Sluice-box designs and their operating conditions adopted by small scale miners in PNG, who use them for the recovery of gold from alluvial deposits, vary widely. Some use small flowrates to increase the fine gold recovery at the expense of efficient separation while others use high flowrates resulting in high throughput rates with increased fine gold losses.

This paper describes how a non-linear optimisation procedure could be used to identify the optimal conditions of sluice configuration and operating flowrate, in order to maximise the metallurgical efficiency of sluice-boxes treating an alluvial deposit with given gold and gangue size distributions.

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Sluice boxes have been used for the recovery of heavy minerals for over a thousand years and are still being in small scale gold mining operations. In Papua New Guinea, at present, over four thousand gold miners are involved in small scale operations, a majority of whom rely on these sluice boxes for the recovery of gold. The most common design in use is a simple wooden box consisting of a launder of rectangular cross-section, 1-2m long, 0.3-0.5m wide and 0.2-0.3m high, inclined at 5-15 degrees to the horizontal with wooden riffles, often transverse strips to impede the flow and retain the segregated heavies (see Fig.1). The amount of gravel and wash water fed onto the sluice varies widely. The process of feeding the gravel and removing the large pieces of gangue by hand is usually continued for about a week before the box is cleaned by 'panning' to recover the trapped gold.

Users of sluice boxes in PNG, rely on them for the primary concentration of nugget gold as well as very fine particle gold, both in the same pass. As with any mineral processing operation treating a widely sized feed, this process has to be inefficient, at least in the recovery of finer gold. The standard practice adopted by national miners has been to use a low water flow rate\(^1\), which has brought about mixed results. It has helped to retain increased amounts of finer gold which otherwise would be lost in the tailings, but the agitation within riffle compartments at these flow rates is minimal and in some cases, non-existent. Under these conditions, the separations achieved are poor and even the removal of gangue needs to be done manually, which leads to lower throughput rates, thereby alleviating the advantages of continuous operation. Some of the major disadvantages of feeding a widely sized feed material on to sluice-boxes have been discussed elsewhere\(^2\).
SCOPE OF PRESENT WORK

A majority of the alluvial deposits currently being worked contain a high proportion of fine gold, in some cases, amounting to over 50% passing 100. The recovery of gold of this size by conventional sluicing has been found to be only
about 40%. As such any improvements in the design of sluice-boxes to recover the fine gold or determination of their optimum operating conditions, would be of great advantage to their users. Typical gold bearing gravel consist of a large proportion of quartz sand (over 95%), some heavy minerals such as magnetite and a small quantity of gold. Hence primarily, the performance of the sluice-box in recovering the valuables ought to depend on the extent of the movements of gangue and gold particles. A mathematical model has been developed based on a criterion similar to the Shield's criterion used in sediment transport theory, to determine the amount of material of a given size and density recovered in a sluice of a known configuration (ie. given riffle height and riffle spacings). Work has also been done to determine the relative proportions of different materials that stays within a riffle compartment under a given set of operating conditions; when the feed consists of a mixture of particles of different densities and sizes.

In this work, the model obtained from the above analysis has been used to optimise the design and operating conditions in order to maximise the "metallurgical efficiency", in processing a given alluvial gold bearing deposit.

EXPERIMENTATION

All experiments were carried out on a perspex sluice box (half size scale model of the prototype) of 1.25m long, 0.15m wide and 0.15m channel height, with closely spaced grooves on each of the vertical sides along its length to take interchangeable transverse riffles of various heights at various spacings. The inclination of the sluice was kept at 10 degrees to the horizontal throughout the experiments. Initial flow pattern studies were carried out using dye injection, while the subsequent tests were carried out by feeding a measured quantity of closely-sized solids of different densities and sizes, at various water flow rates, and combinations of various
riffle heights and riffle spacings. During each run, the weight of solids trapped within each riffle compartment was measured. Feed materials used were mainly closely-sized quartz sand of specific gravity 2.65. In the absence of gold particles, some tests were also carried out using lead shots and magnetite particles of different sizes, the specific gravities of which were 10.0 and 4.6 respectively, in order to detect any trends in the proportions of various mineral species in a mixed feed that gets trapped in a riffle compartment.

PERFORMANCE TRENDS

Observed Patterns

Figure 2 is a typical set of results showing the distribution of feed material (quartz sand of average size 843 mm) into successive riffle compartments at various water flow rates. Observations made during the tests revealed that there are
three modes of particle transport associated with these results.

Mode 1 - At sufficiently low flow rates, the solids entering a riffle compartment does not initially move but build up against the downstream riffle until it becomes almost full. As it builds up, the particles in the top surface layer starts to roll and/or slide over the lower layers onto the next compartment. This gives rise to the steep straight lines of Fig.2 because the amount of sand collected per riffle compartment is nearly equal.

Mode 2 - At moderately higher water flow rates, the extent of erosion of the surface layers due to turbulence, increases and therefore the amount of solids retaining between two successive riffles becomes lower but practically constant as before, giving rise to the straight lines with slightly lower gradients in Fig.2.

Mode 3 - At higher flow rates, a large proportion of the solids is carried downstream and only the material occupying the 'dead zones' within each riffle compartment was left behind, thus giving rise to the lines with smallest gradients. These dead zones were situated at the bottom of the sluice, closer to the corners of the compartments and also adjacent to the riffles, where the intensity of turbulence was not sufficient to support particles in suspension. Since the flattening of the curves at larger distances was due to progressive depletion of the solid, the initial segments of the curves in Fig.2 were considered straight lines with decreasing gradients at increasing flow rates. The gradients of these straight segments were then evaluated by linear regression. Physically, the gradients represent the weight of solids retained per riffle compartment \( W_0 \). Fig.3 is a typical plot of \( W_0 \) versus water flow rate \( Q \), for a sand of given size and density. The different lines correspond to different runs with riffles of constant height placed at various riffle spacings. Similar plots were also prepared for runs with various riffle heights while keeping riffle spacings constant. Both these sets of tests resulted in plots similar to Fig.3. As can be seen from Fig.3, each curve
is associated with a plateau at low flow rates (corresponding to mode 1), suddenly dipping to another plateau at high flow rates (corresponding to mode 3). This characteristic shape was observed in almost all such plots.

Factors Affecting Sediment Entrainment

The mechanisms of sediment entrainment due to fluid flow is known to be dependent on the magnitude of the flow as well as the particle characteristics such as size, density and shape. At low flow rates, the particles in the surface layers of a settled bed starts to move downstream by rolling and/or sliding. As the flow rate is increased more and more particles are lifted from the bed and would travel by 'saltation' where intermittent suspension and deposition of particles occur. On increasing the flow rate further, the lifted particles will be supported by the turbulent forces, thereby giving rise to a fully suspended flow.

The conditions required for the onset of particle entrainment due to turbulence has been well documented in the literature\textsuperscript{6,7}. The onset of turbulent suspension of particles
is thought to be dependent on the boundary shear stress and the intensity of turbulence acting over the surface layers. In open channels, the particle entrainment has been shown to depend on the Shield's criterion ($\theta$), defined by,

$$\theta = \frac{\tau_0}{\int (s-1)dg} \quad \text{or} \quad \theta = \frac{U_*^2}{(s-1)dg}$$  (1a)

where $\tau_0$ = boundary shear stress
$U_*$ = boundary shear velocity ($\tau_0 = \int U_*^2$)
$\int$ = fluid density
$d$ = diameter of particle whose specific gravity is 's'
$g$ = gravitational acceleration

Initiation of particle suspension, is known to occur when this criterion reaches a characteristic threshold value dependent on a "Reynolds number" ($X_t$) given by;

$$X_t = \frac{U_* d}{\nu}$$  (1b)

where $\nu$ = kinematic viscosity of the fluid.

When fully developed turbulence is established around the grains, the threshold value of the Shields criterion becomes constant. In the case of sluice-boxes, it has been shown$^8$ that in addition to these criteria, Particle Reynolds number is also an important parameter in the determination of the condition for the onset of turbulent suspension of particles.

It is also known that when the flow rate and in turn the Shields criterion increases above the threshold value, more and more particles go into suspension accordingly.

**Particle Entrainment in Sluice-boxes**

In addition to the mechanisms of particle transport discussed above in relation to unisized single density particles, there is evidence to assume that other mechanisms also occur when the feed consists of a mixture of particles of various sizes and densities. Like in many gravity separation devices in mineral
processing, mechanisms such as consolidation trickling, hindered settling and/or free settling can occur depending on the nature of the prevailing operating conditions.

**MATHEMATICAL MODEL**

It has been shown that when the feed consists of unisized single density particles, the amount retained \((W_0)\) within a riffle compartment under a given set of operating conditions, may be calculated using a modified criterion similar to the Shield's criterion. The development of the basic model used for this calculation has been described elsewhere. This model is given by:

\[
\ln(W_0) = A \ln(\beta) + B
\]

where the quantity \((\beta)\), defined by:

\[
\beta = \frac{Q}{[(s-1)d]^{0.5}}
\]

is thought to represent the Shields criterion, and thus, considered relevant to the analysis of particle entrainment in sluice boxes. It must be noted that, unlike Shields criterion, \(\beta\) is dimensional and units of measurement is important. In this analysis dimensions of \(Q\) and \(d\) are ml/s and microns (\(\mu m\)) respectively, while \(s\), the solids specific gravity is dimensionless. \(A\) and \(B\), are both functions of riffle height and spacing which can be evaluated by the regression equations,

\[
A = 2.9 + 0.004 H -0.2 P -0.42 \ln(d) \quad (4a)
\]
\[
B = -4.0 +0.43 H + 0.55 P + 0.88 \ln(d) \quad (4b)
\]

where \(H = \) riffle height (cm) and \(P = \) riffle spacing (cm)

However \(W_0\) is subject to the bounds \(W_{max}\) and \(W_{min}\), given by;

\[
W_{max} = 831 + 147 \ H + 61 \ P \quad (5 \ a)
\]
\[
W_{min} = -600 + 87.2 \ Ln(d) + 47.5 \ H -5.5 \ P \quad (5 \ b)
\]

which correspond to the transport mechanisms corresponding to rolling/sliding regime and fully developed turbulent suspension, respectively.

Since the original model was developed primarily using data on sand, and in the absence of data on Wmin and Wmax for high density materials, in the present analysis the values of W0 for such materials have been calculated by adjusting the sand recoveries according to:

\[ W_{0h} = W_0 \times S_h / 2.65 \]  

(6)

where \( S_h \) is the specific gravity of the higher density material. It is based on the assumptions that a riffle compartment get filled to the same volume at a given flowrate and that the voidage of the beds formed of the higher density materials and those of the sand are nearly the same.

Figure 4 is a log-log plot of the observed values of W0 versus those calculated from Eq.2, covering a wide range of feed and operating conditions, and gives an idea of the validity of the model. The experimental data covered combinations of a range of particle sizes from about 200 \( \mu \)m to 1000 \( \mu \)m, riffle heights of 3 to 8 cm. and riffle spacings of 4 to 12 cm, at water flow rates from about 90 ml/s up to 600 ml/s per cm width.

When the feed consists of a mixture of particles of different sizes and densities, different proportions of these mineral species would settle out in a riffle compartment under the
prevailing flow rate as a result of the competition among them.

Experimental data obtained from laboratory tests indicate that mechanisms such as consolidation trickling, which is known to occur in tables, also act upon the material trapped within a riffle compartment. From data obtained using a feed mixture of lead shots ($s = 10.0$), magnetite ($s = 4.6$) and sand ($s = 2.65$) of various sizes, a tentative model has been established by regression analysis. It must be noted however that initial trials to correlate the amounts retained of each mineral species, with the dimensionless criteria discussed earlier did not give a reasonable fit, mainly due to simultaneous existence of several mechanisms of particle transport.

The relative proportions of each mineral species recovered in a riffle compartment depends on the relative proportions in which they were present in the feed, and also on the amounts of such material that would have retained if the feed had consisted only of one individual component at a time. Based on this observation, an equation has been developed by regression analysis, which is capable of describing the observed data on all mineral species in the feed mixture, with a reasonable degree of accuracy (ie. with a coefficient of determination of
80\%). It is given by;

\[ W_i = -3.0 + 1.47 (W_{0i} \cdot f_i) \]  

(7)

\( W_i \) is the weight retained of a mineral species present in the feed mixture, \( W_{0i} \) is the amount retained of that material under the same operating conditions if the feed had comprised only of those particles. \( f_i \) is the mass fraction of those particles in the feed mixture.

The data used for the above regression covered a range of flow rates from about 100 to 400 ml/s, densities of 10, 4.6, 2.65, and particle sizes, ranging from about 0.150 to 1.0 mm. on a 10 cm. wide sluice. Figure 5 shows a comparison of the observed and calculated values of \( W \) from a mixed feed using Eq.7.

**OPTIMISATION OF PERFORMANCE**

One of the major problems faced by small scale gold miners who rely on sluice-boxes is their inability to select the size and spacing of riffles, and the optimal flowrate to maximise the recovery of gold. An attempt has been made in the present work to use the tentative model described above, to optimise the gold recovery from a known deposit. From the model it is clear that the optimal conditions are dependent on the nature of the deposit, ie the size distribution of gold and gangue, and the relative proportions in which they are present.

Due to the nature of the present model it was decided that a non-linear optimisation procedure was the best suited for the problem. A routine from the Numerical Algorithms Group (NAG) library, the routine E04FDF was chosen for this purpose. This procedure\(^2\) minimises a function which can be expressed as a sum of squared functions (ie. performs a least-square fit).

Objective function = Minimise \( \{ \mathbf{g}^T \mathbf{g} = \sum_{i=1}^{m} g_i^2(x) \} \), \( x \in \mathbb{R}^n \)  

(8)

where the \( i^{th} \) element of the \( m \)-vector \( \mathbf{g} \) is the function \( g_i(x) \).
This routine performs an unconstrained minimisation, using a search procedure, without the need for the user to provide the derivatives.

**Objective Function**

Eventhough the real practical objective is to maximise the recovery of gold, it is not suitable directly as the objective function, for use with the procedure chosen above. Hence several objective functions were tried with varying degrees of success. First, recovery of gold was chosen as the objective function; but the results were not practically feasible as the gangue recovery too was high. Secondly, the difference between recoveries of gold and gangue was chosen. However, because the chosen procedure was minimising the sum of squares, again it gave results corresponding to the recoveries of both gold and gangue close to unity. Thirdly, the "metallurgical efficiency (E)", defined in traditional texts as;

\[ E = \text{Grade} \times \text{Recovery} \]  

(9)

was chosen as the objective function after multiplying it by a negative sign, as this quantity needs to be maximised. Again, it failed because the procedure was minimising \( E \), as the negative sign vanishes in squaring, thus resulting in either low recoveries and/or low grades.

However, the following objective function gave more realistic results. i.e.

\[ \text{Objective function} = \text{Minimise} \{ \exp(-\text{Grade} \times \text{Recovery}) \} \]  

(10)

Here, as the objective function was being minimised the term (Grade*Recovery) was maximised. Table I shows the feed characteristics used on a sample problem and Table II the results of the optimisation corresponding to various starting values. As with most non-linear optimisation problems, different starting values resulted in different optimal values. In order to increase the sensitivity of the analysis, the
### TABLE I  Feed size distribution data

<table>
<thead>
<tr>
<th>Average size of size interval (µm)</th>
<th>mass % retained</th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>gold s = 18.0</td>
<td>magnetite s = 4.6</td>
<td>sand s = 2.65</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>0.05</td>
<td>0.05</td>
<td>0.15</td>
<td></td>
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<tr>
<td>722</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
<td></td>
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<td>500</td>
<td>0.05</td>
<td>0.15</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>353</td>
<td>0.05</td>
<td>0.20</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>0.05</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>177</td>
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<td>0.10</td>
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<tr>
<td>125</td>
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<td>0.10</td>
<td>0.10</td>
<td></td>
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<tr>
<td>88</td>
<td>0.30</td>
<td>0.10</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>0.35</td>
<td>0.10</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

Grade of gold = 100 g/tonne (assumed)
Grade of magnetite = 900 g/tonne (assumed)

### TABLE II  Results of Optimisation

<table>
<thead>
<tr>
<th>Objective function</th>
<th>Starting Point</th>
<th>Optimum Cond.</th>
<th>Optimal Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q, ml/s</td>
<td>H, cm</td>
<td>P, cm</td>
<td>Qo, ml/s</td>
</tr>
<tr>
<td>Exp(-R*G)</td>
<td>300</td>
<td>4.0, 6.0</td>
<td>272</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>4.0, 6.0</td>
<td>385</td>
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<tr>
<td></td>
<td>200</td>
<td>4.0, 6.0</td>
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<td>257</td>
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<td>282</td>
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<tr>
<td></td>
<td>272</td>
<td>3.5, 6.0</td>
<td>257</td>
</tr>
<tr>
<td>100<em>Exp(-R</em>G)</td>
<td>272</td>
<td>3.5, 6.0</td>
<td>257</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>4.0, 6.0</td>
<td>289</td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>3.0, 8.9</td>
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</tr>
<tr>
<td></td>
<td>400</td>
<td>6.0, 8.0</td>
<td>387</td>
</tr>
</tbody>
</table>

R = Recovery  
U = Upgrading ratio  
G = Grade
objective function was modified by multiplying it by a factor of 100. This modification somewhat improved the results. The above procedure was repeated with several data sets depicting finer and coarser gold size distributions compared to that of sand. The resulting optimal values were in satisfactory agreement with practical observations.

For the illustration given above, it appears that the best suited riffles should be about 3cm in height placed at about 8cm intervals with flowrates about 280 ml/s for a 10cm wide sluice-box.

DISCUSSION

It must be noted that the model used in the present study is by no means a very accurate one. Nevertheless, it indicates the trends of the experimental observations satisfactorily. With more experimental data, particularly with denser particles, a more refined model of the sluice-box may be formulated.

Another point of interest, is the form of the objective function used in this work. There is considerable controversy over the use of single valued efficiency parameters as opposed to the use of "performance curves" which indicate the behaviour of particles according to some characteristic property being exploited in a given piece of equipment\(^{11,12}\). It may not be the best criteria but probably suffice for the present work.

There is also some concern as to whether the recovery of magnetite should be included as part of the valuables. It may be appropriate in that, small scale miners tend to visibly observe the behaviour of these particles in order to assess the performance of their sluice-boxes, as gold is present only in small quantities and hence not readily observable.

CONCLUSIONS

A mechanistic approach towards the modelling of sluice box
operations has been reviewed. Based on a modified version of the Shields criterion of sediment transport theory, a tentative model has been formulated to predict the performance, covering a wide variety of feed and operating conditions.

Using this model, the application of non-linear optimisation procedures to evaluate the optimal sluice configuration and optimal operating flowrate for the processing of a given deposit, has been established.

ACKNOWLEDGMENTS

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REFERENCES


