. 4, according to the calculated water flow to irrigate a given crop.

Table 1 presents the different types of boundary conditions and his equations, and its location on the contours of the model can be seen in Fig. 4. We add that was considered the effect of volume forces (gravitational field).

Table 1. Boundary conditions model.

Boundary conditions			
Type and condition	Value	Equation	Units
Wall 1: No Slip		$u=0$	
Wall 2: Slip		$\underset{\sim}{v}\cdot\underset{\sim}{n}=0$ (2) and $\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)=0$	
Inlet 1: Velocity	0.73	$\underset{\sim}{v}=-U_0\cdot\underset{\sim}{n}$ (1)(2)	m/s
Outlet 1: Velocity	6	$\underset{\sim}{v}=U_0\cdot\underset{\sim}{n}$ (1)(2)	m/s
Outlet 2: Pressure	0	$\left[-p\underset{\approx}{I}+\mu\left(\nabla\underset{\sim}{v}+\left(\nabla\underset{\sim}{v}\right)^T\right)\right]\underset{\sim}{n}=-p_0\underset{\sim}{n}$ (2)	Pa

(1) U_0 is input velocity value in the surface specified
(2) $\underset{\sim}{n}$ is a vector normal to that surface

The model is discretized with an unstructured mesh type, calibrated for fluid dynamics, composed by 57,200 free triangular elements, with a maximum element size of 7.8 mm and minimum element size 0.09 mm. Figure 5 shown the detail of meshing.

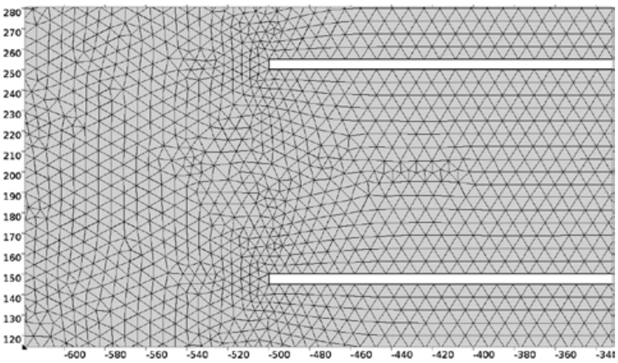

Figure 5. Two-dimensional mesh in the area of the entrance of the pre-filter.

Figure 6 shows a surface plot of the magnitude of the velocity, and a graphic the streamlines of the velocity field.
To the right, there is a color table, where the reddish tones correspond to higher speed and the blue to the lower speed. Water enters from the left to the channel portion of the model with an average velocity of 0.73 m/s.

It is noted that the original direction of the flow does not influence on the inlet velocity of the pre-filter. The colors in the graph show a symmetry marked. This is because the flow velocity is relatively low, and because influence the depth to which has been submerged the pre-filter.

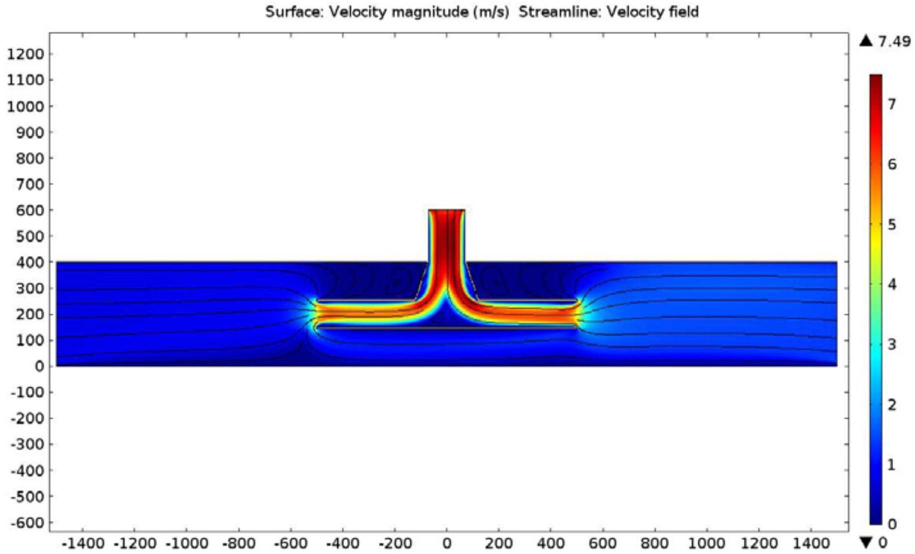

Figure 6. Velocity graphic: Surface and streamline

Figure 7 shows graphs of magnitude velocity for three different channel cross sections. It is observed that the section x = -1000 mm the velocity profile is not affected by the presence of the pre-filter. However, in a section x = -600 mm close to of the pre-filter the velocity profile has changed. Also, the graph shows that the slope of the three curves near the origin of coordinates is different, although similar for the corresponding curves to x = -500 mm and x= -600 mm. This means that the shear stresses in the riverbed increases as we approach the entrance of the pre-filter. The increase in shear stress predisposes the sediment transport from the river bottom.

When applying Eq. (6) and (7) for the given characteristics of the river, a critical shear stress of 1.45 N/m^2 was obtained (Degiovanni, *et al*., 2013). The values of the shear stresses in the simulated model are small compared to the value of the critical shear stress. This indicates no movement the particles of channel bed, and therefore, there is not entrainment of particles towards the suction pipe.

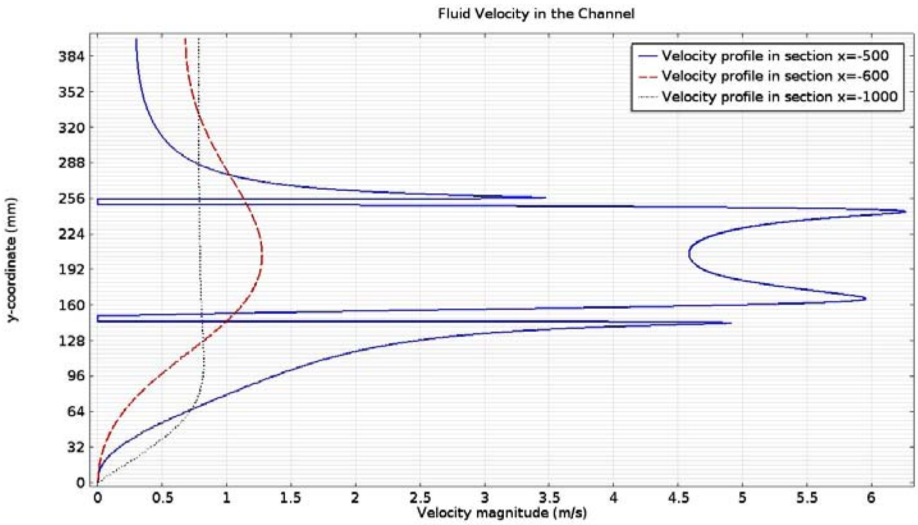

Figure 7. Velocity profile in three cross sections of channel.

3. CONCLUSION

In this paper we have presented a methodology that is able to adequately simulate the flow produced by the suction of a pumping system to drive shallow surface water. The numerical simulation allows to establish when will occur sediment drag from the submerged surface and the particle size that could be dragged. At the same time, with the technique presented, you can do a parametric analysis of sediment drag varying speeds entry of the fluid (Inlet 1 in Fig.

4) and for various flow rates required for irrigation (Outlet 1 in Fig. 4). With the skills acquired it is intended, in the near future, advance in three-dimensional simulations that allow design the first prototype.

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