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The impact of design approximations on the operational performance of an irrigation scheme

A case study in Malaysia

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Abstract. A method is presented to analyse the impact of the selection of irrigation gates on operational performance of the Sungai Muda Irrigation Scheme in Malaysia. The method examines the discharge capacity of the water control gates at all levels in order to compare the specific water supply (the ratio of supply to command area) with the specific water demand which is the required hydromodule. The term hydromodule is the reciprocal of "water duty" and thus has units of litres/second/hectare. The greater the deviation between the two, the greater the potential loss of control during the operation of the scheme. The method is relatively simple but is more complex in this particular example as two hydromodules are used for the irrigation of basin rice; one for the presaturation period and one for the normal supply period. The most common cause of loss of water control is found to be provision of oversized turnout gates at the head of secondary and tertiary canals. Such design approximations enable more water to be used in those command areas thus leading to waste and to shortage of water in other areas. It is suggested that during design and rehabilitation of irrigation schemes, the operational implications of design approximations should be examined more carefully.

Key words: canal irrigation, design, gates, equitable distribution, management, rice, Malaysia

Water control in irrigation

Water control devices (at widely varying levels of sophistication) are provided in all irrigation schemes in order to facilitate management of water distribution. The relationship between the choice of technology and manageability of the system has been explored by various authors (notably: Horst 1983 & 1990; Juriens 1984), whose conclusions may be summarised as follows; "good water control is facilitated by the presence of well-designed irrigation structures that can deliver known water flows without complicated operation mechanisms, and which encourage 'management willingness' to use the structures correctly" (Lankford 1992). Poor performance of irrigation systems has generally been seen as the consequence of deficiencies in management and the issue of unrealistic design has received too little attention (an exception is Plusquellec et al. 1994). The relationship between design and manageability is too often overlooked by designers and design assumptions on how gates will be operated are often not fulfilled (Murray-Rust & Snellen 1993).

This paper examines how deficiencies within the design process may adversely impact on the precision of water control. It demonstrates how coarse design approximations, whereby gates in a few sizes are produced in batches for command areas that are widely varying, lead to bottlenecks or excessive flows (which could be described as 'internal leaks') within irrigation systems. Bottlenecks occur where the maximum possible flow is inadequate to supply a command area and examples are undersized gates and canal sections. Internal leaks occur where the maximum supply of water allowed through a structure is excessive for the command area, for example caused by an oversized gate.

A quantitative method of assessing the level of designed-in water control is presented. The method calculates the *specific supply* by dividing the maximum discharge capacity of the turnout gates by the command area served by the gate. The specific supply, which is the ratio of water supply to area (1/sec/ha), is then compared to the target *specific water demand* which is the hydromodule. The hydromodule is the crop and system water requirement (1/sec/ha) after accounting for losses at different levels of the irrigation system (i.e. reciprocal of 'water duty').

The method has two steps, first the calculation of the specific supply for each command area served by a gate, and second the calculation of the ability of the offtaking canal system gates to route the flow discharged by the higher canal. This latter calculation is necessary as this routing ability affects the actual supply by causing backing up of water. For the purposes of this analysis, the maximum discharge capacity of the gate in question is determined by its widest setting when the upstream and downstream water levels are at their required design values.

The method can be used to determine whether the correct specific supply is obtained first at the headworks, then in the main canal, and then at each subsidiary canal level. The final test of control is the specific supply at the lowest distribution level; the farm-offtake gate. By working down the system to see if designed specific supply is too large or too small, the analysis shows up sources of design weakness where, in the operation of the scheme, control of water is likely to suffer. If the design of water control is accurate, then the specific supply at each level should be the same as the hydromodule when adjusted for system losses. This analysis gives a picture of the theoretical control due to design and indicates where management has to compensate by ensuring gates are adjusted correctly.

Case study system

The Sungai Muda Irrigation Scheme is located on the mainland part of the State of Pilau Pinang in Malaysia, just south of the much larger Muda Irrigation Scheme. The irrigation system, which is 6766 ha in size, is currently being rehabilitated by the State Department of Irrigation and Drainage (DID). Sungai Muda is a run-of-river scheme built for basin-irrigated rice. Water is pumped directly out of the Muda river into one main canal that runs south from the pump station. From the main canal, nine secondary canals flow west or southwest supplying tertiary canals that generally flow south. Relief is subdued and gradients are in the order of 1 in 1000.

Turnout design utilises the constant head orifice (CHO) type of gate to both control and measure water discharges. These gates have been noted in several studies as being difficult to operate accurately (Plusquellec et al. 1994; Weaving 1991) because of the complex operation of two sluice gates on the structure. The upstream sluice gate sets the flow whilst the downstream gate is adjusted to obtain a head difference of 60 mm between the water level in the structure chamber and the water level in the parent canal. The maximum discharges used in this paper were determined on the assumption that the upstream gate is used to control flow, although higher discharges could be obtained in places by altering both gates.

Irrigation follows a typical schedule for rice; the season begins with a presaturation supply delivered to a portion (approximately one third) of a secondary command unit to saturate the soil and ensure a standing water layer of about 100 mm depth. After 15 days of presaturation flow, water supply is reduced by half to a level known as normal (or maintenance) supply. Normal supply flows continuously throughout the season until four weeks before harvest when water is cut off to allow the fields to dry out. The delivery of both a presaturation and a normal supply results in two hydromodules being used to design the canal and turnout system.

This use of two hydromodules for irrigation design of basin-rice schemes, which is the common method in South East Asia (Clark et al. 1982), makes the design analysis more complicated. Therefore for the purposes of demonstrating the method, gate design is assessed for the third presaturation period when water demand is highest and when equity problems show up clearest. It is during this period that presaturation flows are delivered to approximately one third of a given command area and normal supply to the rest.

Calculations are tabulated for all secondary canals, and then all tertiary canals on one secondary canal (i.e. canal D). Using the tables, example calculations are described for one water flow path through the scheme. The path (see Figure 1) is from the headworks of the main canal through Secondary Canal D and Tertiary Canal D-1 to the farm offtakes. Of course, the method

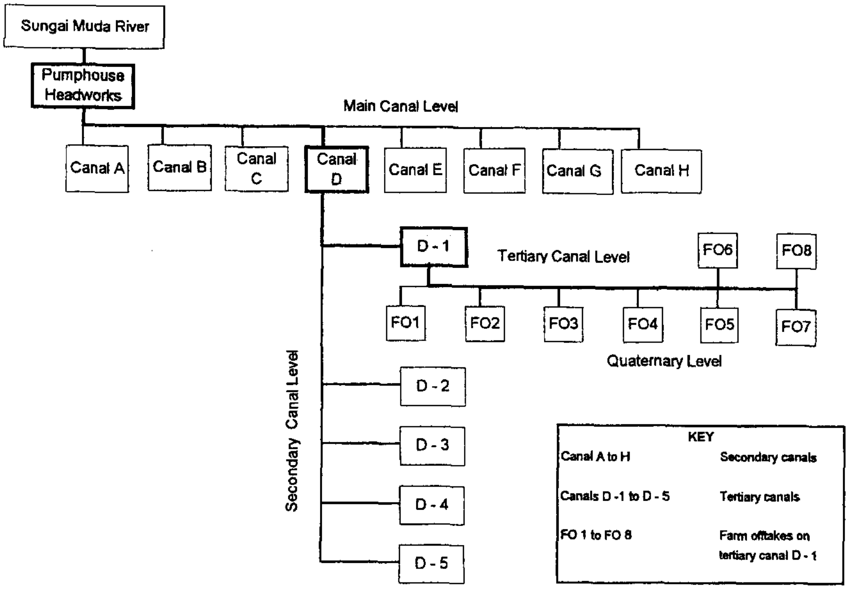

Figure 1. Schematic representation of part of the Sungai Muda Irrigation Scheme showing the path of analysis of design of water control.

Table 1. Rice-irrigation hydromodules for different levels of the Sungai Muda Irrigation System.

Level	Efficiency	Hydromodule (l/sec/ha) Presaturation	Normal
Main intake	95%	4.27	2.13
Secondary canal gate	90%	4.05	2.03
Tertiary canal gate	95%	3.65	1.82
Farm offtake (for field)	75%	3.47	1.73
Crop level	net	2.60	1.30

of analysis could be applied to all secondary and tertiary canals to build up a picture of control weaknesses throughout the system.

To design the rehabilitation works for the scheme, DID use efficiency figures and presaturation and normal hydromodules for different levels of the irrigation system as given in Table 1. For example, at the crop level, the presaturation hydromodule is 2.60 l/sec/ha and the normal supply hydromodule is 1.30 l/sec/ha. The field efficiency is taken as 75%. From Table 1 it can be noted that the overall efficiency of the system if 61%.

Table 2. Gate sizes and maximum discharge capacities for secondary canals in the Sg. Muda Irrigation Scheme.

Secondary canal unit	Area served (ha)	CHO Gate diameter (feet or mm)	Maximum flow (Q) through gate (l/sec)	Maximum demand flow required in period 3 (l/sec)	Balance of supply over demand (l/sec)
A	1418	Twin 5′-0″	3334	3515	–181
B	797	Twin 5′-0″	3334	2218	+1116
CA	294	1200 mm	770	1192	–422
C	1023	Twin 5′-0″	3334	2461	+873
D	198	1200 mm	770	579	+191
E	296	1200 mm	770	797	–27
F	1412	Twin 5′-0″	3334	3937	–603
G	420	Twin 4′-0″	1047	1176	–129
H	908	Twin 5′-0″	3334	2585	+749
Total	6766		20027	18452	

Analysis at the main intake level

The first step is to determine the specific supply at the main intake and compare this to the design presaturation hydromodule at that level. The pumphouse is currently being upgraded to deliver approximately 20,000 l/sec and the area of the whole scheme is 6766 ha. This represents a presaturation specific supply of 4,43 l/sec/ha at the main intake level based upon the peak requirement period. The specific supply of 4.43 l/sec/ha is closely matched to the specific demand (hydromodule) of 4.27 l/sec/ha (see Table 1).

The second part of assessing water control in the main canal is to determine whether the flow sent down the canal can be accepted (or routed) by the designed discharges from the turnouts supplying the secondary canals. There are nine secondary canals with a variety of head-gate sizes (Table 2) and their total discharge capacity is 20,027 l/s. Thus the total flow coming down the main canal can be accepted through the secondary gates.

Analysis at the secondary system level

The effect of design approximations in the secondary canal system on the specific supply and its comparison with the required hydromodule can then be determined. To do this it is first necessary to calculate the over- or under-supply through the gates at the head of the secondary canals, the results of

Table 3. Calculation of peak water demand for the secondary unit D.

Type of supply	Hydromodule l/sec/ha	Area supplied ha	Total supply (l/sec)
Normal	2.03	110	223
Presaturation	4.05	88	356
Total			579

which are given in the final column of Table 2. Once this has been done, the effect of the discharge on the specific supply can be calculated.

For example the secondary canal unit D is supplied by a constant head orifice gate with a 1200 mm orifice diameter which can give a maximum discharge of 770 l/sec. To calculate the over- or under-supply, it is then necessary to calculate the peak demand of the secondary unit. This is carried out in Table 3 for the third irrigation schedule using hydromodules taken from Table 1 for the secondary canal level; 4.05 l/sec/ha for presaturation supply to 88 ha (= 356 l/sec) and 2.03 l/sec/ha for normal supply to 110 ha (= 223 l/sec). Adding these together gives a peak demand of 579 l/sec. Therefore the gate oversupplies unit D by 191 l/sec.

The calculation of the specific supply figure is not straightforward because in the secondary unit there is an area receiving presaturation supply and an area receiving normal supply. Table 4 shows the calculation of presaturation specific supply from data in Table 3 and compares it with the required presaturation hydromodule. For example in Secondary Canal D it is first assumed that the extra water (191 l/sec) is taken in proportion to the area served by the two different types of supply. Thus the area receiving presaturation supply which is 88 ha of 198 ha gets 0.444 of 191 l/sec (= 85 l/sec) and the area receiving normal supply gets 0.556 of 191 l/sec (= 106 l/sec). So, the total supply to the presaturation area is 356 + 85 = 441 l/sec and the total supply to the normally supplied area is 223 + 106 = 329 l/sec. Dividing these supplies by their respective command areas gives a presaturation specific supply of 5.01 l/sec/ha and a normal specific supply of 2.99 l/sec/ha.

The oversized gate for Canal D clearly increases the specific supply from the required presaturation hydromodule of 4.05 l/sec/ha to the potential specific supply of 5.01 l/sec/ha. This creates an opportunity for excessive use of water in unit D. On the other hand, the final column of Table 4 shows that "bottlenecks" have been designed into the secondary canals supplying units A, CA, E, F and G. For example area F is under- supplied by 0.43 l/sec/ha

Table 4. Effect of maximum secondary canal discharges on specific supply and comparisons with required hydromodule.

Secondary canal unit	Balance of over or under supply for whole unit (l/sec)	Total command area for secondary unit (ha)	Area supplied by presaturation flow during schedule III (ha)	Proportion of presat. area of whole command unit	Required hydromodule for presaturation area (l/sec/ha)	Required flow for presat. area (l/sec)	Proportional change of flow for presaturation area (l/sec)	Corrected flow for presat. area (l/sec)	Corrected specific supply for presat. area (l/sec/ha)	Difference in specific supply for preset. area (l/sec/ha)
A	–181	1418	316	0.223	4.05	1280	–40	1239	3.92	–0.13
B	1116	797	297	0.373	4.05	1203	416	1619	5.45	1.40
CA	–4.22	294	294	1.000	4.05	1191	–422	769	2.61	–1.44
C	873	1023	191	0.187	4.05	774	163	937	4.90	0.85
D	191	198	88	0.444	4.05	356	85	441	5.01	0.96
E	–27	296	96.2	0.325	4.05	390	–9	381	3.96	–0.09
F	–603	1412	530.5	0.376	4.05	2149	–227	1922	3.62	–0.43
G	–129	420	160	0.381	4.05	649	–49	599	3.74	–0.31
H	749	908	367	0.404	4.05	1486	303	1789	4.87	0.82

File: MALGATE

Table 5. Effect of tertiary canal gate discharges on specific supply and comparisons with required hydromodule.

Tertiary canal	Area served (ha)	Gate diameter (mm)	Max flow (Q) through gate (l/sec)	Required hydromodule (l/sec/ha)	Specific supply (l/sec/ha)	Balance in specific supply (l/sec/ha)
D-lL	25.7	600	186	3.65	7.23	+3.58
D-2L	44.2	600	186	3.65	4.21	+0.56
D-3L	22.0	600	186	3.65	8.45	+4.80
D-4L	18.4	450	109	3.65	5.92	+2.27
D-5L	29.0	450	109	3.65	3.75	+0.10

because a gate supplying 3334 l/sec has been installed for a command area that requires 3937 l/sec.

Analysis of the tertiary system level

The calculation of the specific supply from the tertiary canals in secondary canal D is shown in Table 5. For example, the gate at the head of tertiary Canal D-1L is 600 mm diameter and discharges a maximum of 186 l/sec which results in a specific supply of 7.23 l/sec/ha (186 l/sec divided by the command area, 25.7 ha). The required hydromodule is 3.65 l/sec/ha which shows that this design approximation gives a gate almost twice as large as necessary. Without correction by the gate keeper this will almost certainly lead to over-use of water (an internal "leak") and a shortage elsewhere.

Table 5 can also be used to check whether the flow down secondary canal D can be accepted by the tertiary system. There are five tertiary canals in secondary unit D. Canals D-1 to D-3 have CHO's with orifices 600 mm diameter and canals D-4 and D-5 have 450 mm CHO's. According to design, the maximum discharge of the 600 mm gate is 186 l/sec and that of the 450 mm gate is 109 l/sec. The total flow taken by the six canals is $(3 \times 186) + (2 \times 109) = 776$ l/sec. In addition there are 16 farm- offtakes directly situated on the secondary canal that can each accept from 5 l/sec to 14 l/sec with the design head of water. Thus all the offtakes leading from the secondary canal can take a total of 856 l/sec to 1000 l/sec which is more than the maximum flow that comes down canal D (770 l/sec). This means that the turnout gates on secondary canal D can successfully route their flow without causing a backing-up of water.

Table 6. Calculation of farm offtake area, pipe discharge and specific supply (for the presaturation period only) for Tertiary Canal D-1.

Farm	Flow from pipe (l/sec)	Area supplied (ha)	Specific supply (l/sec/ha)	Required hydromodule (l/sec/ha)	Balance in specific supply (l/sec/ha)
FO 1	9.7	3.94	2.46	3.47	–1.01
FO 2	11.0	2.90	3.79	3.47	+0.32
FO 3	11.6	3.27	3.55	3.47	+0.08
FO 4	12.4	2.44	5.08	3.47	+1.61
FO 5	9.2	3.38	2.71	3.47	–0.76
FO 6	7.5	3.21	2.34	3.47	–1.13
FO 7	7.5	3.41	2.20	3.47	–1.27
FO 8	5.8	2.86	2.03	3.47	–1.44
Total	74.7	25.41			

Analysis at the field level

The first task is to determine the specific supply of individual farm offtakes along Canal D-1 (refer Table 6). With the canal at the full supply level (FSL) during the presaturation period, the flows of different FO gates vary from 5.8 l/sec to 12.4 l/sec (determined using a head–discharge relationship at FSL). To calculate the command area that each farm offtake supplies – called the farm offtake supply area (FOSA) – it was assumed that each FOSA does not have solid boundaries because of seepage across bunds between fields. Thus, the area of the FOSA was estimated by taking an imaginary line from the FO gate directly across the line of slope to the drain at the opposite side of the field. FOSA areas were found to vary from between 2.4 to 3.9 ha.

The specific supply is calculated by dividing the presaturation flow of each of the eight FO gates by the FOSA area. The specific supply was found to range from 2.03 l/sec/ha to 5.08 l/sec/ha, which can be compared to the required hydromodule of 3.47 l/sec/ha. The final column in Table 6 shows the variation in the specific supply at the field level and indicates the design of control during presaturation supply at the farm offtake level. The deviation of the specific supply from the hydromodule at the crop (or field level) is from 57% below to 47% above the required presaturation hydromodule of 3.47 l/sec/ha. The lack of control at the field level is due to two design factors; a wide range of FOSA areas caused by incorrectly located farm offtakes and variations in flows due to differences in command. Although such variations may not directly lead to large yield losses, they could if combined with changes in

Table 7. Differences in the specific supply from the required hydromodule for the presaturation period for different levels of the Sungai Muda Irrigation Scheme analysed via a selected path.

Irrigation level of the scheme	Required presaturation hydromodule (l/sec/ha)	Maximum designed specific supply (l/sec/ha)	Minimum designed specific supply (l/sec/ha)
Main	4.27	4.43	4.43
Secondary	4.05	5.45	2.61
Tertiary	3.65	8.45	3.75
Field	3.47	5.08	2.03
(Crop)	2.60	3.81	1.52

supply from the distribution canals, lead to significant water shortages in localised areas.

As with the tertiary system, it is necessary to determine whether the field (or quaternary) system can accept the incoming canal water without backing up. The water flowing into the tertiary unit at peak requirement is 94 l/sec. The combined discharge of the eight farm offtakes is 75 l/sec, which is 19 l/sec less than the inflow; which gives an excess of about 2.4 l/sec per offtake. According to the discharge rating curve for the FO gate an additional 80 mm head is required to pass the 2.4 l/sec flow, which is available because the freeboard in the canal is 380 mm. Therefore, allowing for a small surcharge, the flow sent down Canal D-1 can be routed through the offtakes on that canal.

Summary of variations in specific supply compared to the hydromodule at different levels of the irrigation system

The difference in the specific water supply from the required hydromodule is an important calculation as it shows how exact the "designed-in" water control is on the irrigation system. Table 7 summarises these differences for the five levels; main, secondary, tertiary, field and crop for the chosen path of analysis. The specific supply at the crop is calculated from the field figures derived in Table 6 by allowing for the field efficiency of 75%.

Figure 2 graphs the results given in Table 7 and indicates the difference between the hydromodule and actual specific water supply. The greater the difference between the hydromodule and specific supply, the greater the potential loss of water control. At the head of the secondary canals, gate design has resulted in both over- and under-supply of water. At the head of the tertiary canals on Secondary Canal D, most of the gates are larger than necessary, and none are restricting supply. At the field level, the design approximation of

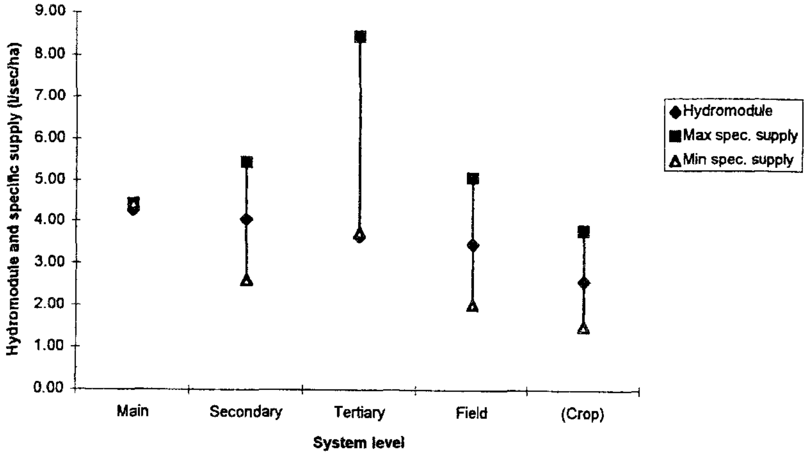

Figure 2. Graph of differences between the required presaturation hydromodule and the actual specific supply (both l/sec/ha) based on gate design approximation of the Sg. Muda Irrigation System.

farm offtake command areas caused by the siting of the farm offtakes leads to both under and over supply at this level. By referring to Figure 2, the largest difference on this particular path of analysis was found at the tertiary level and is due to a greatly oversized turnout gate at the head of canal D-3L.

Design approximation and their effect on operation

Design approximation on a canal irrigation scheme can create severe operational problems in attempting to maintain equity of supply. Where gates are too large, gatekeepers need to throttle back gate settings, and come under pressure from farmers for doing so. Where gates are too small, as was found in the Sungai Muda case, water shortages are likely. Design approximations are commonly used to standardise design and construction, and to save money in the short-term. However the longer term implications of poor operation and inequity of supply on performance and productivity must also be considered. It is almost impossible to operate canal systems at high efficiency if the incorrectly sized gates are difficult or complicated to adjust and if water levels are dynamic and affect upstream and downstream gate discharges. To overcome the potentially high cost of constructing each gate individually, it would be possible to make sets of gates that are uniform but have smaller incremental changes than are currently selected.

Jurriens (1980, 1984) suggested that studies should be carried out to investigate what makes a system so difficult to operate. We have shown that one such source of difficulty is the use of design approximations. The method in this paper quantitatively analyses the potential impact on water supply of design approximations and is useful because it serves as a check for irrigation engineers during the design of a system. Too often, designers do not think of the gatekeepers who have to ensure equitable supply and whose job would be made easier if the system was designed with equity in mind. This entails designing and building gates that are accurately sized for the water demand of their command area. A method such as the one in this paper could also be used by irrigation specialists wishing to investigate aspects of design when appraising the performance of irrigation schemes.

Design engineers will naturally wish to allow a safety factor to compensate for poor construction or even occasionally extremely high demand peaks. Some margin is probably beneficial, but above a certain amount of slack, the disadvantages of poor water control begin to outweigh any possible advantages of flexibility. Guidelines need to be developed so the system is a balance between cost-effective construction, meeting the needs of the crops and farmers, and encouraging good water control. It is suggested that discharge capacities should not be greater than 110 to 115% of required peak flow for any water control gate. This would still allow gates to be approximately designed but utilising much smaller increments in sizes.

Conclusion

Potential loss in water control was quantitatively analysed by studying the relationship between command areas and maximum gate discharges to determine the variation of the actual specific water supply from the hydromodule (the specific water demand). It was found that gates were rarely the correct size for the area they served. Both over- and under-sized gates were used at the head of the secondary and tertiary canals of the Sungai Muda Irrigation Scheme. Where gates were larger than necessary it could be argued that by careful and correct operation, the hydromodule supplied at the headworks could be maintained at the correct value down the system to the farm offtakes. In practice, gates were frequently opened to their maximum limit. When this occurs, the specific supply differed from the hydromodule by up to 3.55 l/sec/ha at each system level effectively doubling supply. In some cases this may be reduced by backing-up of water, but often farmers take the additional water which inevitably causes shortages elsewhere.

The design approximation leading to under-sized gates is likely to lead to a bottleneck in supply and water shortages. In this particular case the field research found no evidence to suggest that water control under normal climatic conditions was limiting rice production. This was due to sufficient monsoon rainfall that made the irrigation supplementary and masked the effect of poor water control. However, there were reports that during periods of low rainfall and water shortages, water control was insufficient to ensure equal distribution of limited supplies (DID, personal communication, 1992). It is highly likely that the combination of both under- and over-sized gates is likely to disrupt equitable supplies still further. It is argued here that one of the main causes of unequal supply is due to the use of incorrect gate sizes that come about as a result of using standard or approximate gate design for different command areas. Under normal climatic circumstances, although there is little agricultural impact, the internal leaks become losses and thereby cause unnecessary pumping costs.

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