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Drouge tracking by image processing for the study of laboratory scale pond hydraulics

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Abstract

Waste stabilisation ponds are one of the most widely used methods of wastewater treatment for small communities throughout the world. The treatment efficiency of waste stabilisation ponds is directly linked to their hydraulic regime, but to date pond hydraulics have been poorly researched. Because of climatic variation these low velocity, long residence time systems are difficult to systemically study in the field. An alternative is to undertake research on scale-model ponds operated under controlled conditions in a laboratory. This paper details a procedure that uses image processing for quantifying the velocity distribution and flow pattern within a scale-model pond using image processing. This technique is outlined in detail and examples of results derived from its application are presented. It is concluded that this technique is both effective as a relativity cheap and fast method of quantifying the flow behaviour in scale-model ponds. Furthermore because it continuously records the flow behaviour over a period of time, it can highlight unsteady-state flow behaviour that could otherwise go undetected when using other flow measurement techniques.

Keywords: Hydraulics; Image processing; Scale models; Wastewater ponds

1. Introduction

For thousands of communities around the world the only thing standing between raw sewage and the environment, into which it is ultimately discharged, is a waste stabilisation pond. The performance of wastewater stabilisation ponds is strongly dependent on the time the wastewater spends in the pond environment, which is a direct function of the hydraulic regime of the pond. Collection of repeatable and representative research data on the hydraulics of waste stabilisation ponds is therefore of interest. More specifically such information would be particularly useful for the validation of computational fluid dynamics (CFD) models [1–3]. For example, the output shown in Fig. 4 is that of a laboratory-scale model of a waste stabilisation pond. This pond was designed maintaining Froude number similarity so as to be representative of a full-scale system and then, at a constant flowrate and with a controlled climate, was used to test a wide range of hydraulic design variations. This wide range of experimental data was then able to be directly compared and contrasted against simulated results obtained using a CFD mathematical model.

The majority of hydraulic studies on waste stabilisation ponds have been undertaken on full-scale field ponds [4–12]. However, these 'field' systems are never in the steady state as they have transient inflow rates. Additionally, they have large surface areas that are exposed to constantly changing wind and temperature conditions. Because ponds have long hydraulic residence times (weeks) and, therefore, very slow internal flow velocities, they are significantly affected by such conditions. Field studies may, therefore, only ever be indicative of the hydraulic behaviour resulting from the conditions that existed during the study period.

An alternative method for the collection of repeatable and representative research data on the hydraulics of waste

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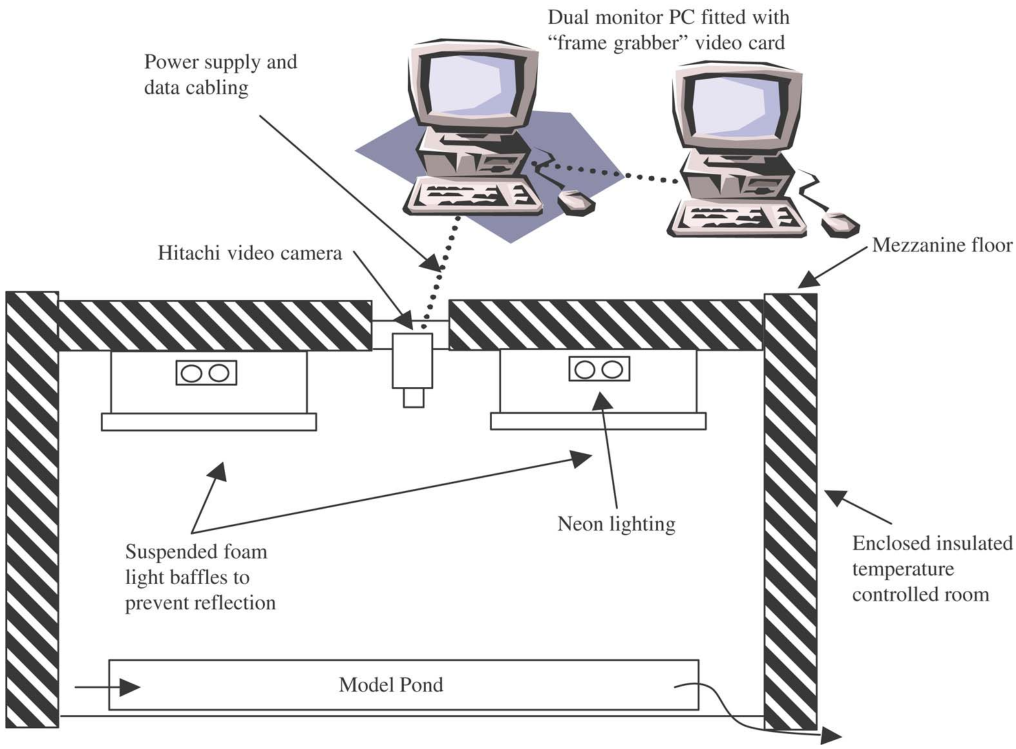

Fig. 1. Overview of the experimental set-up of the physical model.

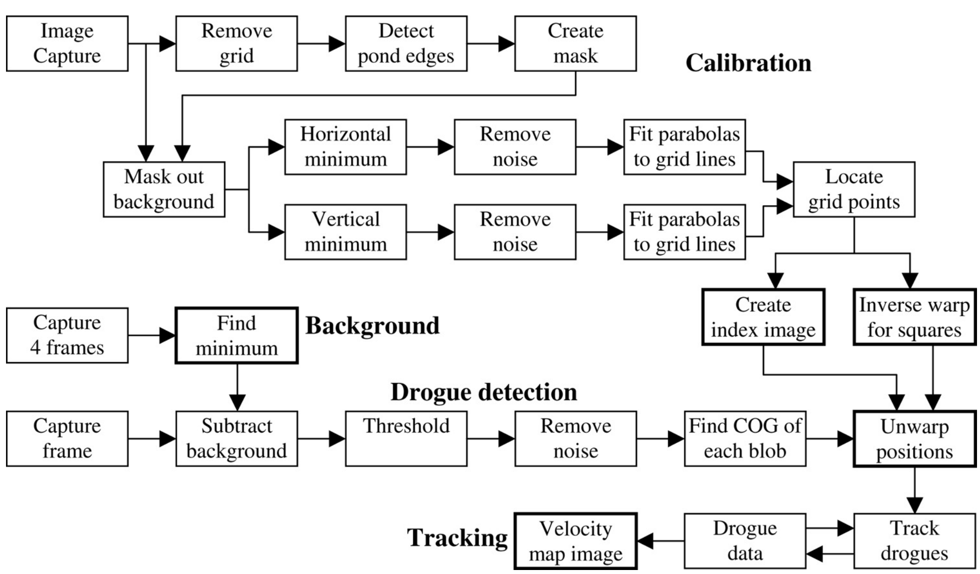

Fig. 2. Image processing operations used with the model pond. The boxes with the heavy borders are the outputs of a step.

Nomenclature

S_Q scale factor for flow;
S_L scale factor for length.

stabilisation ponds is needed. This has led researchers to increasingly consider hydraulic studies using scale-model ponds under controlled laboratory conditions.

The predominant experimental technique used to date, in both field and laboratory experiments, has been stimulus response, dye tracer studies. This involves adding a ‘slug’ of dye at the inlet and measuring the concentration leaving the outlet. This technique, however, does not directly quantify the flow velocity and mixing patterns that actually exist within the pond. Rather it measures the final ‘response’ at the outlet that the internal flow regime produces. Being able to quantify the actual flow pattern and velocity distribution

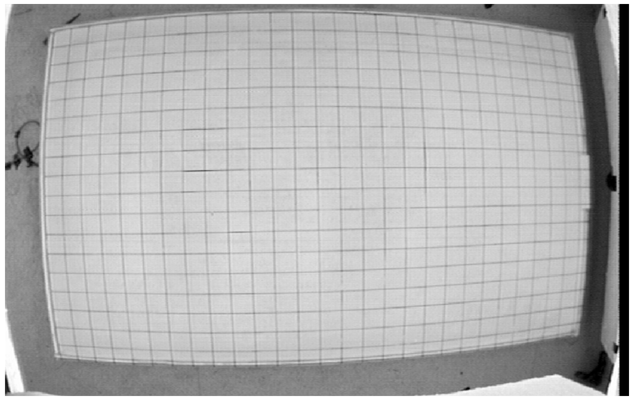

Fig. 3. A calibration image of the rectangular pond, showing the severe geometric distortion.

within the pond would be very valuable as its gives direct insight to the flow pattern.

The key hydraulic parameters of interest in pond design are ‘short-circuiting’ and the degree of ineffective ‘dead space’. Short-circuiting is where influent tracks around a pond and exits the outlet in a very short space of time. Because the treatment of pollutants in a pond generally follows exponential decay kinetics, this means that if even a small percentage of wastewater short-circuits the pond then this has a large impact on the overall treatment efficiency. By being able to directly measure the flow pattern and velocities, the higher velocity channelling that creates short-circuiting problems can actually be observed. Indeed the time taken for influent to move from the inlet around past the outlet can be estimated from the inspection of length and velocities in this channel’s flowpath. Alternatively zones where low velocity flow exist circulating in eddies separate to the main pond circulation are areas that contribute to the dead space of the pond. Having the ability to visualise the actual hydraulics that are creating such problems would clearly be invaluable when it then comes to devising remedies to these shortcomings.

Many instruments such as propeller-type current meters typically used elsewhere for hydraulic research cannot accurately measure the very low flow velocities that exist in a model pond. The use of a laser Doppler system is feasible, but these instruments are expensive and building up a velocity distribution over a pond, point by point, is time consuming. By contrast image processing is relativity cheaper and can be set up so as to record numerous data points automatically over a period of time. It is then possible to process this raw positional data into velocities and flow paths and produce the results as a colour graphic.

The objective of this paper is to detail and report on the technique of applying image processing for drogue tracking in a laboratory-scale waste stabilisation pond. To date this technique has never previously been applied for waste stabilisation pond hydraulic research.

2. Model/prototype pond and experiments undertaken

The model was housed within a confined, constant temperature room to minimize temperature changes and exposure to air currents. The prototype (full-scale) pond that the model represented was 32.58 m in length, 21 m in width and 1.5 in depth. A length scaling factor (S_L) of 1:12 was used which set the internal dimensions of the model at:

$$\text{Length}_{\text{model}} = 2.715 \text{ m}$$
$$\text{Width}_{\text{model}} = 1.750 \text{ m}$$
$$\text{Depth}_{\text{model}} = 125 \text{ mm}.$$

The model’s flowrates were set to maintain Froude Number similarity with the prototype and had the following scaling factors:

$$S_Q = S_L^{2.5} = 498.8;$$
$$S_T = S_L^{0.5} = 3.464.$$

While it is not the intention of this paper to report on the results of all the experiments that were undertaken on this scale pond, it may be useful to summarise the type of work that was carried out. This included testing different flowrates (and so hydraulic retention times—see Table 1); the effect of baffling; different inlet and outlet positioning; and different inlet designs including [14]:

- Small: 60 mm diameter (5 mm at 1:12 scale); directed along the horizontal axis of pond; positioned at mid-depth;
- Large: 120 mm diameter (10 mm at 1:12 scale); directed along the horizontal axis of pond; positioned at mid-depth;
- Vertical: 120 mm diameter (10 mm at 1:12 scale); directed vertically discharging towards the base of the pond, positioned 25 mm below water surface.

3. Image processing

To track the flow, small drogues (ten test tubes with their tips painted black and carefully filled with water so as to make them neutrally buoyant) were placed in the pond and swept around with the flow. To ensure that these drogues were representative of the fluid movement, testing of this technique was undertaken using a tracer dye. This involved placing drops of dye around the tubes. It was observed that the tubes and the dye moved at equal velocities, suggesting that the drag of the tube tip through the surface tension was negligible.

The image processing system consisted of a video camera with a wide-angle lens, positioned facing down through a hole in the ceiling of the laboratory. This relayed images to a computer equipped with an image capture card as illustrated in Fig. 1.

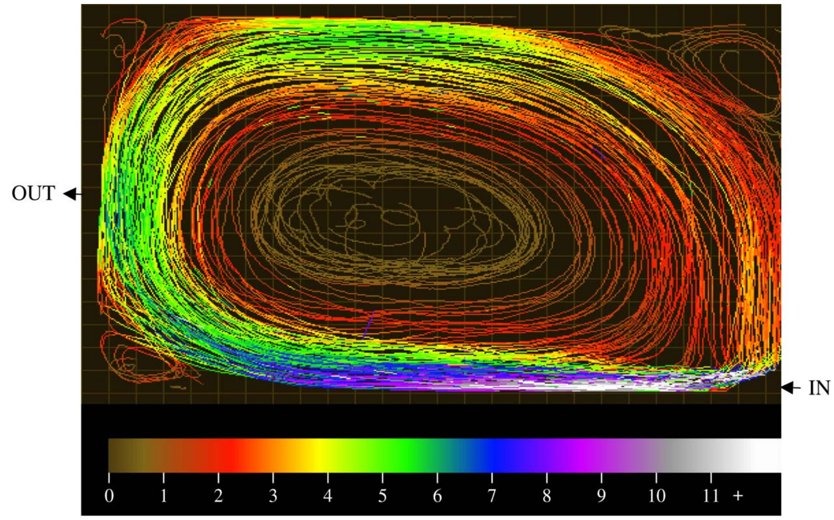

Fig. 4. Output of image processing on a scale model of a waste stabilisation pond, flow = 0.412 m^3/day. The *colour* scale at bottom indicates velocity in centimetres per second.

Table 1
Summary of retention times and flowrates tested in the model pond [14]

Prototype HRT	1.5 day	5 days	10 days	15 days
Model HRT	0.433 days (10.4 h)	1.44 days (34.6 h)	2.89 days (69.3 h)	4.33 days (103.9 h)
Prototype flowrate	684 $\frac{m^3}{d}$	205.3 $\frac{m^3}{d}$	102.6 $\frac{m^3}{d}$	68.4 $\frac{m^3}{d}$
Model flowrate	1.37 $\frac{m^3}{d}$ (952.3 $\frac{ml}{min}$)	0.412 $\frac{m^3}{d}$ (285.8 $\frac{ml}{min}$)	0.205 $\frac{m^3}{d}$ (142.8 $\frac{ml}{min}$)	0.137 $\frac{m^3}{d}$ (95.23 $\frac{ml}{min}$)

The processing of the images is split into four distinct steps. These are:

1. image calibration,
2. background determination,
3. drogue detection, and
4. tracking.

These steps are illustrated in Fig. 2.

The calibration step is performed once, when the system is set up. It only needs to be repeated if either the model pond or camera is moved. The background estimation step is performed at the start of each experimental run. The drogue detection step is performed on each frame processed, and produces a data file with the drogue positions from each frame. The tracking is performed later using the output data file, and produces the velocity map. Each of these steps is described in more detail later.

A limitation of the geometry is that the camera must have a wide angle of view for any reasonable-sized model pond. A consequence of this is that the images are subject to severe geometric distortion with off-the-shelf lenses. This distortion is illustrated in Fig. 3. While severe, this distortion does not change with time, thus allowing the distortion to be characterized empirically, and the data adjusted accordingly.

To characterize the distortion, a large sheet of white plastic marked with a black rectangular grid was attached over the top of the model pond. The spacing between the lines on the grid was constant at 100 mm. Even though the resolution of each pixel is only 3–5 mm, there is sufficient contrast between the black lines and white plastic for the lines to be easily detected. The calibration procedure consists of the following steps:

(1) The calibration sheet is placed over the pond. Careful alignment is made of the top and left edges (as visible from the camera) of the pond as these are the reference edges.
(2) An image is captured of the calibration sheet. Such an image is shown in Fig. 3.
(3) A morphological closing operation [13] is used to remove the calibration lines, enabling the edges of the pond to be located. This effectively segments the image onto the pond.
(4) Finding the local minimum pixel value within a horizontal window detects the darkest pixels in the vertical lines, and similarly the horizontal lines can be detected by finding the local minimum within a vertical window. Any breaks within the detected lines are filled using a morphological filter, and small noise points are discarded.
(5) A parabola is fitted to the data points detected for each line. This allows the line location to be estimated to subpixel accuracy, reducing the effects of digitization noise.

(6) The grid points are located by finding the intersections between the corresponding horizontal and vertical parabolas.
(7) For each square within the grid, an inverse perspective warp is calculated to transform the warped square back to a straight square. The locations of each square in the input image are stored in an 'index image' that can be used later for the drogue tracking.

With the low flow velocities, it was sufficient to capture an image of the drogues every 10 s. To simplify the detection of the drogues a 'background' image (no drogues present) was constructed in the following manner:

(1) Four images of the pond (with drogues) were captured at 10 s intervals.
(2) The background image was created by selecting for each pixel the maximum value from each of the input images. The motion of the drogues meant that each image point did not have a drogue at that location in at least one of the images. Since the drogues were black, and the pond bottom was white, the maximum value from the images always corresponded to the pond background.

Once the background had been detected, the drogues could be located and tracked as follows:

(1) An image is captured of the drogues within the pond.
(2) The background image is subtracted from this. Subtracting the background effectively removes for the clutter from outside the pond, and any variation in lighting across the pond.
(3) The drogues, being black, have a large difference in pixel value from the background, while the rest of the image has only a small difference. The image after subtracting the background is therefore thresholded to detect the drogues.
(4) In the detected image, isolated noise points ('blobs' with area less than 3 pixels) are discarded, and the centre of gravity of each of the remaining blobs is determined. This effectively locates each drogue to subpixel accuracy.
(5) The raw location data of each drogue is inputted to the 'index image', which was produced previously, to determine which grid it is located in. From this, the corresponding warp transformation is applied to correct for the distortion and finally the corrected positional data can be saved to file.
(6) The drogue position and velocity determined from previous images are then used to extrapolate forward to predict where the drogue should be in the current frame. The drogue closest to the predicted position is assumed to be the same drogue (there are no other identifying marks to distinguish between the multiple drogues within the image). By now knowing the current and prior positions, the average velocity during the 10-s interval can be determined.
(7) A line is drawn in the output image showing the 'track' of the drogue. This is a straight line connecting the previous position with the current position. The line is colour coded with the magnitude of the velocity to provide a visual map of the flow velocity distribution. A typical output image after several hours of tracking is shown in Fig. 4.

This technique has now been used extensively for quantifying the hydraulics for a wide range of experimental configurations on a scale-model pond [14]. A particular benefit of this technique was realised via an unexpected result. In the majority of pond configurations tested the experiment would be started and quickly settle into a well defined, steady-state behaviour. However, occasionally image tracking undertaken over several days showed that the flow pattern, which had settled into a single main circulation, would inexplicably flip into two counter-current circulations for a period of some hours and then flip back to a single circulation. The fluid mechanics behind this unusual behaviour has yet to be further researched. The important point of this, however, is that for most other flow measurement techniques such as tracer studies or point-by-point velocity analysis, this non-steady-state flow behaviour would have either gone unobserved or would have yielded very confused results. By contrast, the application of the image processing technique presented here, which allows continuous tracking of multiple drogues over a lengthy period of time, allows for very clear observation of such flow behaviour.

4. Summary and conclusions

There is a strong need for improved research into pond hydraulics. The use of scale-model ponds tested under controlled conditions in the laboratory is an important experiment method for such work. The technique of using image processing for drogue tracking in these ponds has been demonstrated to be a particularly effective way of quantifying their hydraulic regime and can be considered as a valuable complement to traditional tracer studies. It is relatively cheap and effective compared to other techniques that are available for measuring flow velocities such laser Doppler, for example. It is effective at quantifying the actual flow pattern and velocity distribution across the pond. This technique can be started and left to automatically track the flow pattern over a period of days. In so doing, it has the advantage of clearly highlighting any unsteady state fluctuations in the ponds behaviour that might otherwise go unnoticed. This paper represents the first publication of the application of image processing for waste stabilisation pond hydraulic research.

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