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Gravity Currents in a Vegetated Valley of Trapezoidal Shape

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ABSTRACT

In this study lock-exchange experiments are performed in a tank of rectangular upper cross section and a lower vegetated valley of trapezoidal shape to study the effect of drag resistance, due to vegetation, on gravity currents. Many natural and man-made channels are approximately trapezoidal. For the simulation of the vegetation the bed is covered by flexible grass vegetation (height of vegetation, h_v=2.0cm) of different submergence ratio h_v/H (h_v=height of vegetation, H=water depth). The motion of the gravity current is monitored with a digital video of high definition, the front velocity is measured and the height of the front is captured. Twenty four experiments are performed, twelve inside the trapezoidal section (H/H_{tr}=0.4, 0.6 or 0.8) and twelve over the trapezoidal section (H/H_{tr}=1.2, 1.4 or 1.6). The initial Reynolds number, based on the height of the valley and the reduced gravity, is greater than 10000 for all cases indicating that the gravity currents are turbulent. Results are compared with those of similar experiments without vegetation (Keramaris and Prinos, 2010) and hence the effect of the vegetation drag resistance on the motion of the current is investigated. The main conclusion of this study is that the shape of the tank plays a significant role in the propagation of gravity currents. The presence of trapezoidal increases the velocity of gravity currents in comparison with triangular or orthogonal shape.

Keywords: Gravity currents; Valleys; Lock-exchange; Vegetation bed; drag resistance; Front velocity; Digital video.

NOMENCLATURE

B	bottom width	t*	dimensionless time
Fr	Froude number	U	current speed
g	gravity	V	volume of the current
g´	reduced gravity	w	current width
H	height of the current	W	width
H	water depth	x*	dimensionless distance
H_0	height of the water over the valley		
H_{tr}	depth of the valley	γ	relationship between light and dense fluid densities
h_v	height of vegetation	ρ_{sw}	density of saltwater
L	total length	ρ_w	density of freshwater
L_1	distance between the lock gate and the rest of the tank		

1. INTRODUCTION

Gravity currents (also called density currents) are buoyancy-driven flows which manifest either as a horizontal current of heavy fluid running below light fluid, or as a current of light fluid above heavy fluid. In some applications the gravity current manifests as a combination of these two, and in this case, they are also called intrusions. Gravity currents can be produced with very small density differences (of a few percent), yet they can still travel for very long distances. Examples of these flows are thunderstorm fronts, volcanic eruptions, oil spills on the ocean and snow avalanches

(Simpson, 1997).

Oldham and Sturman (2001) investigated the effects of relatively dense emergent vegetation on convective flushing of shallow wetlands with low Reynolds number flow using experiments in a laboratory convection tank and a wetland mesocosm.

Shin *et al*. (2004) described a new theory and experiments on gravity currents produced by lock-exchange which suggested that the dissipation due to turbulence and mixing between the current and the surrounding ambient fluid is unimportant when the Reynolds number is sufficiently high. They provided an alternative theory that predicts the current speed and depth based on energy-conserving flow. A related problem which has been studied experimentally is the flow of gravity currents down rumps into a horizontal surface. There has been much less research on gravity currents flowing along valleys.

Antenucci *et al*. (2005) have studied a constant flux flow along a V-shaped channel into a reservoir to model the spread of pathogens. Constant flux currents along sinuous channels have been investigated using saline current to model turbidity currents (Keevil *et al*., 2006).

Takagi and Huppert (2007) examined Newtonian viscous gravity currents propagating along horizontal and inclined channels with semicircular and V-shaped boundaries. The mathematical equations are compared with data from laboratory experiments. Geological applications of the results are discussed.

Also Takagi and Huppert (2008) used a model of unidirectional Stokes flow on rigid surfaces to obtain a variety of different propagation rates of viscous gravity currents, which arise by considering different releasing rates at the source inside channels that change shape down the flow. Also the position of a current inside either an extremely narrow or nearly V-shaped channel that gently widens along the flow is studied and shown to be proportional to a power of time.

The effect of vegetation is also important and few studies have been performed for gravity currents in a vegetated tank of rectangular cross section. Zhang and Nepf (2008) investigated the exchange flow between the vegetated and open regions of surface water systems with differences in water density. A laboratory experiment has been conducted, using a random array of rigid, emergent cylinders to represent the canopy region. The main conclusion is that the gravity current in the open region moves at a constant speed set by the initial inertial condition, while the speed of the current in the vegetative region is controlled by the canopy drag and decreases with time. The total discharge rate is also controlled by the vegetative drag, decreasing with increasing canopy drag and also decreasing slowly with time.

Keramaris and Prinos (2008) performed lock-exchange experiments in which the bed is covered by grass-type of vegetation of different submergence ratio h_v/H (h_v=height of vegetation, H=water depth). The vegetation densityranging from 0.08 to 0.30 and vegetation density (number of shoots per squared meter), ranging from 3 shoots/cm^2 to 6 shoots/cm^2.The effects of density ratio, submergence ratio and channel slope on the motion of the current were investigated. The main conclusions of this research are: (a) the submergence ratio h_v/H affects the motion of the gravity current. Increase of h_v/H results in decrease of the travelling distance due to the increased vegetation resistance, (b) increase of density difference results in increasing travelling distance of the current and increased velocities of the gravity front, (c) increase of bed slope results in increasing travelling distance of the current and increased velocities of the gravity front and d) the effect of the bed roughness (vegetation) is not significant close to the lock. For dimensionless distance x* greater the 2.0 the effect is pronounced. For the same x*, the dimensionless time t* increases with increasing vegetation height due to increased vegetation resistance.

Few experimental studies have been performed for gravity currents in a valley. Monaghan *et al*. (2009a) investigated the motion of saline gravity currents propagating horizontally in a tank of rectangular upper cross section and lower V-shaped valley by lock-exchange experiments and a box model. The presence of valley results in three major differences in the gravity current compared to that flowing along a flat bottom. These are : i) the front of the current is approximately parabolic ii) for sufficiently large time t the velocity of the current in the V-shaped valley varies in the flat bottom case and iii) the width of the current in V-shaped valley decreases with time t. They have used the box model to predict the effect of changing the slope of the valley after obtaining good agreement between experiments and box model results. The result is that for equal volume currents, the steeper the valley the faster the flow.

Also Monaghan *et al*. (2009b) in their paper extended previous studies of saline gravity currents at high Reynolds number flowing along a tank with a V-shaped valley. They used experiments and a box model to determine the primary features of the flow. The front of the current is approximately parabolic. The results can be described with remarkable accuracy by a box model using a generalization of the equation for sedimentation from a turbulent medium.

Keramaris and Prinos (2010) investigated the motion of saline gravity currents in lock-exchange experiments which are carried out in a tank of rectangular upper cross section and a lower valley of trapezoidal shape. This is considered as more realistic model of the valleys which occur in nature. The experiments are performed for equal depths of heavy and light fluid on both sides of the lock gate.Density difference between salt water and clear water is varied between 0.1% and 0.4% and hence the effect of density difference on the motion of the gravity currents is also investigated.

The movement of the gravity current is monitored with a digital video of high definition, the front velocity is measured and the height of the front is captured Twenty four experiments were performed twelve inside the trapezoidal section (H=4, 6 or 8cm) and twelve over the trapezoidal section (H=12, 14 or 16 cm). The initial Reynolds number, based on the height of the valley and the reduced gravity, is greater than 10000 for all cases indicating that the gravity currents are turbulent. The main conclusions of this research are: a) the gravity current propagates with a parabolic head. The current with the greater difference density difference 0.4%) travels faster than the others in both cases (H=4cm and H=16cm). This is due to the fact that the velocity of the gravity current increases with increasing density difference, b) the effect of density difference is more pronounced in the case of composite section than the trapezoidal section, c) the dimensionless distance x* is plotted against the dimensionless time t* for both orthogonal and trapezoidal valleys. The effect of the valley section on the motion of the current is clear. Also results from the box model of Monaghan *et al*. (2009) for triangular valleys of different side wall steepness indicate the dependence of the current motion on the geometry of the valley and d) the dimensionless distance y is plotted against the dimensionless time τ. There is a good agreement between the results of this study with similar experiments in V-shaped valleys performed by Monaghan *et al*. (2009).

The problem of thermosolutal convection in a couple-stress fluid layer through a porous medium to include the effects of vertical magnetic field and vertical rotation has been discussed by Kumar (2012). Recently Banyal (2013) has investigated thermal instability of a couple-stress fluid heated from below and derive the necessary condition for the onset of instability as a stationary convection.

Recently Kumar *et al*. (2015) has studied the onset of convection in a couple-stress fluid saturated porous medium under the influences of varying gravity, suspended particles and uniform magnetic field. The necessary condition for the onset of instability and the sufficient condition for the non-existence of convection at the marginal state in the absence and presence of couple-stress parameter have also been obtained by using Rayleigh-Ritz and Cauchy-Schwartz inequality.

In this study lock-exchange experiments are performed in a tank of rectangular upper cross section and a lower vegetated valley of trapezoidal shape to study the effect of drag resistance, due to vegetation, on gravity currents. For the simulation of the vegetation the bed is covered by flexible grass vegetation (height of vegetation, h_v=2.0cm) of different submergence ratio h_v/H from 0.125 to 0.5 (h_v=height of vegetation, H=water depth). Twenty four experiments are performed twelve inside the trapezoidal section (H/H_{tr}=0.4, 0.6 or 0.8) and twelve over the trapezoidal section (H/H_{tr}=1.2, 1.4 or 1.6) for the grass-type of vegetation. Results are compared with those of similar experiments without vegetation (Keramaris and Prinos, 2010) and hence the effect of the vegetation drag resistance on the motion of the current is investigated. Also the results are compared with those for rectangular cross section (Shin *et al*., 2004) without vegetation and box model results of Monaghan *et al*. (2009a, 2009b) for triangular valleys also without vegetation. The comparison indicates that the effect of the valley geometry and the steepness of the side walls on the motion are significant.

2. EXPERIMENTAL PROCDURE-MEASUREMENTS

Experiments were conducted in a tank of a composite cross section, which consists of a rectangular upper cross section and a lower trapezoidal shape. For the simulation of the vegetation the bed is covered by flexible grass vegetation of different submergence ratio h_v/H (h_v=height of vegetation, H=water depth). The height of vegetation was 2cm (photograph 1). The dimensions of the tank are: width W=23cm, height H=25cm high and total length L=5m. The trapezoidal section of the valley has the following dimensions: bottom width B=5cm, height H_{tr}=10cm and side slope 1:1.The tank was separated into two reservoirs by a removable thick vertical partition, which was removed at the start of the experiments. One reservoir (without vegetation) was filled with H=4, 6, 8, 12, 14 or 16cm of well-mixed saltwater of density ρ_{sw} and the other (with vegetation) with freshwater of density ρ_w ($\rho_w<\rho_{sw}$) until the free surface in both reservoirs was aligned. Density difference between salt water and clear water was varied between 0.1% and 0.4% (ρ_w=1000kg/m^3, ρ_{sw}=1010 or 1020 or 1030 or 1040kg/m^3). Twelve experiments were conducted inside the trapezoidal section (H/H_{tr}=0.4, 0.6 or 0.8 for four different densities) and twelve over the trapezoidal section (H/H_{tr}=1.2, 1.4 or 1.6 for four different densities). The distance from the lock gate to the front edge of the current head is denoted as x (figure 1).

The slope of the channel was horizontal. Experiments began with the removal of the vertical partition. Gravity current is generated, due to the horizontal density gradient, after the removal of the partition. The heavier fluid propagates towards the lighter fluid reservoir along the bottom of the tank and the lighter fluid propagates along the free surface in the opposite direction. For flow visualization, the saltwater was dyed with rhodamin (red color). Series of images were captured using a camera mounted on a stationary tripod in front of the tank after the initiation of the current. These recordings were subsequently analyzed to determine the front position and velocity as functions of time, by measuring the time required for the front to travel fixed-length intervals marked on the tank. A digital camera was used for the viewing of current and then the height and the position of the current front measured (photograph 1).

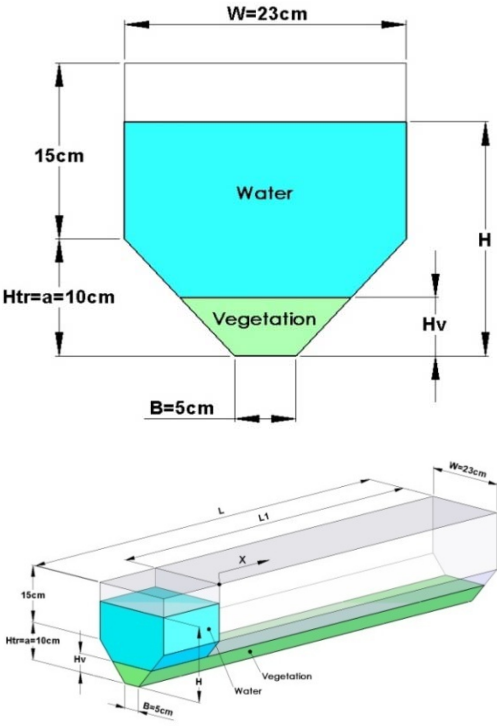
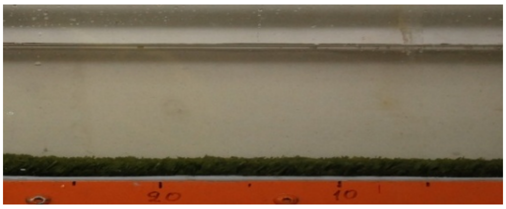
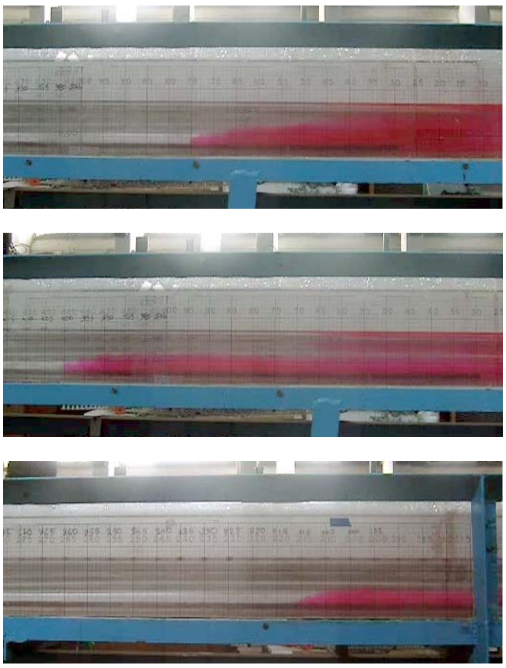


Fig. 1. Tank dimensions and symbols used.



Photograph 1 Flexible Grass Vegetation (h_v=2.0cm)



Photograph 2 Gravity Current (H/H_{tr}=1.2 cm, Density Difference 0.3%) at three locations (x=50 cm, x=100 cm, x=170 cm)

3. ANALYSIS OF RESULTS

In figure 2 the effect of density difference on the motion of the gravity current is examined. The current with the greater difference (density difference 0.4%) travels faster than the others in both cases (H/H_{tr}=0.4 within valley and H/H_{tr}= 1.6 composite). This is due to the fact that the velocity of the gravity current increases with increasing density difference. The effect of density difference is more pronounced in the case of composite section than the trapezoidal section. Also, as we expect the gravity current without vegetation travels faster in comparison with that with vegetation.

In figure 3 the effect of relative depths H/H_{tr} on the motion of the gravity current is examined for the same density difference 0.1%. As it is observed, the gravity current with the greater $H/H_{tr,}$ travels faster in all cases for the vegetation. The gravity current without vegetation travels faster in comparison with that with vegetation.

In figure 4 the dimensionless distance x* is plotted against the dimensionless time t* from the opening of the gate for currents within orthogonal and trapezoidal valleys. The distance x is made dimensionless with the water depth H (x*=x/H) and the time t from the lock exchange with the parameter:

$$\sqrt{g(1-\gamma)/H} \quad (t^{*}=t\sqrt{g(1-\gamma)/H}, \gamma=\rho_w/\rho_{sw})$$

Figure 4 includes box model results of Monaghan *et al*. (2009a, 2009b) for triangular valleys (slope of the valley is 12°, 23° and 41° to the horizontal with respective depths of the valley 0.03m, 0.06m and 0.12m) together with our experimental results for trapezoidal valley (with side slope 1:1) and results for orthogonal valley (Shin *et al*., 2004). The effect of the valley geometry and the steepness of the side walls on the motion are significant. Also, as we expect the presence of vegetation reduce the velocity of these gravity currents.

In figure 5 the results of this study are compared with similar experiments performed by Monaghan *et al*. (2009a, 2009b) and with similar experiments without vegetation performed by Keramaris and Prinos (2010). As it is shown in figure 5 the dimensionless distance x* is plotted against the dimensionless time t*. The distance x is made dimensionless with the parameter l and the time t with the parameter σ. The former parameter l is defined as: $l=\left(\frac{2V}{aw}\right)$, V= volume of the current ($V=L_1 w(H_0+\frac{1}{2}a)$ (L_1=distance between the lock gate and the rest of the tank, w=current width, H_0 =height of the water over the valley, a= depth of the valley), and $\sigma=\frac{1}{Fr}\sqrt{2/g'a}$, where Fr=Froude number is defined as : $Fr=U/\sqrt{g'h}$ (U=current speed, h= height of the current and g′ is the reduced gravity with $g'=g(\rho_{sw}-\rho_w/\rho_{sw}$ with g=9.81

m/s^2).This Froude number differs from the Froude number based on wave propagation As it is observed (figure 5) the presence of vegetation reduces the velocity of these gravity currents.

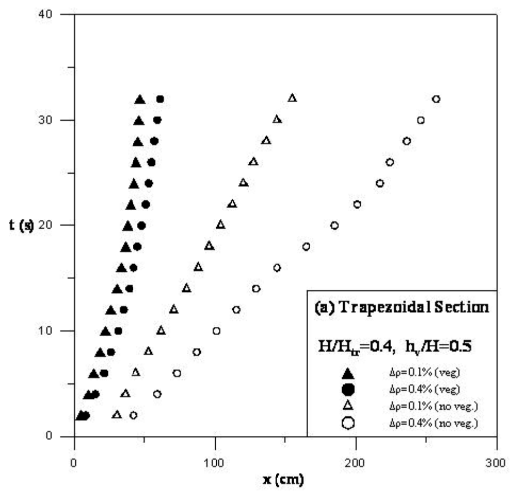


Fig. 2a. Effect of density difference on the motion of gravity current for vegetated and non-vegetated bed for trapezoidal section.

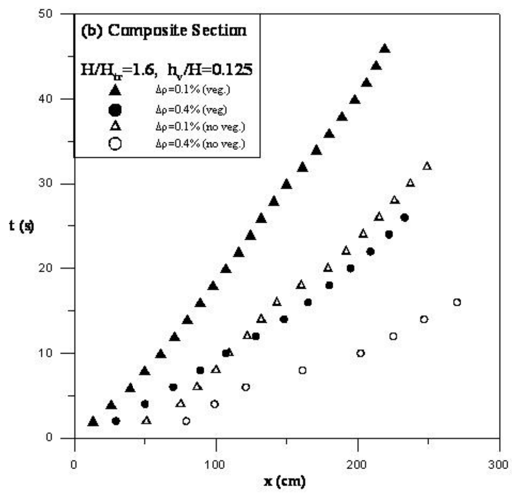


Fig. 2b. Effect of density difference on the motion of gravity current for vegetated and non-vegetated bed for composite section.

4. CONCLUSIONS

In this study lock-exchange experiments are performed in a tank of a composite cross section (an upper rectangular cross section and a lower trapezoidal cross section with a vegetated bed) to study the effect of drag resistance, due to vegetation, on gravity currents. The lock-exchange experiments are performed for equal depths of heavy and light fluid in both sides of the lock gate. The gate separates the two fluids (water and saltwater) with density difference 0.1%, 0.2%, 0.3% and 0.4%.

The main conclusion of this study is that the shape of the tank plays a significant role in the propagation of gravity currents. Especially the presence of trapezoidal increases the velocity of gravity currents in comparison with triangular or orthogonal shape.

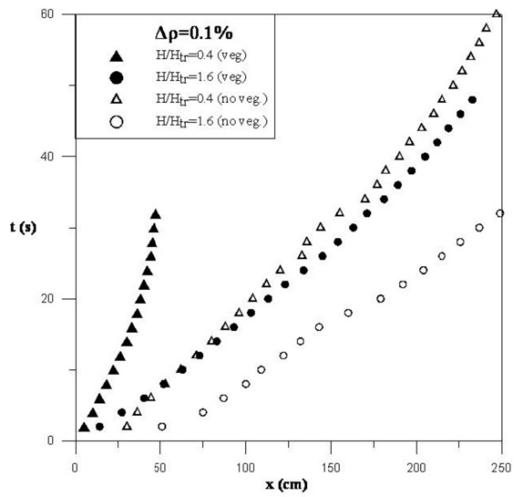


Fig. 3. Effect of relative depth H/H_{tr} on the motion of gravity current for vegetated and non-vegetated bed.

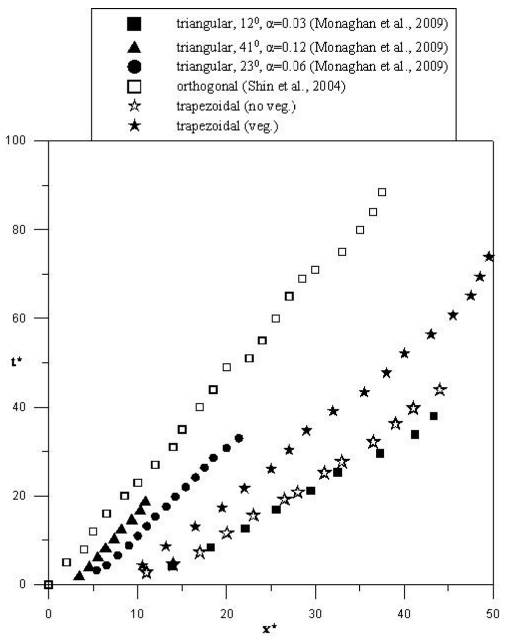


Fig. 4. Time development of gravity front for triangular, orthogonal and trapezoidal cross section (dimensionless).

Other main conclusions of this study are:

- The gravity current propagates with a parabolic head. The current with the greater difference density difference 0.4%) travels faster than the others in both cases (Trapezoidal section and composite cross section). This is due to the fact that the velocity of the gravity current increases with increasing density difference.
- The effect of density difference is more pronounced in the case of composite section than

the trapezoidal section. The gravity current with the greater H travels faster in all cases. The gravity current without vegetation travels faster in comparison with these with vegetation.

- The dimensionless distance x* is plotted against the dimensionless time t* for both rectangular and trapezoidal channels. The effect of the cross section on the motion of the current is clear. Also results from the box model of Monaghan *et al*. (2009a, 2009b) for triangular valleys of different side wall steepness indicate the dependence of the current motion on the geometry of the valley.
- The dimensionless distance x/l is plotted against the dimensionless time t/σ. There is a satisfactory agreement between the results of this study with similar experiments in V-shaped valleys performed by Monaghan *et al*. (2009a, 2009b) and Keramaris and Prinos (2010).

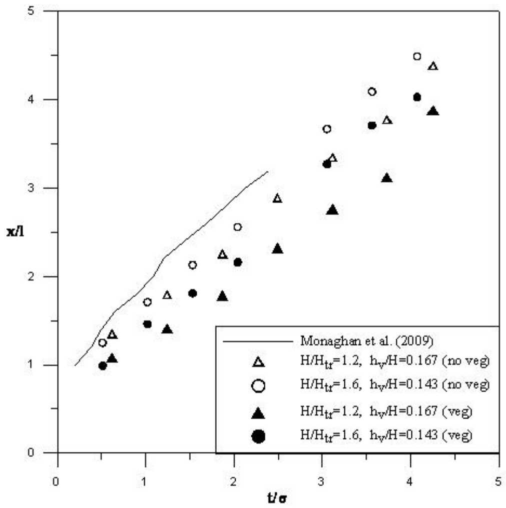


Fig. 5. Time development of gravity front for a valley of composite cross section (dimensionless).

REFERENCES

Antenucci, J. P., J. D. Brooks and M. R. Hipsey (2005). A simple model for quantifying cryrtospridium transport, dilution and potential risks in reservoirs, *J. Am Water Works Assoc*. 97, 86-93.

Banyal, A. S. (2013). A mathematical theorem on the onset of stationary convection in couple-stress fluid, *J. Appl. Fluid Mech*. 6(2), 191-196.

Keevil, G. M., J. Peakall, J. Best and K. J. Amos (2006). Flow structure in sinuous submarine channels : velocity and turbulence structure of an experimental channel, *Mar.Geol*. 229, 241-257.

Keramaris, E. and P. Prinos (2008). Gravity currents over a vegetated bed, *Proc. of International Conference on Fluvial Hydraulics, RiverFlow* 1, 305-310, Cesme-Izmir, Turkey.

Keramaris, E. and P. Prinos (2010). Gravity Currents in a Valley of Trapezoidal Shape, *Proc. of International Conference on Fluvial Hydraulics, RiverFlow* 599-604, Braunschweig, Germany.

Kumar, K., V. Singh and S. Sharma (2015). On the onset of convection in a dusty couple-stress fluid with variable gravity through a porous medium in hydromagmetics, J*. Appl. Fluid Mech*. 8(1), 55-63.

Kumar, P. (2012). Thermosolutal magneto-rotatory convection in couple-stress fluid through porous medium, J*. Appl. Fluid Mech.* 5(4), 45-52.

Monaghan, J. J., C. A. Meriaux, H. E. Huppert and J. Mansour (2009). Particulate gravity currents along V-shaped valleys, *J. Fluid Mech*. 631, 419-440.

Monaghan, J. J., C. A. Meriaux, H. E. Huppert and J. M. Monaghan (2009). High Reynolds number gravity currents along V-shaped valleys. *European Journal of Mechanics B/Fluids* 28, 651-659.

Oldham, C. E. and J. J. Sturman (2001). The effect of emergent vegetation on convective flushing in shallow wetlands: Scaling and experiments, *Limnol. Oceanorg.* 46(6), 1486-1493.

Shin, J. O., S. B. Dalziel and P. F. Linden (2004). Gravity currents produced by lock-exchange, *J.Fluid Mech.* 521, 1-34.

Simpson, J. E. (1997). Gravity Currents in the Environment and the Laboratory, *Cambridge Univ. Press*, New York.

Takagi, D. and H. E. Huppert (2007). The effect of confining boundaries on viscous gravity currents, *J. Fluid Mech*. 577, 495-505.

Takagi, D. and H. E. Huppert (2008). Viscous gravity currents inside confining channels and fractures. *Phys. Of Fluids* 20, 023104-1-6.

Zemach, T. and M. Ungarish (2013). Gravity currents in non-rectangular cross-section channels: analytical and numerical solutions of the one-layer shallow-water model for high-Reynolds-number propagation*. Phys. Fluids* 25(026601), 1–24.

Zhang, X. and H. M. Nepf (2008). Density-driven exchange flow between open water and an aquatic canopy,*Water Resources Research* 44, 1-12.