18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

A model for optimizing forest road drain spacing

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Abstract: Unsealed roads are necessary infrastructure required to manage forested catchments. They form linear features in the landscape that intersect, concentrate and redirect flow paths which can alter catchment hydrology and in-stream water quality. However, water quality is only affected if runoff and sediment generated on the roads are delivered to the streams. Road runoff and eroded sediment can enter the stream at 1) stream crossings, 2) via gullies at drain outlets that concentrate the flow all or part of the way to the stream, or 3) via diffuse overland flow. Hairsine et al. (2002) developed a simple probabilistic model for diffuse overland flow. It uses the concept of the 'volume to breakthrough', which is the volume of runoff required to enter an area before discharge is observed at the downslope boundary of that area. The model only requires variables of distance of drain outlet from the stream, road contributing area (or road length), road infiltration rate and a designer rainfall event to calculate runoff volume. The model has been applied to a number of forest catchments to assess the adequacy of road drainage. Where road drainage is determined to be inadequate, the model can be used to determine the location of "new drains" by maximizing contributing road area as determined by the distance the drain outlet is from the stream. However, this method results in many new drains being placed close to existing drains along road segments.

The aim of this paper is to describe a new model that optimizes the placement of new drains along unsealed roads with the object of minimising the total number of new drains required while still disconnecting road runoff from adjacent streams. The optimization routine is constrained by a minimum distance between drains (shortest practical distance to construct drains) and the maximum road length between drains as predicted by the volume to breakthrough model. The problem is solved by finding the position and rainfall so that no runoff reaches the stream for a given number of drains. By iterating this for differing number of drains, one can then select the drain number to match the given rainfall. The model places n drains along the road at increasing positions $x_1, x_2 \ldots x_n$ with $x_n = b$, where b is an existing drain or stream crossing. Each drains an area (length) of road $x_i - x_{(i-1)}$. From each position x_i the length to the stream is known l_i and the maximum flux F_i that can be sustained before the stream is connected is known. That is, $l(x)$ and $F(x) = \alpha l(x)$ are known functions and α is a coefficient. The mathematical aim is to find the positions x_i, in metres, and the number of drains n so that for a given rainfall r, (mm/hr), no runoff reaches the river.

The model was applied to a segment of the Vanity's Crossing Road for which 'volume to breakthrough' modeling indicated 13 of the 15 drains where highly connected to the stream. Road managers wanted to install a limited number of additional drains along the road to dis-connect road runoff from the stream. The drain spacing model was run by systematically increasing r until the prescribed number of drains was reached that would prevent runoff connection for the rainfall amount. The model optimally placed "additional" drains along the road, some of which clustered around stream crossings. The optimal location for 8 additional drains where found however, for any increase in r, a further 4 additional drains would be required making a total of 12 new drains. This resulted because the systematic increase in r doesn't necessarily provide a proportional increase in drain number. Never-the-less the model described found the optimal locations for additional drains along a road to prevent runoff connecting with the stream for a designer rainfall event. Fewer new drains where required to disconnect road runoff from the stream than predicted by an existing model which simply maximized road lengths between drains. This was achieved numerically by searching for the locations along road segments which have the greatest distance from the stream.

Keywords: *Roads, drains, connectivity, water quality, overland flow.*

1. INTRODUCTION

Unsealed roads are necessary infrastructure required to manage forested catchments. They are linear features in the landscape that intersect, concentrate and redirect flow paths which can alter catchment hydrology (Wemple et al., 2001). Runoff from unsealed roads exhibit sediment concentrations ranging from 70 mg/L (Reid and Dunne, 1984) to 130,000 mg/L (Croker et al., 1993) which can threaten water quality and in-stream ecology if delivered to the stream (Richardson, 1985). Road runoff and eroded sediment can enter the stream at 1) stream crossings, 2) via gullies at drain outlets that concentrate the flow all or part of the way to the stream, or 3) via diffuse overland flow (Fig. 1). The majority of road-drain outlets discharge onto hillslopes as diffuse overland flow.

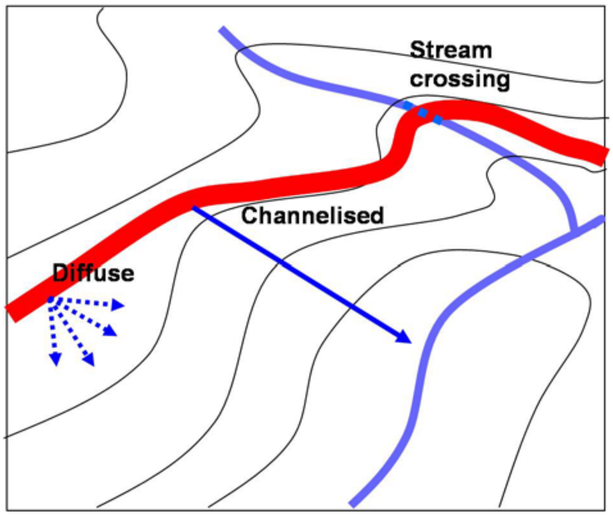

Figure 1. The main pathways for road runoff and sediment to connect with stream

Hairsine et al. (2002) developed a probabilistic model for diffuse overland flow. It uses the concept of the 'volume to breakthrough', which is the volume of runoff required to enter an area before discharge is observed at the downslope boundary of that area. The model only requires variables of distance of drain outlet from the stream, road contributing area (or road length), road infiltration rate and a designer rainfall event to calculate runoff volume. The model has been applied to a number of forest catchments to assess the adequacy of road drainage and the degree of road-stream connectivity (Takken et al., 2006, 2008). Where road drainage is determined to be inadequate, the model can be used to determine the location of "new drains". For example, if a drain outlet is close to a stream then the next drain up the road would need to be relatively close to give a small contributing road area hence, small runoff volume that would infiltrate before connecting with the stream. Alternatively if a drain outlet is distant from a channel then its contributing road area can be relatively large. This can be applied iteratively up along the road however many new drains end up being placed relatively close to existing drains up along the road. Another issue with this methodology of applying the model is that streams have an inherent tendency to meander as do roads. Hence, the distance between roads and streams are variable, even for a road following a stream. Therefore maximising road length for the placement of a new drain may not be the best solution, particularly if some shorter road length places the new drain at a location that is further from the stream which then would allow a significantly longer road segment before the placement of the next new drain. The aim of this paper is to describe a model that optimises the placement of new drains along unsealed roads within the constraints of existing culvert drains and a maximum road length between drains determined by the probabilistic volume to breakthrough model.

2. THE MODEL

The mathematic problem of finding the minimum number of drains, and their positions, so that for a given rainfall no runoff and sediment reaches the stream is solved by addressing the problem in reverse: for a given number of drains, find the position and rainfall so that no runoff reaches the stream. By iterating this for differing number of drains, one needs then only choose the drain number to match the given rainfall.

The model studied here assumes a horizontal road running long the x-axis from $x = a$ to $x = b$ where a and b are existing drains and with a stream defined for $y > 0$. Runoff flows from a finite number of drains along the road, then vertically to the stream (along y a constant). It is a merely technical matter to define arbitrary water flow directions and non horizontal streams. For this model we assume that water runs from left to right, in the positive x direction along the road, carrying sediment to the nearest drain before then moving towards the stream, shown in the positive y direction (Fig. 2). Runoff plume length and volume reaching the stream, if any, is determined by the probabilistic volume to breakthrough model. This calculates road runoff volume as rainfall for a 10 year event minus road infiltration rate (set at 11.74 mm/hr; Croke et al., 2006) multiplied by the road area contributing to the drain. If the runoff volume is large enough, and the length to the stream short enough, road runoff will reach the stream, which is to be avoided. As with the volume to breakthrough model, it is assumed that runoff is lost uniformly with length of drainage to the stream, l, thus the maximum flux F that can be sustained before runoff reaches the stream is proportional to the length l. The model places n drains along the road at increasing positions $x_1, x_2 \ldots x_n$ with $x_n = b$. Each drains an area (length) of road $x_i - x_{(i-1)}$ since material flows from left to right along the road. From each position x_i the length to the stream is known l_i and the maximum flux F_i that can be sustained before the stream is connected is known. That is, $l(x)$ and $F(x) = \alpha l(x)$ are known functions and α is a coefficient. Our aim is to find the positions x_i, in metres, and the number of drains n so that for a given rainfall r, [mm/hr], no runoff reaches the river.

The problem is illustrated for three drains with the last drain position known $x_3 = b$ in Fig. 2. Here the unknowns are x_1, x_2 and r, where r is the maximum rainfall possible so that no runoff reaches the stream. Thus we solve three equations

$$r(x_1 - a) = F(x_1) \qquad (1)$$

$$r(x_2 - x_1) = F(x_2) \qquad (2)$$

$$r(b - x_2) = F(b) \qquad (3)$$

with $F(x)$, a, b known. This is easily extended to more drains.

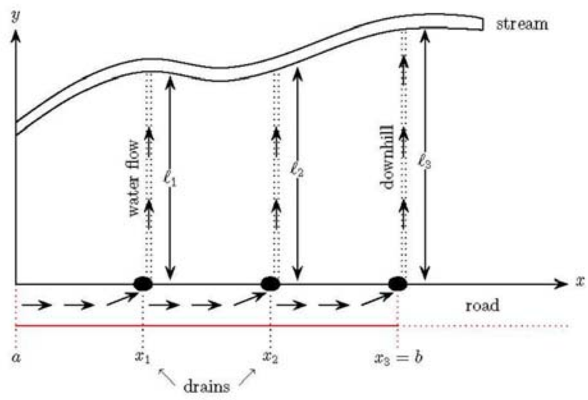

Figure 2. Schematic of road and river, with flow from drains at x_i to the river, along length l_i.

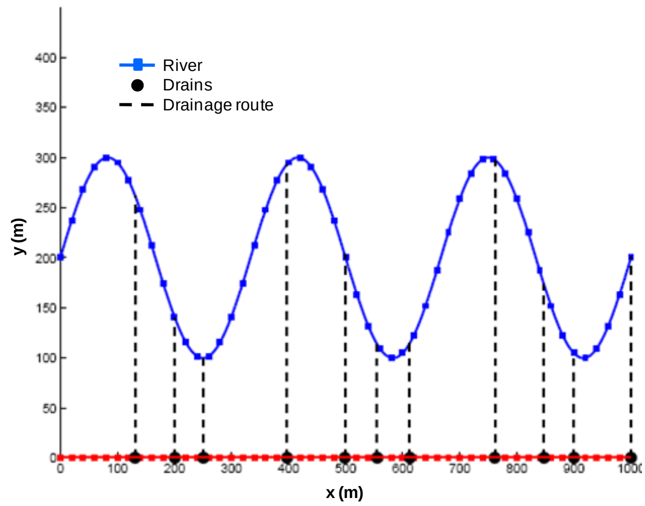

Figure 3. Optimal drain placement for a sinusoidal river. Here eleven drains ensure that rainfall up to 12 mm/hr does not produce enough runoff to connect with the stream.

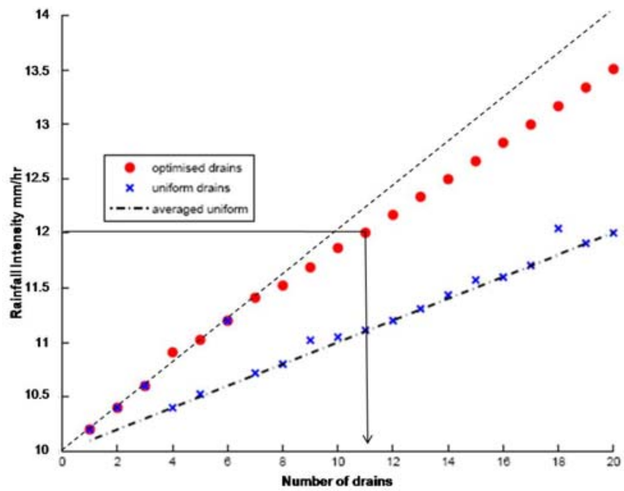

Figure 4. Maximum rainfall rate for a given optimally-spaced number of drains (dots) and a uniform number of drains (crosses). Also shown is the required rainfall rate of 12 mm/hr and the resulting eleven drains needed.

Fig. 3 illustrates a sinusoidal river where the stream and road are defined using discrete data points which are suitably interpolated. For example, for a prescribed rainfall amount (e.g., 12 mm/hr for 30 min), Fig. 4 shows 11 drains are required to prevent runoff connecting with the stream in the scenario presented. Also plotted is the relation between rainfall and drain number if the drains were placed uniformly along the road. Under this scenario, 20 additional drains would be required as opposed to just 11 drains when spaced optimally.

The model allows tabular input of terrain height, river and road positions, and uses the method of steepest descent to ascertain the drainage path of the water from a drain along each point in the road to enable a more accurate measure of l_x. Using terrain height the directional flow can be calculated to the drain by calculating drainage area, replacing $x_i - x_{i-1}$ with a function $A(x_i, x_{i-1}, x_{i+1})$ in the calculations.

3. APPLICATION OF THE MODEL TO VANITYS CROSSING ROAD IN THE COTTER CATCHMENT, AUSTRALIAN CAPITAL TERRITORY

The model was applied to a segment of the Vanity's Crossing Road for which 'volume to breakthrough' modeling indicated 13 of the 15 drains where highly connected to the stream (Fig. 5). Road managers wanted to install 10 additional drains along the road to dis-connect road runoff from the stream. The drain spacing model was run by systematically increasing r until the prescribed number of drains was reached that would prevent runoff connection for the rainfall amount.

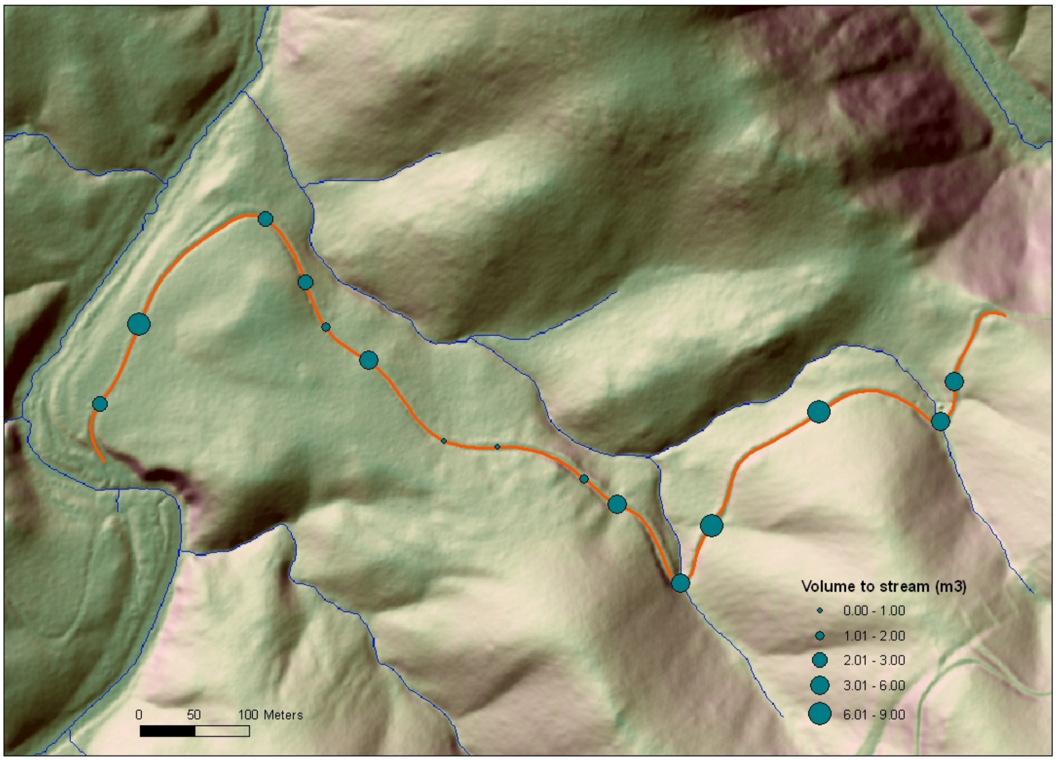

Figure 5. Segment of Vanity's Crossing Road that the drain spacing optimization model was applied. Dots mark the existing drain location with dot size indicating runoff volume reaching the stream for a 10 year rainfall event predicted by the Vbt5 model.

Figure 6 shows the optimum placement of 8 additional drains along Vanity's Crossing Road to prevent runoff connection for a particular rainfall amount. This is further illustrated in Fig. 7 which shows the location and spacing of existing drains and new drains in relation to the river distance from the road. Where the road crosses a drainage channel at approximately 700 and 1000 m along the road (x-axis), the model clusters more drains because of the close proximity to the stream. For any increase in *r*, a further 4 additional drains would be required making a total of 12 new drains. This results because the systematic increase in *r* doesn't necessarily provide a proportional increase in drain number as indicated in the example given in Fig. 8. The difference in location between 8 and 12 additional drains is illustrated in Fig.9.

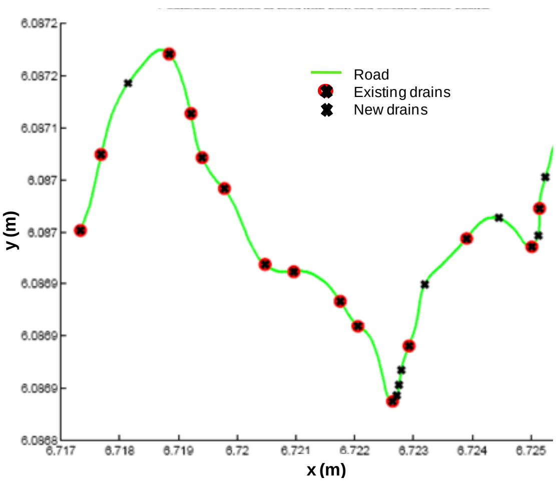

Figure 6. Road position with existing drains and 8 new drains shown. Axis are grid coordinates in metres x 10^6.

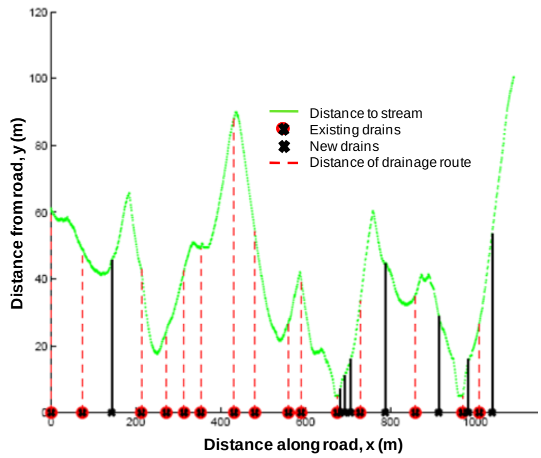

Figure 7. River distance (m) from road with the location of the existing drains and 8 new drains.

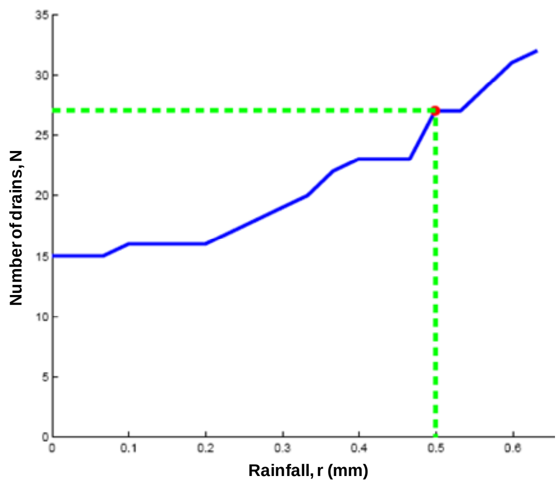

Figure 8. An example of the non-linear relation between rainfall and number of drains for a series of road segments summed together.

4. DISCUSSION AND CONCLUSIONS

Forest managers are faced with the practical challenges of addressing road location and design with respect to minimising water quality decline at a feasible cost. Existing models that can assess road to stream connectivity, for example, WEPP:Road (Flanagan and Nearing, 1995) and Vbt5 (Takken et al., 2008), have limited capacity to inform road managers of the best location for addition drainage. Further, most of the empirical models which are more easily applied in a spatial distributed manner owing to fewer required parameters than physical models, have low temporal resolution; hence provide output as annual averages (Fu et al., *in press*).

The optimum drain placement by the model presented here is constrained by two elements. First is the minimum practical distance between drain constructions which was set to 10 m in this example. The second and most important is the maximum allowable distance between drains (i.e. road contributing area) that can prevent road runoff connecting with the adjacent stream. This is determined by a runoff routing model. The upper constraint can be determined by any number of dispersive overland flow models that are parameterized for the region of application. The upper constraint for this model is the Vbt5 model (Hairsine et al., 2002), a simple empirical overland flow model developed for south-eastern Australia. It is an event-based model which can be used to assess connectivity for a range of rainfall event scenarios. The models is sensitive to the resolution of the DEM used for determining distance to stream and the defined road contributing area.

The optimization analysis for drain spacing within the above mentioned constraints is computationally easy with Equations 1-3 solved numerically in MATLAB. The efficiency of solving the equations means that the model can be applied at the catchment-scale to rapidly assess drainage priority areas. However, at present the model requires data to be exported from a GIS for the analysis in MATLAB and results returned to the GIS for viewing. Work is now underway for the development of ARC GIS extension so the preprocessing and analysis can all be conducted within a single, industry standard software package. The ARC GIS extension will couple the optimization model with the gully threshold model (Croke and Mockler, 2001) to ensure new potential drain outlets do not discharge onto steep hillslopes with the potential to form concentrated flow pathways. This means the gully threshold model will become a third constraint within the optimization model.

In summary, a new model has been described that optimally locates drains to prevent runoff connecting with the stream. This means that fewer new drains may be required to disconnect road runoff from the stream than predicted by existing models which simply maximized road lengths between drains. This is achieved numerically by searching for the locations along road segments which have the greatest distance from the stream. This model can also be applied to find the optimum location for a specified number of additional drains if disconnection is not practical or economically feasible.

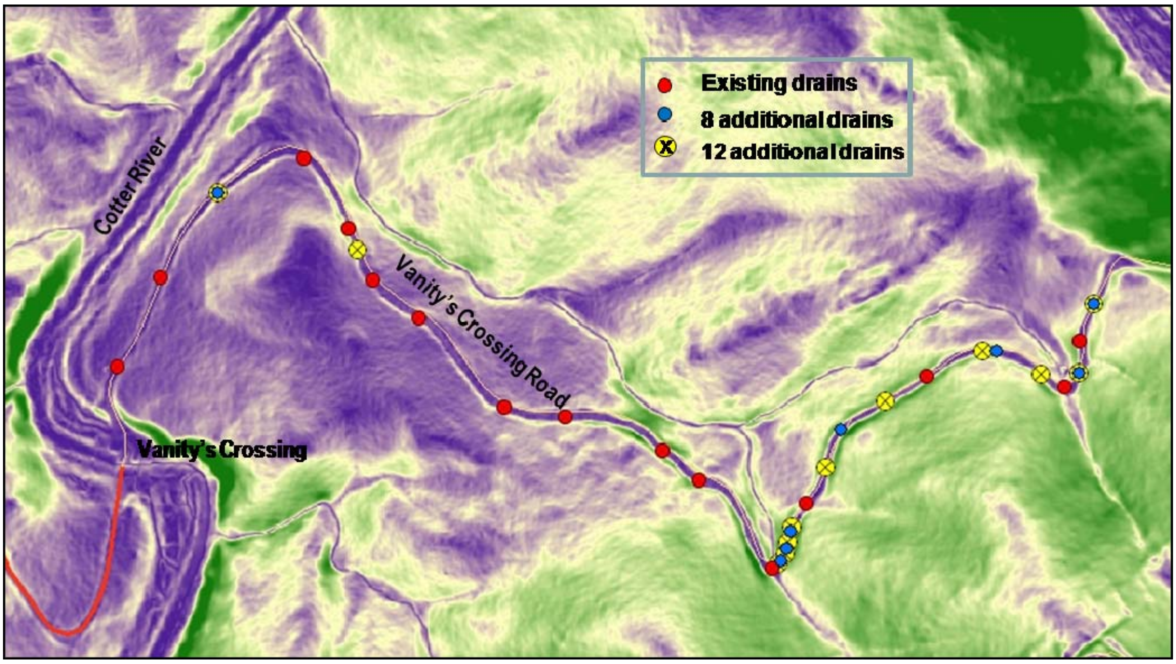

Figure 9. The segment of Vanity's Crossing Road marking the location of the existing, and model results for the location of 8 addition drains and 12 additional drains.

ACKNOWLEDGMENTS

This paper is a product an ARC Linkage project (LP0881993).

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