Sediment deposition from turbidity currents in simulated aquatic vegetation canopies

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ABSTRACT

A laboratory flume experiment was carried out in which the hydrodynamic and sedimentary behaviour of a turbidity current was measured as it passed through an array of rigid obstacles. The obstacles were intended primarily to simulate aquatic vegetation canopies, but could equally be taken to represent other things, for example forests or offshore wind turbines. The turbidity currents were generated by mixing naturally-sourced, poly-dispersed sediment into a reservoir of water at concentrations from 1 to 10 gL⁻¹, which was then released in the experimental section of the flume by removing a lock gate. For each initial sediment concentration, runs with obstacle arrays with solid plant fractions of 1% and 2.5%, and control cases with no obstacles, were carried out. The progress of the current along the flume was characterized by the array drag term, $C_D a x_{toe}$ (where $C_D$ is the array drag coefficient, $a$ the frontal area of cylinders per unit volume and $x_{toe}$ the current toe position along the flume). The depositional flux of sediment from the current as it proceeded was measured at thirteen traps positioned along the flume. Analysis of these deposits divided
them into fine (2.2–6.2 μm) and coarse (6.2-104 μm) fractions. At the beginning of the
development, the gravity current proceeded in an inertia dominated regime until \( C_{Dax_{oe}} = 5 \).
And for \( C_{Dax_{oe}} > 5 \), the current transitioned into a drag-dominated regime. For both fine and
coarse sediment fractions, the rate of sediment deposition tended to decrease gradually with
distance from the source in the inertial regime, remained approximately constant at the early
drag-dominated regime, and then rose and peaked at the end of the drag-dominated stage.
This implies that, when passing through arrays of obstacles, the turbidity currents were able
to retain sufficient sediment in suspension to maintain their flow until they became
significantly influenced by the drag exerted by the obstacles.

**Keywords** gravity current, inertial regime, drag-dominated regime, sediment deposition,

**canopy**
INTRODUCTION

The dynamics of gravity currents have been studied for many years using lock exchange experiments, in which two fluids of different densities within an experimental flume are initially at rest and separated by a lock gate. When the gate is removed, differences in the hydrostatic pressure cause the denser fluid to form a gravity current in one direction along the bottom boundary of the tank, while the lighter fluid flows in the opposite direction above it. Analysis of this flow configuration has been carried out theoretically, notably by Benjamin (1968), and experimentally, notably by Simpson (1982) and Shin et al. (2004). The interface between the two counter-flowing currents will be largely horizontal, but will curve sharply to become near-vertical at their leading edges (Benjamin, 1968). In lock-release gravity currents, three phases can develop, as observed by several investigations (e.g. Marino et al., 2005; Adduce et al., 2012). In the first, inertial phase, the front's position varies as $t^{1/2}$ (i.e. the front velocity is constant); this phase lasts until the motion is affected by reflections from the back wall of the channel. In the second, self-similar phase, the relationship of the front's position to time is dependent on the Reynolds number. In infinite lock release cases where the Reynolds number is low enough that a linear drag law (i.e. the drag coefficient $C_D \approx 1/Re$) can be assumed, it varies as $t^{1/2}$, whereas in cases where the Reynolds number is high enough that the drag coefficient can be assumed constant, it varies as $t^{2/3}$. Ozan et al. (2015) pointed out that currents which begin this phase in the high Reynolds number regime may be slowed sufficiently by drag forces that they transition from the high Reynolds number case to the low Reynolds number case during their evolution. The same authors also found that, in LES models of gravity currents passing through arrays of horizontally-aligned obstacles, the currents were not entirely self-similar (i.e. the positions of the front and body of the current did not have the same dependence on time) because of mixing at the current's interface with the ambient fluid. In their models, the front's position varied as $t^{3/4}$ rather than the $t^{2/3}$ observed by others and predicted by shallow water theory. Finally, the currents may
transition to a third phase in which the dominant force balance is between viscous and
buoyancy forces, and the front’s position varies as $t^{1/5}$.

The effects on lock-released gravity currents of bed roughness have also been studied by
recent laboratory and numerical investigations (e.g. La Rocca et al., 2008; Gonzalez-Juez et
al., 2009, 2010; Nogueira et al., 2013, 2014; and Bhaganagar 2014). The bed roughness
was found to affect the front propagation, the amount of entrainment of the ambient fluid into
the current and the current’s ability to entrain sediments from the bed.

In many situations, there are substantive obstacles to gravity currents, and in these
situations the drag forces that these obstacles impose can dominate both inertial forces and
the drag due to the boundaries of the flow domain. Gravity currents may become drag-
dominated where they propagate into partially or fully vegetated channels, which have been
simulated in laboratory experiments by arrays of rigid cylindrical obstacles (Hatcher et al.,
showed that gravity currents produced by finite volume release of a relatively dense fluid into
a relatively less dense ambient that flow through such arrays of obstacles decrease their
velocity as they proceed such that the position of the current front, $x_c$, evolves following:

$$ x_c \sim \left( \frac{q_o g' d}{C_D \phi} \right)^{1/4} \cdot t^{1/2} $$

(1)

where $q_o$ is the total current volume per unit across-flume distance; $g'$ is the reduced gravity
g'=$g(\rho_c-\rho_a)/\rho_a$ ($\rho_c$ and $\rho_a$ are the current and ambient fluid densities respectively); $d$ is the
individual obstacle width (cylinder diameter); $\phi= (\pi/4)ad$ is the volume fraction of the
obstacles; $a = Nd/A$ is the frontal area of cylinders per unit volume (Nepf, 1999), $N$ is the
number of cylinders, $A$ is the bed area occupied by the cylinder array; and finally $C_D$ is the
array drag coefficient. $C_D$ is a function of the cylinder Reynolds number $Re_c = |u|d/\nu$ (where $\nu$
is the kinematic viscosity of the fluid, and $u$ the toe velocity). For smooth, isolated circular
cylinders and Re values in the range \(1 \cdot 10^5\), \(C_D\) is described by the empirical expression (White, 1991):

\[C_D \approx 1 + 10.0 \text{Re}^{-2/3}\]  

This expression holds for vegetation canopies in which the dimensionless array density, \(ad < 0.03\) (Nepf, 1999).

If situations where drag can be neglected, the gravity current evolution reduces to the classic un-obstructed release from an infinite lock, where the position of the current’s front \(x\) is linear with time and the current propagates at a steady velocity that may be reasonably approximated as (Tanino et al., 2005),

\[x_c \sim \left(\frac{g' \cdot H}{4}\right)^{1/2} \cdot t\]  

After analysing an infinite lock release through obstacles, Tanino et al. (2005) obtained that drag forces dominate inertia, when the array drag is \(C_D aL > 7\) (being \(L\) the current toe position along the flume, \(x_{\text{toe}}\) in the present study). In such case, the dependence of \(x\) is a power dependence with time, in accordance with Hatcher et al. (2000). This leads to a change in the shape of the interface between the gravity current and the ambient fluid. This interface is nearly horizontal during the inertial regime, but takes on a triangular side view profile in the drag-dominated regime (Tanino et al. 2005), such that the interface profile can be used as a criterion to classify flow regimes.

Turbidity currents are a subset of gravity currents, in which the density differences are due to differences between the concentrations of suspended particles in the two fluids. They occur commonly in nature, and may persist for long travel times and produce significant modifications of substrate characteristics via sediment scouring and deposition (Kneller and Buckee, 2000; Hogg and Woods, 2001; Felix, 2002). Unlike gravity currents where the
density differences are due to conservative properties of the fluid, such as salt concentration or temperature, turbidity currents are complicated by the fact that they may entrain sediment particles (by bed scouring) or lose sediment particles (by deposition), increasing or decreasing, respectively, density differences that drive them as they propagate. The propagation and deposition patterns of turbidity currents are governed by both their flow structure and sediment characteristics (concentration and grain size). Aquatic examples of these phenomena are found in reservoirs (Chikita, 1989), lakes (Roget and Colomer 1996; Serra et al., 2002a; Serra et al., 2005; Soler et al., 2009), and oceans (Kneller and Buckee 2002; Felix, 2002; Meiburg and Kneller, 2010). In those turbidity currents it is necessary to introduce a transport equation for the particle concentration to take into account that the driving buoyancy force changes with time and position along the current because of the settling out of the particles which in fact reduces the density difference. Their spatial structure is determined mainly by their grain-size distribution flow behaviour is distinguished depending on whether it is formed by fine or coarse grains), whereas their temporal evolution is determined by both grain-size distribution and concentration (Felix, 2002). Gladstone et al. (1998) found that the distance to which coarse particles are transported within bi-disperse turbidity currents increases substantially as the proportion of fines in the flow is increased, and that adding small amounts of fine sediment to a coarse-grained gravity current has a much larger influence on flow speed, run-out distance and deposition patterns than adding a small amount of coarse sediment to a fine-grained turbidity current.

Hoult (1972) and Fannelop & Waldman (1972) studied the specific problem of lock-release oil slick and Chen (1980) studied spills of other hazardous fluids. Bonnecaze et al. (1993) studied a particle-laden gravity current of finite volume spreading over a rigid un-obstructed horizontal surface, assuming that particles diluted were non-cohesive and monodisperse with equal settling velocity; they applied shallow-water equations that led to a relationship between the length of the particle-driven current, $x_c$, and time since release, $t$, that was found to be $x_c \sim t^{2/3}$. 
When turbidity currents encounter arrays of obstacles, such as vegetation canopies in saltmarshes, lake littoral zones and seagrass meadows, the obstacles’ drag forces act to reduce the currents’ speed, as well as causing decreases in bed shear stress, which lead to reduced erosion and transport of bed sediment (Zong and Nepf 2011; Montakhab et al., 2012). However, work on turbidity currents’ interactions with vegetated canopies and other arrays of obstacles has so far been restricted to understanding their hydrodynamics. As a result, the influence of these interactions on the currents’ sediment transport and deposition is currently poorly understood. Recently, Testik and Yilmaz (2015) have studied the propagation of continuous-flux release gravity currents through emergent vegetation but experiments were conducted with non-Newtonian mud gravity currents. To our knowledge, the novelty of this study is the fact that it has studied the effect of emergent vegetation on a gravity current driven by the presence of suspended particles, and not generated by a saline dissolution. This paper, therefore, sets out to investigate the influences of characteristics of both turbidity currents and arrays of obstacles through which they flow on their hydrodynamic and sedimentary development.

METHODOLOGY

Experiments were conducted in a 4 m long, 0.3 m high and 0.3 m wide methacrylate flume (Fig. 1) that was separated into two sections by a removable vertical lock gate: the shorter section (to the left in Fig. 1A) acted as a reservoir in which the sediment-laden water that would form the turbidity current was prepared, while the longer section (to the right in Fig. 1A) formed the experimental section in which the interaction of the turbidity current with the array of obstacles occurred. The experimental section was populated with vertical PVC dowels intended as generic models of the rigid stems of plants in an emergent vegetation
canopy. Hereinafter, we use the term “canopy” to refer to this array of dowels, and in doing so implicitly acknowledge that they are an artificial, generic model of a vegetation canopy.

This experimental configuration can also be taken to represent a generic model of a much wider range of interactions of turbidity currents with arrays of isolated, rigid obstacles, for example, the propagation of snow avalanches or pyroclastic flow through forests, or of submarine turbidity currents on continental shelves through offshore wind turbine farms.

The dowels’ positions were selected by means of a random number generator, following Pujol et al. (2013). Each dowel had a height of 20 cm and a diameter, \( d = 0.6 \) cm, and was inserted into a perforated PVC base sheet. The canopy density was quantified, following Pujol et al. (2010) using the Solid Plant Fraction (SPF), which is defined as the fractional area at the bed occupied by the dowels, \( SPF = 100\pi(d/2)^2/A \), where N is the number of plants and A is the total bed area. In the present study, in addition to cases where no canopy was present (SPF = 0%), two canopy densities were used. These had SPF of 1% and 2.5%, which correspond to 128 and 320 obstacles \( m^{-2} \), and values of the frontal area of obstacles per unit volume of 0.02 to 0.05 \( cm^{-1} \), respectively (Fig. 1B). These correspond to dimensionless array densities \( ad \) of 0.01 and 0.03, which fall within the range observed in natural vegetation canopies (e.g. \( ad = 0.01 \) to 0.1, Kadlec, 1990).

The flume was filled with water to a height \( H = 12 \) cm, and the lock gate put in place, sealing off the two sections from each other. A volume of 3 litres of water was taken from the reservoir section, to which sediment was added, stirring vigorously for five minutes to ensure full mixture of the particle suspension. The sediment-laden water sample was then returned to the reservoir section and mixed with the remainder of the water therein, giving an initial sediment concentration, \( C_0 \). Five values of \( C_0 = 1, 2.5, 5, 7.5, \) and 10 \( gL^{-1} \) – were used. The sediment was taken from four field sites in the Empordà Marshes Natural Park, located in the North-East of Spain, and was a mixture of clays, silts and very fine sands. Its particle size distribution was determined using a LISST-100 particle size analyser (Sequoia...
Scientific, Inc., WA, USA). This instrument determines the volume occupied by particles in each of 32 size classes logarithmically distributed in the range of 2.5–500 μm. The size distribution was found to be bimodal, with 80% of the mass made up of coarse particles (diameter range: 6.2–104 μm) and the remaining 20% made up of fine particles (diameter range: 2.2–6.2 μm). Based on the classifications of Van Rijn (2007) and Blott and Pye (2012), the coarse particles fell into the category of weakly cohesive particles (fine to coarse silts and small sand particles), and the fine particles into the category of very cohesive particles (clays and very fine silts) (Fig. 2). The peak in Fig. 2 above 104 μm was assumed to represent just a few particles with large volumes, which, due to their small number, were not considered in the analysis.

Once the suspended sediment was well-mixed into the water in the reservoir, and the turbulence caused by this mixing had decayed, the lock gate was lifted to release the sediment-laden water, which flowed into the experimental section as a turbidity current. Speeds of experimental currents were of 2-3 orders of magnitude higher than settling velocity of coarse particles, and of 3-4 orders of magnitude higher than settling velocities of fine particles being therefore sufficiently high to suspend the particles in a well-mixed state. Thirteen sediment traps (ST1 to ST13), with volumes of 21.3 mL each, were placed on the bottom of the experimental flume section at 20 cm intervals, starting 20 cm from the lock gate (Fig. 1A) and finishing at 10 cm the end of the flume. These collected sediment deposited from the turbidity current as it proceeded along the flume. When the current arrived at the far end of the canopy, the traps were covered with lids to avoid collection of sediment that settled out of the current after it had been reflected by the end wall. They were then collected for size distribution analysis using the LISST-100. By integrating across all of the particle size classes, the total volume of particles in each trap was obtained (Serra et al. 2002b, 2005). This was then transformed into deposited sediment mass assuming that the density of the particles was 2.798 g·cm⁻³ (the standard value for the density of silt particles, Mandal and Maiti, 2015). This density is used because 80% of the sediment
volume was made up of silt particles (Figure 2). The deposited mass per unit bed area was converted to a depositional flux rate at each sediment trap by dividing by the time over which the deposition occurred. Five turbidity sensors, T1 to T5, (Seapoint Turbidity Meter, Seapoint Sensors Inc., NH, USA) and two CCD cameras mounted on stationary tripods over the tank (Fig. 1A), were used to measure the time evolution of the current’s front and determine its speed. This was done in two ways: firstly, by dividing the distance between pairs of turbidity sensors by the difference in the time taken for the front to reach them, and secondly from the images captured by the CCD cameras. The front’s position was located on these images using edge detection. Parallax error was less than 4% in these images and was not corrected for in the analysis. Variations of 2% were found between velocity values calculated from the turbidity sensor data and the camera images.

Fifteen experimental runs were carried out (Table 1), covering the full matrix of combinations of five values of initial sediment concentration, C₀, (1, 2.5, 5, 7.5, and 10 gL⁻¹) and three different canopy densities (SPF values of 0, 1 and 2.5%).

RESULTS

Advance of the turbidity current

The progression of the leading edge – or “toe” as it is called by Tanino et al. (2005) – of the turbidity current was analysed. In non-vegetated experiments, its distance from the lock gate, x[toe], was plotted against time (t) for the five experimental runs (Fig. 3A). For all sediment concentrations, x[toe] presents a power trend. At later times the loss of particles reduced the buoyancy force driving the current, causing deviations from x[toe] ∝ t. This behaviour can also be found in cases where SPF ≠ 0 (Fig 3B, 3C) for which the deviation is more accentuated due to the effect of vegetation which also influences the current speed.
Gravity currents generated in not vegetated experiments flowed with a constant speed along the whole flume following inertial regime, resulting in agreement with Rottman and Simpson (1983) findings. In vegetated experiments (SPF 1% and 2.5%), although they were carried out by an infinite release, the gravity current transitioned from the inertial to the drag-dominated regime (as finite volume releases do). Presumably this is caused because reflections from the back wall travel through un-obstructed fluid whereas the particle-driven current is propagating through the obstacles resulting in a slowing down speed which therefore can interact with the reflected bore... In order to elucidate the moment at which the gravity currents in the vegetated cases changed from the inertial to the drag-dominated regime, it was studied the temporal dependency of data from the SPF=1% and SPF=2.5% runs. As can be seen in Figure 4A, at early times, the behaviour of the gravity currents flowing through vegetation canopies had a $-t^{1/3}$ dependency (Equation 3), in agreement with the findings of Tanino et al. (2005), and similar to that of the gravity current in the non-vegetated case, but once the drag effect of the vegetation became more significant, it reduced current speed and it was found a dependency of the toe position with $t^{1/2}$ in agreement with the findings of Hatcher et al. (2000). The point at which this change occurred was used to deduce that the transition from the inertial to the drag dominated regime occurred and it coincided with $C_Da x_{toe}= 5$ value (where $C_D$ is the array drag coefficient, $a$ the frontal area of cylinders per unit volume and $x_{toe}$ the current toe position along the flume). Tanino et al. (2008) found that $C_D a L= 7$ (where L corresponds to $x_{toe}$ in this manuscript). This value is smaller than the one found by Tanino et al. (2008), implying that particle-driven currents are affected by vegetation drag earlier than salinity-driven gravity currents. Data which $C_D a x_{toe} \geq 5$ are plotted against $((q_0 \cdot g' \cdot d)/(C_D \cdot \phi))^{1/4} \cdot t^{1/2}$ (Equation (1) from Hatcher et al, 2000) (which incorporates the effect of sediment concentration – quantified as $g'$ – and the effect of the canopy – quantified via $C_D$ and $\phi$, although models salinity driven currents) in Fig. 4B.
The agreements were found regardless of both the initial sediment concentration and the canopy density because particle-driven currents behave similarly to saline ones before appreciable settling occurs. In Figure 4B in the range of the x axis from 200 cm to the end of the flume measurements slightly deviate from the general trend $t^{1/2}$ depending on the initial sediment concentration. The model developed by Hatcher et al. (2000) corresponded to salinity-driven gravity currents; therefore since particles were not included in the model, the experimental results might slightly shift from those obtained by Hatcher et al. (2000). The reason might be in the fact that laden gravity currents might loss sediment particles as they travel along the flume. It is expected that this process has a greater effect for denser gravity currents.

In addition, while the time dependence between $x_{toe}$ and $t$ is in accordance with that predicted by both, Tanino et al. (2005) and Hatcher et al. (2000), depending of the regime, a slower slope was found. In the inertial regime, our data follow a slope of 0.4 while a higher slope of $\sim$1 was found by Tanino et al. (2005). In the drag-dominated regime, our data follow a slope of 0.7 while a higher slope of $\sim$2 was found by Hatcher et al. (2000). This smaller slope values are occasioned because the models which have been used to compare both regimes ($x_{toe}^{-t}$ and $x_{toe}^{-t^{1/2}}$) corresponded to salinity-driven gravity current instead of being a particle-laden current. Experiments developed with particle-driven currents change their speed when settling occurs and also, it has to been in account the effect of particle capture on the cylindrical stems (Palmer et al. 2004). This loss of sediment causes a reduction on current speed happening therefore in a decreasing gradient, as found.

Sediment transport and deposition

Figure 5 presents the depositional flux rates for runs with an initial sediment concentration of 1 gL$^{-1}$ at the thirteen sediment traps within the canopy. The not-vegetated cases (SPF = 0%)
show a clear difference between the depositional flux rates of the fine and coarse particle fractions, with the fine fraction peaking approximately two-thirds of the way down the canopy, while the flux of coarse particles decayed essentially monotonically with distance from the lock gate. These patterns are similar to those found in experiments on bi-disperse turbidity currents with the same initial proportions by mass as were used here – 80% coarse particles and 20% fine particles – carried out by Gladstone et al. (1998). In those experiments, the depositional density of the fine fraction reached its maximum value at a position that was independent of the initial concentration of fines, and the coarse fraction deposition was greatest nearest to the lock gate.

The plots of depositional flux rates in the runs where canopies are present (Fig. 5 B,C,E and F) show the flow regimes through which the turbidity current develops: the initial, inertial regime \( (C_{\text{Daxtoe}} < 5) \), and the drag-dominated regime \( (C_{\text{Daxtoe}} \geq 5) \). For experiments with the presence of vegetation, only a ~62% (SPF 1%) and a ~38% (SPF 2.5%) of the sediment from the gravity current penetrate within the canopy when compared with the not vegetated experiment. Furthermore, the SPF = 1% canopy causes the depositional flux rates of fine and coarse particles (Figs. 5B and 5E) to decay consistently from the lock gate through the inertial regime, and to reach their minima at \( L \approx 200 \text{cm} \). In the beginning of the drag-dominated regime, these flux rates remain essentially constant, a slight increase at the end of the flume is caused by the fact that deposit values at each sediment tramp (ST) have been divided by the time over which the deposition occurred, for this reason last ST value were removed because the elapsed time biased the data from the plot. In the denser canopy runs (SPF = 2.5%, Figs. 5C and 5F), flux rates remain essentially constant along the flume. It can be also seen that the flux rates are higher here than for the corresponding SPF = 1% cases, as the current is moving slower.
Fine and coarse sediment log depositional flux rates for all runs are plotted in Figs 6 and 7 respectively. Across all of these plots there is a consistent pattern of greater initial sediment concentrations leading to larger depositional flux rates. The fine particles in the not-vegetated (SPF = 0 %) runs with initial sediment concentrations of 1 and 2.5 gL$^{-1}$ (Fig. 6A) had maximum depositional flux rates at $x = 180$ and 220 cm, respectively, while in experiments with higher initial concentrations, the maximum fine particle depositional flux rates are found at ST12, the furthest sediment trap from the lock gate ($x = 240$ cm). For the SPF = 1% and 2.5% cases (Figs. 6B and 6C, respectively), the fine particle depositional flux rates for lower initial sediment concentrations (1 and 2.5 gL$^{-1}$) reached minima at runout distances of $x = 200$ and 220 cm, while in the higher initial concentration cases (5, 7.5 and 10 gL$^{-1}$), these rates were constant up to the same point, and increased slightly thereafter. It can also be seen that curves were gathered in two groups depending on their initial concentration: low initial concentration (1, 2.5 g/l) and high initial concentration (5, 7.5, 10 g/l).

Depositional flux rates of coarse fraction sediments in not-vegetated runs (SPF = 0%) with low initial sediment concentrations (1, 2.5 and 5 gL$^{-1}$) decreased with runout distance until $x$ = 200-220 cm (Fig. 7A). Runs with sediment concentrations of 7.5 and 10 gL$^{-1}$ had constant coarse fraction depositional flux rates from $x = 0$ to 200 cm and increased thereafter. In runs with vegetation (Fig. 7B and 7C), the coarse sediment depositional flux rates decreased with runout distance until $x = 200$ cm in a similar fashion for all initial sediment concentrations. In the SPF = 1% cases (Fig. 7B), differences in the depositional flux rates between low (1 and 2.5 gL$^{-1}$) and high (5, 7.5 and 10 gL$^{-1}$) initial sediment concentrations were more accentuated. As seen before with fine sediments, curves were also gathered in two groups depending on their initial concentration: low initial concentration (1, 2.5 g/l) and high initial concentration (5, 7.5, 10 g/l). As shown in Fig. 8, the amount of coarse particles in the deposited sediments diminished along the flume. The amount of fine particle deposition was maximum at ST12, the sediment tramp located at $x = 240$ cm, (corresponding to $C_{DAX_{loc}}$ values of 12 (for sediment concentration 5 gL$^{-1}$, SPF 1%) and 42 (for sediment concentration...
2.5 gL$^{-1}$, SPF 2.5%). At this point, and for an initial sediment concentration of 5 gL$^{-1}$, regardless of the canopy density (Fig. 8C and 8D) both the fine fraction and the coarse fraction were found in larger concentrations than at traps further upstream. This supports the theory that finer particles increase the distance to which coarser particles are transported, in agreement with the findings of Gladstone et al. (1998).

DISCUSSION

Our results demonstrate that when turbidity currents develop in an array of isolated, rigid obstacles (intended here to simulate vegetation canopies), the patterns of deposited sediment depend on whether the current is in an inertia-dominated regime or a drag-dominated regime. For each canopy density, a drag coefficient may be calculated and used to quantify the array drag $C_D a_x t_{oe}$ at each downstream location, $x_{t_{oe}}$, of the gravity current front. This defines the regime of the flow, and conveniently classifies it (Hogg and Woods et al. 2001; Tanino et al. 2005) and thus its depositional flux rates.

*Gravity flow characteristics within a canopy*

In Tanino et al.'s (2005) data, if $C_D a L < 7$, the gravity current was inertia-dominated, whereas if $C_D a L > 7$ it transitioned to a drag-dominated regime, being fully drag dominated if $C_D a L > 18$. In our study, where a particle-driven gravity current was studied instead of Tanino et al.'s salinity-driven gravity current, the $C_D a L (C_D a x_{t_{oe}})$ threshold value for the beginning of the transition from the inertial regime to the drag-dominated regime was $C_D a x_{t_{oe}} = 5$.

Analysis of frontal progression of gravity currents through arrays of obstacles in finite lock-release experiments shows that it in the initial inertial regime $x_{t_{oe}} \sim t$ and in the subsequent drag-dominated regime $x_{t_{oe}} \sim t^{1/2}$ (Tanino et al., 2005, Zhang and Nepf, 2008). Our results, although found in an infinite lock-release set up, show the same behaviour. As the gravity
current is initiated just before the canopy starts, the volume fraction of solid that current has
to face is so high that the gravity current flows slower than it would, allowing the bore,
generated in the back wall, to catch up with the front. At this moment the flow transitions to a
drag-dominated regime $x_{\text{toe}} \sim t^{1/2}$ in agreement with Hatcher et al. (2000). The differences in
the slope (proportionality constant) between our results and those of Tanino et al. (2005) and
Hatcher et al. (2000) mentioned above may be due to the characteristics of density-varying
agent within the current and vegetation set up. While Tanino et al. (2005) and Hatcher et al.
(2000) used a salinity-driven current, our experiments have been with a particle-driven
current. Again, the loss of particles settling out and by canopy capture caused a decrease of
its density and as a result a decrease of its speed. In summary, this study provides evidence
to support the theory that the dynamical balance between the array drag and the streamwise
pressure gradient (which is the basis of the predictions of Hatcher et al., 2000) provides a
good description of the propagation of a poly-disperse turbidity current for a finite-volume
release through an array of isolated, rigid obstacles. In addition, the vegetation distribution
along the flume differs from the Tanino et al. (2005) and Hatcher et al. (2000), starting just
after the lock gate, the sudden encounter with canopy causes a slower speed that current
would have compared with the whole flume covered with vegetation and in consequence a
lower value of the slope of the trend between $x_{\text{toe}}$ and $t$ in both the inertia and the drag-
dominated regime.

Depositional sediment fluxes from the gravity current

As pointed out by Felix (2002), sediment concentration and velocity can influence flow
behaviour independently. Within an array of isolated obstacles, such as a vegetation canopy,
the obstacles’ presence may induce momentum loss due to both, or either, decreasing
velocity (due to their drag) and decreasing density (due to sediment deposition), and these
two mechanisms need not to occur at the same time because the different time scales on
which they take place. In our experiment, variations in sediment concentration (and its rate of decrease due to deposition) and frontal speed were both primarily determined by whether the current was in an inertia-dominated or drag-dominated regime. In the inertia-dominated regime, the speed of propagation was slightly diminished and the depositional flux rate of the sediment decreased with time. In the drag-dominated regime, the speed of propagation decreased with time more quickly, and the depositional flux rate of the sediment increased with time.

Bonnecaze et al. (1996) and Harris et al. (2002), found that smaller particles are more easily transported than large particles, and that this causes the magnitude and downstream position of the depositional maximum to be greater for small particles. This occurs because while the coarse particles settle out, the fine particles remain in suspension and thus maintain the density difference between the current and the ambient. This was clearly observed in our experiments for the lowest initial sediment concentration (1 gL$^{-1}$) in the absence of a canopy, while at high particle concentrations, the depositional rate of both the fine and coarse particle fractions was still rising when the current front reached the end of the flume.

From the results of all of our runs, the depositional flux rate was found to depend on the canopy density, and the initial sediment concentration of the current, and to differ depending on whether the fine or coarse particle size fraction was being considered. These dependencies are summarised in Fig. 9 where it is plotted the depositional flux rate, normalized by the initial advective (horizontal) sediment flux at the lock gate (calculated by multiplying initial sediment concentration by initial current speed). This dimensionless flux rate decreased with $C_0\alpha_{\text{lock}}$ for both the fine (Fig. 9A, B) and coarse (Fig. 9C, D) fractions when the gravity current was in the inertial-dominated regime, whereas it increased at the end of the drag-dominated regime. This was found for all runs except for the fine fraction in
the cases where the initial sediment concentration was high (10 gL⁻¹) and the canopy density was low (SPF = 1%), in which the rate increased through the inertia-dominated regime.

For lower canopy density (SPF = 1%), the dimensionless normalised depositional flux rates for both size fractions is stratified, decreasing gradually with decreasing initial concentration (Fig. 9A and 9B). The same overall trend was found for the denser canopies (SPF = 2.5%), but the data splits into two clear groups: for both particle size fractions, dimensionless normalised depositional flux rates for the larger initial sediment concentrations (5, 7.5 and 10 gL⁻¹) are approximately one order of magnitude larger than those for the smaller initial sediment concentrations (1 and 2.5 gL⁻¹). It has been found that that this distinction occurs whether the C_D is larger or lower than 2. Therefore, denser canopies act to segregate sediment pattern from the gravity current, depending on its initial sediment concentration, whether the C_D is larger or lower than 2.

In the SPF = 1% cases, the dimensionless normalised depositional flux rates reached minima and began to increase in the beginning of the drag-dominated zone (5 < C_Dax toe), while for the SPF = 2.5% cases, this occurred only when the current reached the end of the drag-dominated regime. Thus, for both the fine and coarse fractions, maximal dimensionless normalised depositional flux rates occurred in the drag-dominated regime. The increase in depositional flux rates at this relatively late stage implies that the currents are able to retain much of their suspended material until they become significantly impeded by the drag of the canopy. The ratio of the current’s advective speed to the particles’ fall speed in the inertia-dominated regime is 955 for particles of 4 μm diameter and 375 for particles of 20 μm diameter (where fall speed was calculated assuming Stokes’ Law) and in the drag-dominated regime is of 128 for particles of 4 μm diameter and 50 for particles of 20 μm diameter, indicating the dominance of advective processes in the inertial regime. This dominance is likely to be enhanced by the action of the vertical turbulent component of velocity within the current, which helps to maintain the particles in suspension. This effect is
likely to be greater in the inertial regime than in the drag-dominated regime, since the ratio of
the cylinder Reynolds number associated to the front (toe) of the current in the inertial
regime to that in the drag-dominated regime is 2-4.

In summary, the propagation of particle-driven gravity currents, and the patterns of
deposition that they create which are reported here were found to be functions of canopy
density, suspended sediment characteristics (sediment concentration and grain size) and
distance from the current’s source. The evolution of the currents and their depositional
patterns may be categorised into an early, inertia-dominated stage in which deposition rates
mainly decrease monotonically, and a late drag-dominated stage, in which deposition rates
tend to peak. These stages are effectively delineated, by values of the array drag term
\( C_{D \text{ax}} \text{toe} < 5 \) (inertia-dominated) and \( > 5 \) (drag dominated), which are close, but not identical,
to those reported for salinity-driven gravity currents by Tanino et al. (2005).

Canopies act on gravity currents in first place allowing only a part of particles to flow into,
therefore, the presence of canopies not only play an important role in the sediment
deposition within the canopy but also in regions before the canopy, where a great amount of
sediment is deposited compared without the presence of vegetation. Once inside, coarse
particles settle monotonically from the first moment while finer particles run further from the
beginning of the canopy. Then a sediment gradation depending on distance from the canopy
edge is found, being located the coarse sediments (fine to coarse silts and small sand
particles) near the edge while finer sediments (clays and very fine silts) are located at further
distances.

NOMENCLATURE

a, frontal area of the cylinders per unit volume
ad, dimensionless array density
\( c_0 \), initial sediment concentration
\( C_D \), Drag coefficient
1 d, dowel diameter
2 \( \phi \), vegetation volume fraction
3 g', reduced gravity based on the density difference between the two layers
4 H, height of water
5 L, distance of the turbidity current front from the lockgate (L=x_{toe}) used in Tanino et al. (2005)
6 n, vegetation porosity
7 PVC, particle volume concentration
8 \( q_o \), total current volume per unit across-flume distance
9 Re, flow Reynolds number
10 Re_c, cylinder Reynolds number
11 SPF, fractional plant area at the bottom occupied by stems
12 x_{toe}, distance of the turbidity current front from the lockgate
13 u, instantaneous current front velocity

REFERENCES


CAPTIONS TO TABLES

Table 1. Summary of Experimental Conditions and parameters.

CAPTIONS TO FIGURES

Figure 1. (A) Side view of the laboratory flume which is divided by a removable, sealing partition (lock gate) into two reservoirs. The smaller, lefthand one is filled with water to a depth H=12cm and suspended sediments of an initial concentration, C₀. The righthand one contains a random array of emergent cylindrical obstacles (PVC dowels, representing rigid vegetation), and is filled with water to the same depth, H. The vertical coordinate is z, with z=0 at the bed (increasing upwards), and the longitudinal coordinate is x, with x=0 at the lock gate (increasing to the right). The vertical dashed lines indicate the position of five turbidity sensors (T1–T5). Thirteen sediment traps (ST1-ST13) are situated on the bed of the flume; ST1 is 20 cm to the right of the lock gate, and each subsequent trap is a further 20cm to the right. (B) Dowels’ horizontal positions generated to have a canopy randomly distributed with a SPF of 1 and 2.5 %.

Figure 2. The bimodal particle size distribution (particle volume concentration, PVC, plotted against particle diameter, d) of the natural sediments used for generating the gravity currents. The distribution splits into fine particle (F.P: 2.5 µm < φ < 6.2 µm) and coarse particle (C.P: 6.2 µm < φ < 104.0 µm) fractions.
Figure 3 Temporal evolution of the front of the turbidity current for runs with array densities of (A) Not-vegetated; (B) SPF = 1 and (C) SPF = 2.5%.

Figure 4. Temporal variation of the length of the turbidity current for runs within array densities of SPF=1% and SPF = 2.5%. (A) The dashed line illustrates the time dependence predicted for inertial dominated conditions (m= 0.4, $r^2=0.93$, n=47, p<<0.01). (B) The dashed line illustrates the time dependence predicted for drag dominated conditions (m=0.7, $r^2=0.94$, n=82, p<<0.01).

Figure 5. Depositional flux rates plotted against distance from lock gate for experiments with an initial concentration $C_0= 1\text{gL}^{-1}$. The lefthand panels (A, B and C) show results for the fine particle fraction for SPF = 0 (Not-vegetated) 1 and 2.5% respectively. The righthand panels (D, E and F) show corresponding results for the coarse particle fraction. For runs where an array of obstacles is present i.e. SPF ≠ 0 (B, C, E and F), the white areas correspond to the quadratic drag-dominated regime ($C_D a x_{toe} < 5$) and the grey zones correspond to the linear drag-dominated regime ($C_D a x_{toe} > 5$).

Figure 6. Semi-logarithmic plot of the depositional flux rate against distance for the fine particle fraction (particle diameters < 6.2 μm) for different initial sediment concentrations (1, 2.5, 5, 7.5 and 10 gL⁻¹). The panels show results for runs with (A)Not-vegetated; (B) SPF = 1%; and (C) SPF = 2.5% canopies.

Figure 7. Semi-logarithmic plot of the depositional flux rate against distance for the coarse particle fraction (particle diameters 6.2 - 104 μm) for different initial sediment concentrations (1, 2.5, 5, 7.5 and 10 gL⁻¹). The panels show results for runs with (A) Not-vegetated; (B) SPF = 1%; and (C) SPF = 2.5% canopies.
Figure 8. Depositional flux rates plotted against particle diameter for 4 sediment traps (ST1, ST4, ST7 and ST12) from runs with: (A) $C_0 = 2.5 \text{ gL}^{-1}$ and SPF = 1%, (B) $C_0 = 2.5 \text{ gL}^{-1}$ and SPF = 2.5%, (C) $C_0 = 5 \text{ gL}^{-1}$ and SPF = 1%, and (D) $C_0 = 5 \text{ gL}^{-1}$ and SPF = 2.5%.

Figure 9. Dimensionless depositional flux rates (normalised by the initial depositional flux rate - calculated by multiplying initial sediment concentration by initial current speed) plotted against the array drag, $C_D a_{x_{loe}}$. Panels A and C correspond to sparse canopy and B and D to denser canopy. The white zone corresponds to inertial-dominated regime ($C_D a_{x_{loe}} < 5$) and the grey zone to the drag-dominated regime ($C_D a_{x_{loe}} > 5$).
Fig. 1
Fig. 2
Fig. 3
Fig. 4
Fig. 5
Fig. 6
Fig. 7
Fig. 8
Fig. 9