Hydraulic modelling of drip irrigation systems used for grass establishment on steep slopes

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Abstract

Erosion damage to railway embankment and cutting steep slopes (batters) causes a significant cost of remediation within the coal railway network of Central Queensland, Australia. It has been established that grass cover of 60% reduces erosion by over 90%. Given that water is a scarce commodity in the semi-arid environment, a more efficient water use cost-effective drip irrigation system is imperative. The hydraulic modelling of drip irrigation systems design is presented. It takes into account the velocity head change and a proper selection of the friction coefficient formula based on the Reynolds number. Fittings and emitter insertion head loss are incorporated into the hydraulic model. A case study of the use of the hydraulic model to analyse the drip irrigation systems is presented.
Keywords: steep slopes, drip lateral, irrigation, hydraulics, embankment, grass establishment.

1 Introduction

Erosion of railway embankment and cutting batters within Central Queensland, Australia, increases maintenance costs, risks of outages and derailments, interruptions of normal train operations and environmental degradation. The QR (Queensland Rail) funded HEFRAIL Research Project with Central Queensland University has demonstrated that 60% grass cover on railway embankment batters reduces erosion by over 90% compared with the bare scenario. Further increase in grass cover increases the erosion reduction up to 99% [1–3]. Drip irrigation systems, consisting of laterals with equally spaced emitters and uniform slope, have been identified as an integral part of grass establishment to

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control erosion on railway embankment steep slopes (batters) within the semi-arid region [2, 4–6]. Water is a scarce commodity and may be sourced from existing water mains, existing or temporary excavated ponds/ dams/ creek water holes, or temporary tanks filled periodically by water trucks. The choice of water source depends on availability and costs.

There have been several studies of the hydraulics of drip laterals [e.g. 7]. Yildirim and Agiralioglu [8] have reviewed and compared the performance of some approaches for solving the hydraulics of drip laterals. Basic differences in the approaches are essentially the inclusion or not of the velocity head and minor losses due to emitter insertion, and the treatment of the emitter discharges as constant or variable along the lateral. However, the forward-step method proposed by Hathoot *et al* [9] has been described by many authors [e.g. 10, 11] as the most accurate method. This method takes into account the velocity head change and a proper selection of the friction coefficient formula based on the Reynolds number which varies along the lateral. Recent studies have shown that emitter insertion head loss contributes to a significant proportion of the total head losses, in particular where the emitter numbers are high within the lateral, and needs to be taken into account [11–13].

Field values of emitter characteristics may be significantly different from the manufacturer supplied values as a result of manufacturing variations, micro-topography, clogging, and water quality [12, 14]. Gyasi-Agyei [14] has presented a novel approach for field scale assessment of the uncertainties associated with the drip lateral parameters. This paper gives an example of the use of the hydraulic model presented in Gyasi-Agyei [14] to simulate drip lateral designs at multiple sites of a new railway spur line.

2 The hydraulic model

2.1 Single Lateral

Emitter discharge varies along the lateral with maximum value at upstream and zero at the end. Consider the lateral in fig. 1 having inlet pressure head H_0 and discharge Q_0, and equal emitter spacing s. It is more convenient to cut the lateral midway between two emitters at the connection point to the submain. Hence the head loss in this small section needs to be taken into account when estimating the pressure head at the first emitter. The discharge q_i (L.h^{-1}) from an emitter i is determined by the rating curve

$$q_i = kH_i^x \qquad (1)$$

where H_i (m) is the pressure head in the lateral at the emitter i, x is the emitter discharge exponent characterizing the flow regime and emitter type, and k is emitter discharge coefficient.

The Forward-Step Method equation [14]

$$H_{i+1} = H_i + \frac{3}{2gA^2}\left[Q_i^2 - Q_{i+1}^2\right] - \left[\frac{8s}{\pi^2 gD^5} f_{i+1} + \frac{\alpha}{2gA^2}\right]Q_{i+1}^2 - ss_o \qquad (2)$$

is used to solve for the emitter pressure and discharges forwards. In eqn. (2) $s_o=(z_{i+1}-z_i)/L$ is the constant slope of the lateral (positive for uphill and negative for downhill), D(m) is diameter, A(m^2) is cross-sectional area, H_i(m) is the pressure head at emitter i, Q_i(m) is discharge flowing to emitter i, s(m) is emitter spacing, and L(m) is the length of the lateral. The friction coefficient f_{i+1} is defined by

$$
\begin{aligned}
f_{i+1} &= \frac{64}{R_{i+1}}, \quad R_{i+1} \le 2000 \qquad \text{laminar flow} \\
f_{i+1} &= \frac{0.316}{R_{i+1}^{0.25}}, \quad 3000 < R_{i+1} \le 10^5 \quad \text{turbulent flow} \\
f_{i+1} &= \frac{0.130}{R_{i+1}^{0.172}}, \quad 10^5 < R_{i+1} < 10^7 \quad \text{fully turbulent flow}
\end{aligned} \tag{3}
$$

where R_{i+1} is the Reynolds number. Eqn. (2) was proposed by Hathoot *et al* [9] except for the addition of the local head loss term due to emitter insertions estimated as kinetic head multiplied by the emitter head loss coefficient α.

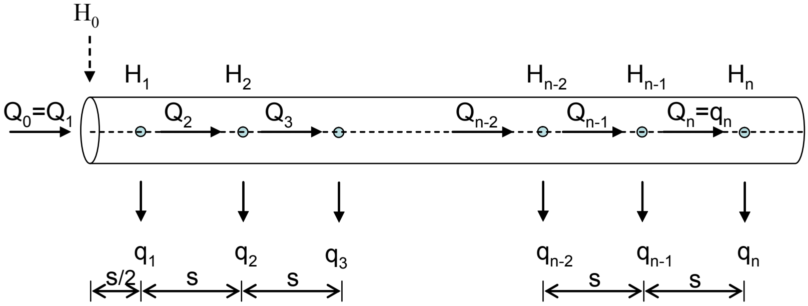

Figure 1: Single drip lateral hydraulic features.

For a given lateral inlet pressure H_0 the emitter discharges are obtained by solving eqn. (2) forwards. Initially the inlet discharge $Q_0=Q_1$ is assumed and used with eqn. (3) to evaluate the friction coefficient f_1. With eqn. (2) H_1 is calculated, followed by the calculation of q_1 using eqn. (1), and then calculation of Q_2 which equals Q_1-q_1. The calculation is repeated for the next emitter downstream until the last emitter discharge q_n is estimated. For a given lateral's characteristic parameters and inlet pressure, there is a unique solution of Q_0 such that

$$
Q_0 - \sum_{i=1}^{n} q_i = 0, \quad Q_n = q_n > 0 \tag{4}
$$

In other words, it is a problem of finding the root (Q_0) of a non-linear function of eqn. (4). The greater than zero condition is important since below a threshold value of Q_0 for a fixed inlet pressure there is no flow through the last emitter. Any root finding algorithm can be used to solve eqn. (4). Brent root finding algorithm, which combines root bracketing, interval bisection, linear interpolation and inverse quadratic interpolation, is used with the lower and upper values of Q_0 defined by $0.1nkH_0^x < Q_0 < nkH_0^x$ to solve eqn. (4).

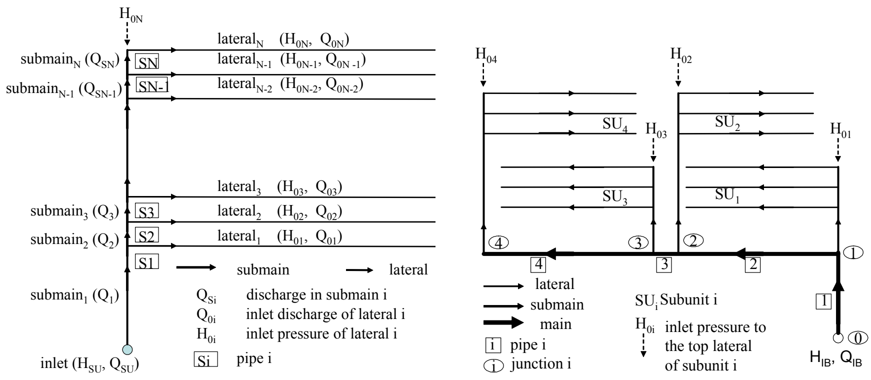

Figure 2: An irrigation subunit (left) and an irrigation bay with multiple subunits (right).

Similar concepts used for a single lateral are used for the subunit simulation as depicted in fig. 2 (left). The subunit inlet discharge Q_{SU} is a unique function of the top lateral inlet pressure H_{0i}. Given H_{0N}, Q_{0N} is estimated as explained for the single lateral case. Since Q_0 is the same as the discharge through the top submain, H_{0N-1} is estimated using the Backward-Step energy formula

$$H_{0i-1} = H_{0i} + f_{Si}\frac{8L_{Si}}{\pi^2 g D_{Si}^5}Q_{Si}^2 + L_{Si}s_o + k_{eSi}\frac{Q_{Si}^2}{2gA_{Si}^2} \tag{5}$$

where L_{Si} is the length of submain pipe Si between the laterals. The last term represents changes in geometry and fittings head loss with k_{eSi} the total upstream coefficient for pipe Si. The remaining symbols are as previously defined. Knowing H_{0N-1}, Q_{0N-1} can be estimated and added to Q_{0N} to give the discharge in the submain SN-1, Q_{SN-1}. The process is repeated for the next lateral and submain backwards until the subunit inlet pressure H_{SU} and discharge Q_{SU} are estimated. Hence pressure H_{0N} can be optimised to match the given Q_{SU} and simulated Q^*_{SU} subunit inlet discharges. Hence it is a problem of finding the root (H_{0N}) of a non-linear equation formulated as

$$Q_{SU} - Q^*_{SU}(H_{0N}) = 0 \tag{6}$$

satisfying the conditions given in the single lateral case. Eqn. (6) is solved using a modified Powell's hybrid algorithm which is a variation of Newton's method using a finite-difference approximation to the Jacobian.

To illustrate the principles for multiple subunits consider fig. 2 (right) which consists of four subunits joined to the main pipeline to form a single irrigation bay. Each subunit requires only the inlet pressure (H_{0i}) of the top lateral to estimate the pressure and discharge at the inlet of the subunit as described in the preceding paragraph. From hydraulic principles, pipes flowing away from a junction should have the same upstream pressure equal to the downstream pressure of the pipe flowing into the junction. To satisfy the continuity principle, the total flow into a junction must equal the total flow out of the junction. Therefore the problem can be formulated into a system of M (equal to the number of subunits) non-linear equations with M unknowns (the inlet pressures of the top laterals of the M subunits). Hence

$$\begin{aligned}
&\text{at junction 0:} \quad Q_{IB} - Q_{p1}(H_{01}, H_{02}, H_{03}, H_{04}) = 0 \\
&\text{at junction 1:} \quad H_{0SU1}(H_{01}) - H_{p2up}(H_{02}, H_{03}, H_{04}) = 0 \\
&\text{at junction 2:} \quad H_{0SU2}(H_{02}) - H_{p3up}(H_{03}, H_{04}) = 0 \\
&\text{at junction 3:} \quad H_{0SU3}(H_{03}) - H_{p4up}(H_{04}) = 0
\end{aligned} \tag{7}$$

where H_{piup} is the upstream pressure of main pipe i, H_{0i} is the inlet pressure of the top lateral of subunit i, and H_{0SUi} is the inlet pressure of subunit i, Q_{pi} and Q_{IB} are the discharges in pipe i and the total of the irrigation bay, respectively. Again the conditions given in the single lateral case must be satisfied. The system of non-linear equations is solved by the same procedure used for the single subunit case.

3 Case study: site 7 embankment of Bauhinia Regional Rail Project

3.1 Site description

Bauhinia Regional Rail Project (BRRP) is the construction of a 110 km spur line linking the new Rolleston Coal Mine to the Blackwater rail network at Kinrola in Central Queensland, Australia [6]. Big cuttings and embankments, and bridges and culverts, are major construction activities as a result of the route crossing various terrains from rocky mountainous country in the north to expansive black soil river plains in the south. In order to reduce the treatment costs, only the top 3 m of batters of all embankment sections exceeding 4 m in height and the downstream side embankment batters of the two major flood plains were irrigated. Three rows of driplines (17.6 mm internal diameter, 0.3 m emitter spacing, and 2.5L/h nominal emitter discharge) at 1 m row spacing were set up at the top batter sections of the selected embankments. Field scale assessment of the selected dripline characteristics [14] has indicated the effective parameter values are: $x = 0.493$, $k= 0.71$ and $\alpha=0.252$ which is significantly different from the manufacturer's supplied values of $x = 0.55$, $k= 0.68$ and $\alpha=0.15$. The variations in the dripline parameter values are attributed to manufacturing variations of the emitters, as well as environmental factors and water quality. Site 7, with a maximum height of 11.6 m, is located between 12880 m and 13480 m marks. Fig. 3 shows the layout of the irrigation system and the line drawings of the pipes of the eastern side, noting that the western side line drawings are the same as the eastern except for length of pipe 57.

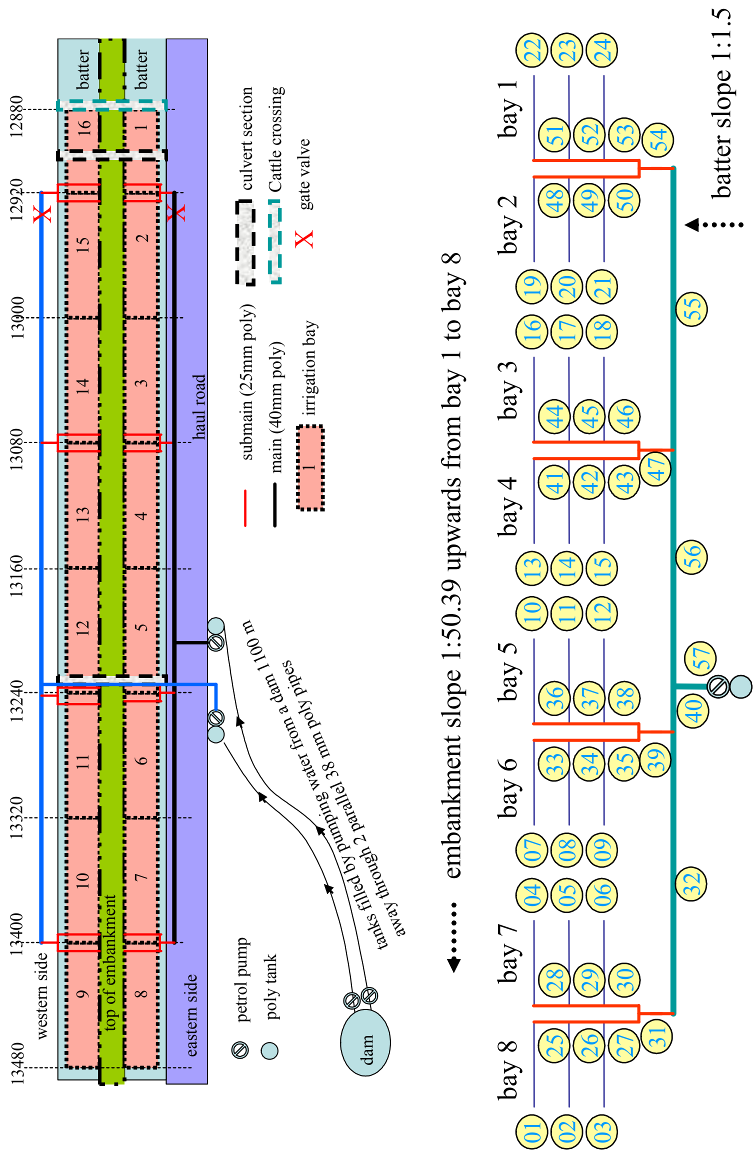

Figure 3: Layout of irrigation systems at Site 7; b) line drawing of the eastern side.

3.2 Hydraulic simulation of eastern side

Table 1 provides the pipe characteristics used in the modelling. Initial experiments at some selected sites of the BRRP project established that to achieve a good uniform wetting front the driplines should not exceed 80 m. A gate valve was installed in the mains to bays 1, 2, 15 and 16 to reduce the higher emitter discharges due to the high elevation drop. The opening area of the gate valves is judged by visual inspections of the wetting fronts. However, the local head loss coefficient ke due to the gate valve is estimated as the value to give similar emitter discharges as for bays 1 and 8.

Fig. 4 depicts the irrigation system curve superimposed on the pump performance curve. ke value of 100 for the gate valve yielded a similar emitter discharges for bays 1 and 8. This implies the gate valve will be nearly shut. For the given conditions, the pump operating point is about 240 L/min at 32 m head. Table 2 gives the characteristics of the 24 driplines at this pump operating point. It is observed that the coefficient of variation (standard deviation/ mean) of the emitters of all bays is small, the maximum being less than 6%.

Water was pumped from a dam 1100 m away through two parallel 38 mm poly pipes to 25,000 L tanks located at the bottom of the embankment as shown in Fig. 3. The measured flow rate through each supply pipe, with independent pump, was about 60 L/min. Hence for one hour irrigation, each pump on the dam has to run for 4 hours (240/60). Due to the expected increase in frictional head losses and emitter clogging by fine sediments in the irrigation water, this factor may be reduced. To minimise this risk, the driplines are flushed on a continuous basis. The hydraulic simulation is therefore a valuable tool to make a prior judgement of costs associated with the drip irrigation.

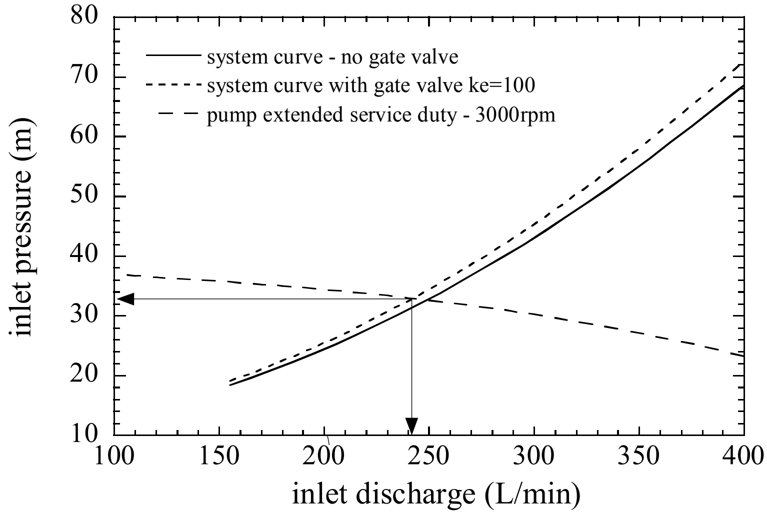

Figure 4: Pump characteristics and system curves.

Table 1: Pipe characteristics used in the simulation.

1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
1	1	25	1	80.00	247.289	248.877	1.08	30	2	31	30	16.00	238.566	247.289	2.70
2	1	26	2	80.00	245.289	246.877	1.98	31	2	32	31	0.01	238.566	238.566	0.18
3	1	27	3	80.00	243.289	244.877	1.98	32	3	40	32	163.00	233.768	238.566	0.60
4	1	28	4	80.00	247.289	245.702	1.08	33	2	34	33	1.00	244.114	244.114	0.60
5	1	29	5	80.00	245.289	243.702	1.98	34	2	35	34	1.00	244.114	244.114	0.60
6	1	30	6	80.00	243.289	241.702	1.98	35	2	39	35	19.00	233.768	244.114	2.70
7	1	33	7	80.00	244.114	245.702	1.08	36	2	37	36	1.00	244.114	244.114	0.60
8	1	34	8	80.00	242.114	243.702	1.98	37	2	38	37	1.00	244.114	244.114	0.60
9	1	35	9	80.00	240.114	241.702	1.98	38	2	39	38	19.00	233.768	244.114	2.70
10	1	36	10	80.00	244.114	242.527	1.08	39	2	40	39	0.01	233.768	233.768	2.11
11	1	37	11	80.00	242.114	240.527	1.98	40	3	57	40	21.00	234.300	233.768	1.80
12	1	38	12	80.00	240.114	238.527	1.98	41	2	42	41	1.00	240.939	240.939	0.60
13	1	41	13	80.00	240.939	242.527	1.08	42	2	43	42	1.00	240.939	240.939	0.60
14	1	42	14	80.00	238.939	240.527	1.98	43	2	47	43	16.00	234.636	240.939	2.70
15	1	43	15	80.00	236.939	238.527	1.98	44	2	45	44	1.00	240.939	240.939	0.60
16	1	44	16	80.00	240.939	239.351	1.08	45	2	46	45	1.00	240.939	240.939	0.60
17	1	45	17	80.00	238.939	237.351	1.98	46	2	47	46	16.00	234.636	240.939	2.70
18	1	46	18	80.00	236.939	235.351	1.98	47	2	56	47	0.01	234.636	234.636	2.11
19	1	48	19	80.00	237.764	239.351	1.08	48	2	49	48	1.00	237.764	237.764	0.60
20	1	49	20	80.00	235.764	237.351	1.98	49	2	50	49	1.00	237.764	237.764	0.60
21	1	50	21	80.00	233.764	235.351	1.98	50	2	54	50	15.00	232.736	237.764	2.70
22	1	51	22	40.00	237.764	236.970	1.08	51	2	52	51	1.00	237.764	237.764	0.60
23	1	52	23	40.00	235.764	234.970	1.98	52	2	53	52	1.00	237.764	237.764	0.60
24	1	53	24	40.00	233.764	232.970	1.98	53	2	54	53	15.00	232.736	237.764	2.70
25	2	26	25	1.00	245.289	247.289	0.60	54	2	55	54	0.01	232.736	232.736	100.18
26	2	27	26	1.00	243.289	245.289	0.60	55	3	56	55	163.00	234.636	232.736	0.60
27	2	31	27	16.00	238.566	243.289	2.70	56	3	57	56	141.00	234.300	234.636	1.80
28	2	29	28	1.00	245.289	247.289	0.60	57	3	58	57	3.00	234.300	234.300	0.00
29	2	30	29	1.00	243.289	245.289	0.60								

Column headings

1) pipe number; 2) pipe type 1 for dripline, 2 for 25 mm submain, 3 for 38 mm mains; 3) upstream connected node; 4) downstream connected node; 5) length (m); 6) upstream elevation (m); 7) downstream elevation (m); 8) upstream connection friction loss coefficient, ke.

NB: additional ke=100 for pipe 54 is due to gate valve.

Table 2: Dripline characteristics at the pump operating point (240 L/min, 32 m).

1	2	3	4	5	6	7	8	9
1	9.51	1.51	0.46	0.023	11.32	2.14	9.40	4.42
2	9.75	1.58	0.49	0.045	11.88	2.20	9.89	4.29
3	10.00	1.66	0.52	0.047	12.47	2.26	10.42	4.17
4	10.14	1.76	0.55	0.027	11.21	2.29	10.71	0.86
5	10.37	1.83	0.57	0.051	11.77	2.34	11.20	0.86
6	10.61	1.91	0.60	0.053	12.37	2.39	11.74	0.86
7	11.88	2.29	0.73	0.036	17.24	2.68	14.76	3.51
8	12.07	2.36	0.75	0.069	17.81	2.72	15.25	3.45
9	12.28	2.43	0.78	0.071	18.41	2.77	15.80	3.40
10	12.38	2.53	0.81	0.040	17.12	2.79	16.07	0.99
11	12.57	2.60	0.84	0.075	17.69	2.83	16.55	1.00
12	12.77	2.68	0.87	0.077	18.30	2.88	17.11	1.02
13	10.66	1.87	0.59	0.029	14.03	2.40	11.85	3.90
14	10.87	1.94	0.61	0.056	14.59	2.45	12.34	3.82
15	11.11	2.02	0.64	0.058	15.19	2.51	12.88	3.74
16	11.23	2.12	0.67	0.033	13.92	2.53	13.17	0.89
17	11.43	2.19	0.70	0.062	14.49	2.58	13.66	0.90
18	11.65	2.26	0.72	0.064	15.09	2.63	14.20	0.92
19	7.90	1.06	0.32	0.016	8.05	1.78	6.46	5.52
20	8.19	1.14	0.34	0.032	8.61	1.85	6.95	5.28
21	8.49	1.22	0.37	0.034	9.19	1.91	7.47	5.05
22	4.58	0.19	0.05	0.005	8.45	2.06	8.71	1.05
23	4.72	0.20	0.06	0.011	9.01	2.13	9.25	0.97
24	4.85	0.22	0.06	0.011	9.57	2.19	9.80	0.90

Column headings
1) total discharge (L/min); 2) total friction loss (m); 3) friction loss due to emitter insertion (m); 4) friction loss due to dripline connections (m); 5) dripline upstream pressure (m); 6) average emitter discharge (L/min); 7) average emitter pressure (m); 8) emitter discharge coefficient of variation (standard deviation / mean) (%).

4 Conclusions

Drip irrigation systems are being routinely used to aid the establishment of grasses on railway embankment steep slopes to control erosion within the semi-arid region of Central Queensland, Australia. The hydraulic modelling approach used to aid the design of the drip irrigation systems has been presented in this paper. It takes into account the velocity head change and a proper selection of the friction coefficient formula based on the Reynolds number. Fittings and emitter insertion head loss are incorporated into the hydraulic model. The hydraulic model was use to design drip irrigation systems at 37 sites on the recently constructed BRRP spur railway line. One of the sites has been used as a case study in this paper. The hydraulic simulation has been found to be a valuable tool to make a prior judgement of costs associated with the drip irrigation system.

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