CANAL OPERATIONS PLANNER III

by

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# Abstract

For many large irrigation systems distributing water equitably is a stated management objective. Canal operations plans specify which canal to operate at what discharge for each irrigation interval to achieve the stated objective. In this research a function of the Gini index is incorporated in to an integer-programme that can develop a canal operations plan. In contrast with earlier canal operations planners which minimize inequity, the operations planner presented herein does not constrain the discharge in a canal to a binary integer. Rather the user can define an allocation cost function which in turn defines the preferred operational range of discharge over which any canal should be operated for any interval. The operations planner can also be modified to permit spillages. The model is applied to a secondary canal in Pakistan and the sensitivity of the results to operational range and permissible spillage are explored. An engineering application of the model is presented.

# Background

The operation of canals in rotation is the practice of operating canals intermittently – typically for a number of days within an interval or alternatively on and off over entire intervals to achieve a particular objective. Levine et al (1976) described rotational irrigation for a number of irrigation systems in Taiwan where the objective of rotational irrigation is; adequacy; timeliness, and correct sequencing. Nam et al (2016) described the practice of rotational irrigation in the Gimjae Irrigation System which abstracts water from the Dongjin River in central South Korea. The objective of introducing rotational irrigation in the Gimjae Irrigation System is not stated explicitly but, they have stated that improvements to the secondary canals were made to ensure; equity, reduce distribution losses; and, improve control. The operation of canals in rotation is intrinsic to the management of canals in Pakistan and north-west India (Kaur et al, 2013). A key characteristic of irrigation systems in this region is that these systems by-design, only provide a fraction of the crop water requirements (Khepar et al, 2000). Seckler et al (1998) estimated that the water delivered through the canal system was only sufficient for one third of the land serviced by the irrigation system. Bandaragoda (1996) and Hussain et al (2011) have confirmed this estimate. For one particular irrigation system in Pakistan, Awan et al (2016) have estimated that the volume of water delivered at the head of tertiary canals is 51% of actual evapotranspiration and groundwater contributes towards a further 47% of actual evapotranspiration. The *warabandi* as described by Malhotra (1982), notwithstanding the literal translation of *warabandi* as fixed turns (Sharma and Oad, 1990), is a comprehensive management system for irrigation systems that are deficit by-design and this includes the operation of canals in rotation.

Santhi and Pundarikanthan (2000) described a planning model for canal scheduling of rotational irrigation with one of the stated objectives as minimizing inequity. In the models developed by Santhi and Pundarikanthan (2000) canals are explicitly placed in logical groups. Canals are typically operated in groups to reduce the labour cost of operating canals and/or due to the location of cross-regulators which allow control of water levels particularly when canals are operated at less than capacity. Often the physical location of canals will determine the logical grouping. Kaur et al (2013) developed upon the model of Santhi and Pundarikanthan (2000) and, applied this development to the Harabhangi Irrigation Project in Orissa, India where again canals are logically grouped. Anwar et al (2016a) described the canal operations plan used to manage irrigation systems in the Punjab, Pakistan. These place canals into the three logical groups of; high priority, medium priority and low priority. In the Gimjae Irrigation described by Nam et al (2016) canals are grouped into an upper region group, and a lower region group. Anwar et al (2016a) developed a linear programme that prepares a canal operations plan while maximizing delivery performance ratio (DPR), the ratio of discharge to canal capacity, where again canals are logically grouped. A number of authors (Bos et al., 2005, Clemmens and Bos, 1990, Clemmens and Dedrick, 1994) advocate the use of delivery performance ratio (DPR) as a performance measure for the operation of canals in a *warabandi* system. The canal operations planner of Anwar et al (2016b) minimizes inequity and does not use any logical grouping.

Distributing water equitably is a key objective of *warabandi* managed irrigation systems (Bhutta and Velde, 1992). Hence by implication a key objective of a canal operations plan for *warabandi* managed irrigation systems must be equity. Improving equity in irrigation systems is often a stated objective for a number of development investments e.g. World Bank (2015), Asian Development Bank (2015). Equity is also identified in the (draft) Pakistan National Water Policy (Government of Pakistan, 2012) and equitable distribution of water is also identified as imperative in key informant interviews by Mustafa (2002). Equity in *warabandi* managed systems has been extensively studied e.g. Latif and Sarwar (1991), Khepar et al., (2000), Shah et al (2016). Molden and Gates (1990) stated that the coefficient of variation could be used as a performance indicator for equity. The coefficient of variation has been used as a performance indicator of equity by others e.g. Nam et al (2016), Kalu et al (1995), Kazebov et al (2009) and the models by Santhi and Pundarikanthan (2000) and Kaur et al (2013). Sampath (1988) compared six measures of equity, including the coefficient of variation, against a set of seven axioms for measures of equity. Sampath (1988) concluded that the Theil index meets all of the axioms except Axiom #7: Normalized Values. Although as discussed by Sampath (1988) any index such as the Theil index that has a finite maximum “*can easily be normalized without altering its cardinal properties simply by dividing by that maximum value*.” Sampath (1988) also acknowledged that the Gini index is the most widely used measure of equity although it does not meet all the seven axioms. The Gini is a normalized index with 0 representing perfect equity, 1 representing total inequity and in a generalized form is given by

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| --- | --- | --- |
|  |  | ∀ *i,j* ∈ *N* …(1) |

where *G* = Gini index; *xi*= variable of interest for the *i*th member in the population; *xj* = variable of interest for the *j*th member in the population; *N* = size of the population; and, = average of the variable of interest for the population. Cullis and Van Koppen (2007) used the Gini in their discussion on equity. Wang et al (2011) used the Gini in the context of domestic water supply, whereas Anwar and Haq (2013) applied the Gini specifically to *warabandi* managed irrigation systems whereby the variable of interest in (1) is the cumulative depth of irrigation supplied. Drezner et al (2009) used the numerator of the right-hand-side in (1) which is described as the mean difference, to determine equitable service by facilities. Anwar et al (2016b) used this mean difference to prepare a canal operations plan with a linear programme that minimizes inequity (LP-INEQ). A key difference between the LP-INEQ model and the models of Anwar et al (2016a) that maximize DPR is that the LP-INEQ model constrains DPR to a binary variable i.e. a canal can either be operated at capacity or shut completely. In comparing the LP-INEQ model with the models that maximize DPR, Anwar et al (2016b) concluded the constraint on DPR as binary is very restrictive and, some variation in DPR from 1.0 is probably permissible. Briscoe and Qamar (2005) suggested that in the context of Pakistan’s irrigation systems, canals should be operated in the DPR range of 0.70 to 1.10. Hence in this research the LP-INEQ model is developed further whereby DPR is no longer binary – rather DPR assumes a range akin to that suggested by Briscoe and Qamar (2005). This research as with the LP-INEQ model, does not use any logical grouping of canals and the implications of this are discussed.

# Materials and Methods

The Analysis section of this paper describes the development of a linear program to prepare a canal operations plan with the objective of minimizing inequity and operating canals at or near capacity or closing the canal. This linear programme is herein referred to as the LP-INEQ+ Model. The’+’ suffix is added to distinguish this model from that presented by Anwar et al (2016b).

In the Results and Discussion section of this paper, results from applying the LP-INEQ+ model to the study area are reported and compared with earlier results. The study area is located in the central Punjab province of Pakistan. The climate of this area can be characterized as arid with large seasonal fluctuations in temperature and rainfall. Annual reference evapotranspiration is in excess of 1,800mm greater than the average annual rainfall of 250mm. Irrigated agriculture is practiced throughout the year. Pakistan’s Indus Basin Irrigation System (IBIS) has two crop seasons. The summer crop season extends from mid-April to mid-October and the winter crop season extends from mid-October to mid-April of the following calendar year. For the purposes of canal operations planning, each crop season is typically divided into eight-day intervals, hence there are 23 intervals in a crop season. Some canal operations plans within the IBIS use a seven-day interval and hence there are 24 intervals in a crop season. The study area, is a typical of the run-of-the-river irrigation systems prevalent in the IBIS. The primary canal (Eastern Sadiqia Canal) receives water from the River Sutlej, a tributary of the River Indus at the Sulemanki Barrage. This primary canal in turn supplies the secondary canals; Malik Branch and Hakra Branch, the latter shown in Figure 1. The secondary canal - Hakra Branch in turn supplies water to 17 tertiary canals listed in Table 1. Table 1 shows the running distance, the distance along Hakra Branch at which each tertiary canal is located, whether it is on the left or right bank of Hakra Branch, the capacity at the head of the tertiary canal, the area irrigated and, the capacity per unit area. The capacity per unit area is not identical for all 17 tertiary canals. Hence even if there were sufficient flow in the secondary canal such that all tertiary canals listed in Table 1 could be operated at capacity and continuously there would be a degree of inequity as a result of these physical characteristics. This inequity is referred to as systematic inequity and any inequity above systematic inequity is attributed to the operation of the tertiary canals, hence operational inequity (Shah et al 2016). Applying (1) to the column capacity per unit area in Table 1 the systematic inequity Gini is 7.28%. The total area irrigated by these 17 tertiary canals is 203,057 ha. A further 19,069 ha is irrigated by turnouts located on the secondary canal Hakra Branch itself (known in the vernacular as direct outlets) and therefore the total area irrigated by Hakra Branch is 222,126 ha. Discharge data for all 17 tertiary canals of Hakra Branch was collected by the authors using electronic instrumentation described in Ahmad et al (2013). Further data was obtained from the Programme Monitoring & Implementation Unit (PMIU) of the Irrigation Department, Government of Punjab (PMIU, 2014).

The model developed in this research is implemented in LINGO 14.0 (for Windows) on a PC operating on Windows 10. The model is applied to data for the Hakra Branch for 3 crop seasons; summer 2014; winter 2014-15; and, summer 2015. The models are developed with a default operational range of +10% and a default permissible spillage of 0%. Using data for summer 2014, the sensitivity of the results to operational range and permissible spillage is also examined. These terms are explained in more detail in the Analysis section.

# Analysis

### Decision variable in the LP-INEQ+ Model

The decision to be taken by the canal operator is at what discharge to operate each tertiary canal for each interval of a crop season. It is more convenient to use DPR rather than discharge, therefore the decision variable in the LP-INEQ+ model is the DPR for each tertiary canal for each interval. DPR is a non-negative real number. A DPR of zero implies a canal is closed. A DPR of 1 indicates a canal is flowing at capacity. A DPR in excess of 1 indicates that the canal is surcharged i.e. operated above capacity whereby the water level in the canal will encroach upon the freeboard of the canal.

### Objective function of the LP-INEQ+ Model

There are two goals of the LP-INEQ+ model hence in this is a dual goal objective. The first goal is to minimize inequity, the second goal is to operate insofar as possible a canal either at capacity, or to close the canal altogether for that particular interval. The variable of interest to be managed equitably is the cumulative volume of water per unit area as described in Anwar and Haq (2013). The Gini in the context of cumulative depth of water delivered by any canal up to and including the current interval is given by

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| --- | --- | --- |
|  |  | ∀ *τ* ∈ *T* …(2) |

where: = Gini-index up to and including current interval ; = cumulative depth of water delivered by canal *n* up to and including current interval ; = cumulative depth of water delivered by canal *m* up to and including current interval ; *N* = size of the population (number of canals in the operations plan); and, = average cumulative depth of water delivered by all canals up to and including current interval . The cumulative depth of water in (2) can be estimated from the discharge in the canal and duration.

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| --- | --- | --- |
|  |  | ∀ *τ* ∈ *T*  (3) |

where = area irrigated by canal *n*; = discharge allocated to the canal *n*  in interval *t* ; and, = duration of interval *t*.

Following Drezner et al (2009), inequity is quantified in the objective function by the RHS numerator of the Gini in (2). The RHS denominator in (2) is a scaling factor that normalizes the Gini. In minimizing (or maximizing) an objective function only the arguments that minimize (or maximize) the objective function are of interest as opposed to the value of the objective function per se. The arguments that maximize the objective function are independent of any scaling term such as the RHS denominator in (2). Therefore the RHS denominator term in (2) can be omitted for the purposes of the objective function. The advantage of using only the RHS numerator in (2) is that the model can be expressed as a linear programme rather than a non-linear programme. A linear programme will solve to a global optimum as opposed to a local optimum. A globally optimalsolution is a feasible solution with an objective value that is as good as or better than all other feasible solutions to the model (LINDO, 2015). The absolute function in the RHS numerator in (2) can be resolved into a set of linear equations and some solvers have this as a built in feature e.g. LINDO (2015) albeit with the health warning that “*This can dramatically increase solution times as well as affect the accuracy of the solution"* LINDO (2015).

To achieve the second goal to operate insofar as possible a canal either at capacity, or to close the canal altogether for that particular interval, it is necessary to define an allocation cost function. The allocation cost is a function of the DPR and needs to be defined a priori by the agency preparing the operations plan. Figure 2 illustrates an allocation cost function. The principle illustrated by Figure 2 is that if the canal flows within a narrow range around a DPR of 1.0, labelled as operational range in Figure 2, or if the canal flows at a DPR of 0.0, the allocation cost is 0.00. Alternatively, if the canal flows at a DPR other than 0.0 or other than the range around canal capacity, labelled as non-operational range in Figure 2, the allocation cost is high. As the model minimizes the allocation cost in the dual goal objective function, the model will attempt to operate a canal at or near capacity (within the operational range) or close flow through the canal. The allocation cost function shown in Figure 2 is user defined and can be customized to reflect the rules and preferences of an irrigation agency. In Figure 2, the dependent variable is the allocation cost and the independent variable is DPR. It is relatively straight-forward to add another independent variable e.g. canal, which could be presented in Figure 2 with multiple lines – one for each canal. If a particular canal has very limited freeboard, or perhaps is in a state of disrepair, it may be undesirable to allow this canal to be operated over capacity. Hence a user could define an allocation cost function specific to such a canal that does not allow the DPR to exceed 1.0. Similarly an allocation cost function may be dependent upon the interval within a crop season e.g. during certain intervals it may be permissible to allow a canal to be operated over a greater range whereas in other intervals it may be necessary to restrict the canal operation to a narrow range. Similarly Figure 2 is a continuous piecewise linear function with 6 breakpoints, however a user can define this function with any number of breakpoints to reflect the users preferences towards canal operations. The +10% operational range shown in Figure 2 is for the purposes of this work referred to as the default operational range.

The dual goal objective function can be expressed mathematically as

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| --- | --- | --- | --- |
|  | | | ∀ *τ* ∈ *T* …(4) |
|  | Inequity cost | Allocation cost |  |

where = objective function of the LP-INEQ+ model up to and including interval; = allocation cost for canal *n* during interval ; = current interval; and, *M*= large positive constant. Hence

|  |  |
| --- | --- |
|  | ∀ *τ* ∈ *T* …(5) |

where = minimum of the objective function of the LP-INEQ+ model up to and including interval *τ*.

In Figure 2 the maximum allocation cost is set to 1 and in (4) the allocation cost is multiplied by a large positive constant. This ensures that a very high allocation cost is imposed if a decision is taken by the model to operate a canal outside of the operational range. The arguments that maximize the objective function are insensitive to the value selected by the user for this positive constant provided the value is sufficiently large that in (4) the allocation cost is orders of magnitude greater than the mean difference term in (4). The large positive constant in (4) is a scalar. It can be defined as a vector over each canal and/over each interval. However given that the allocation cost is already defined over each canal and each interval, and the allocation cost is user defined and can be specified to for example prioritize one canal over another, or one interval over another. Therefore there is little justification to replace the large positive constant by a vector to duplicate what can be already achieved through the allocation cost function.

### Constraints and Variables for the INEQ+ Model

The allocation cost in (4) is a piecewise linear function. This piecewise linear function needs to be defined as a set of linear equations to ensure that the model remains linear and solves to a global optimum. The technique of converting a piecewise linear function to a set of linear equations is often referred to as the lambda method as a weight variable is typically defined with the notation lambda. The weight variable is defined; for each canal, for each breakpoint of the piecewise linear function; and, for each interval. The sum of the weights over all breakpoints of the piecewise linear function is constrained equal to 1

|  |  |
| --- | --- |
|  | ∀ *n* ∈ *N*, ∀ *t* ∈ *T*…(6) |

where = weight for canal *n* at breakpoint *p* for the interval *t*. Furthermore the weight variable has the special property whereby (for any canal and for any interval), either one or at most two weights can be nonzero and, if two weights are nonzero these two weights must be adjacent to each other on a segment of the allocation function. This property of the set of weights is known as a special-ordered-set 2 (SOS2).

|  |  |
| --- | --- |
|  | *n* ∈ *N*, ∀ *t* ∈ *T*…(7) |

For each canal we define

|  |  |
| --- | --- |
|  | ∀ *n* ∈ *N*, ∀ *t* ∈ *T* …(8) |

where = delivery performance ratio for canal *n* for the interval *t*; and, = *x* coordinate of the allocation function for canal *n* at the breakpoint *p* for the interval *t*. From (6), (7) and (8) the weight variable lambda can be determined. This is best explained with a simple example. Figure 3 is a piecewise linear allocation cost function for a hypothetical canal and a hypothetical interval. For the purposes of this explanation to simplify the notation the subscripts denoting canal and interval are omitted. Figure 3 has three segments and hence four breakpoints labelled consecutively as 1,2,3 and 4. Each breakpoint has *x* and *y* coordinates labelled as shown, the subscripts representing each of the breakpoints. The decision variable for the model is DPR. Suppose the model selects a DPR, say dpr\*=0.70 as shown in Figure 3, then for the allocation cost function in Figure 3, (6), (7) and (8) respectively become

|  |  |
| --- | --- |
|  | …(9) |

|  |  |
| --- | --- |
|  | …(10) |

|  |  |
| --- | --- |
|  | …(11) |

The SOS2 property by definition requires at most two of the weight variables to be non-zero and that these two are adjacent. To obtain a feasible solution to (9), (10) and (11), and must be set to zero and (9) and (11) reduce to a set of simultaneous equations

|  |  |
| --- | --- |
|  | …(12) |
|  |

Substituting the values of the breakpoint coordinates and from Figure 3 in (12) the weight variables can be evaluated as .

To add further intuition to this example, if the selected DPR coincides with a breakpoint say dpr\*\*=0.50 in Figure 3 i.e. at breakpoint 3 then (6), (7) and (8) solve to , and (8) is superfluous. In this example where only one of the weight variables is used, whereas the former example two of the weight variables are used. Therefore at most two weights can be non-zero and these weights must be adjacent to each other on the segments of the allocation function – the SOS2 property. Some solvers such as LINGO 14.0 have a built in SOS2 function and resolve (7) internally through a set of linear equations with integer variables. Other solvers do not have a built-in SOS2 function and the linear equations need to be constructed explicitly. In the interest of brevity, this further exposition is not presented here. The lambda method does add to the number of integers in the model which does increase computation times.

From the weight variables the allocation cost is determined by

|  |  |
| --- | --- |
|  | ∀ *n* ∈ *N*, ∀ *t* ∈ *T*…(13) |

where = *y*-coordinate of the allocation function for canal *n* at the breakpoint *p* for the interval *t*.

By definition DPR is the allocated discharge normalized by capacity.

|  |  |  |
| --- | --- | --- |
|  |  | ∀ *n* ∈ *N* ∀ *t* ∈ *T* …(14) |

= discharge allocated to the canal *n*  in interval *t*; and, = capacity of the canal *n*.

For any interval the net discharge available in the secondary canal must be allocated to the tertiary canals during the interval, given by

|  |  |
| --- | --- |
|  | ∀ *t* ∈ *T*  …(15) |

where = net discharge in the secondary canal in interval *t*. The net discharge in the secondary canal is the discharge after subtracting the rated discharge of direct turnouts and assumed losses from the gross discharge of the secondary canal. The net discharge is the discharge that is to be distributed amongst the tertiary canals. Constraint (15) forces the net discharge in the secondary canal to be allocated to tertiary canals i.e. spillage is not allowed. Constraint (15) also prevents the model from spilling all the next discharge and allocating zero discharge to all the canals – which would be always perfectly equitable.

An alternative approach is to permit some spillage whereby (15) is replaced by

|  |  |
| --- | --- |
|  | ∀ *t* ∈ *T*  …(16) |

Where = spillage in interval *t*. Spillage can be constrained by the user to any fraction of the net discharge in the secondary canal, hence

|  |  |
| --- | --- |
|  | ∀ *t* ∈ *T*  …(17) |

where = permissible spillage coefficient ranging 0.0 to 1.0 (inclusive). If this coefficient is set to zero, then from (17), (16) simply reduces to (15). If the permissible spillage coefficient is set to 1.0 then this implies that the model can spill all the water and allocate nothing to the tertiary canals. The permissible spillage coefficient is user defined and needs to be selected judiciously. For the purposes of evaluating the effect of spillage, the end-of-season spillage is defined as

|  |  |
| --- | --- |
|  | …(18) |

Where = end-of-season spillage for a crop season. The sensitivity of solutions to the permissible spillage coefficient is examined in the Results and Discussion.

The LP-INEQ+ model (without spillage – the default case) is represented by the objective function (4), and the constraints and variables (6) to (8) and (13) to (15). To introduce spillage, (15) is replaced with (16) and (17).

Table 2 compares the key characteristics of the LP-INEQ+ model with earlier models. In common with the earlier models, the decision variable in the LP-INEQ+ model is DPR, however this is only constrained as a non-negative real number. The objective function of the LP-INEQ+ is a dual goal function, but unlike the earlier dual goal models (LP-DPR and LP-INEQ), the LP-INEQ+ model minimizes inequity and allocation cost – the latter a function of DPR. The LP-INEQ+ model prioritizes minimizing allocation cost over inequity. Permissible spillage in the LP-INEQ+ cost can be user defined to any non-negative value similar to the LP-DPR model and the LP-INEQ model. The LP-INEQ+ model is a linear programme and hence solves to a global optimum.

# Results and Discussion

### The LP-INEQ+ Model

Table 3 presents results from application of the LP-INEQ+ model to the data for all 17 tertiary canals listed in Table 1 for the summer 2014 crop season and the default operational range (10%) and default permissible spillage (0%). Each cell in Table 3 shows the DPR at which a particular canal should be operated for a particular interval – the decision variable. All canals are operated at a DPR of 1.00+10% or closed altogether (DPR =0.00). The latter are emphasized in bold italic font in Table 3. These results are intuitive as a high allocation cost is imposed if the canal is operated outside of the operational range described in Figure 2 and the model avoids any DPR outside of the operational range. The inequity (measured by the Gini) is 8.62% in the first interval and generally decreases as the crop season progresses with an end of season Gini of just 1.11% i.e. very low inequity. Table 3 also contrasts the Gini using depth of water delivered in each interval as the variable of interest with the Gini using cumulative depth as the variable of interest from (2). For the first interval depth and cumulative depth are identical, hence the Gini for cumulative depth and the Gini for depth are identical. However thereafter there is considerable variation in the Gini for depth. For example, in interval #3 the Gini for depth is very high at 83.37% which indicates considerable inequity. This is because the available discharge in the secondary canal is very low, and the model only operates 3 of the 17 canals which is highly inequitable. However the Gini for cumulative depth in interval #3 is still lower than that in interval #2, indicating that on a cumulative basis the model continues to improve on equity. In using cumulative depth in the objective function, this gives the model a “memory” of all previous allocations and this information is used to inform the current interval allocation.

Anwar et al (2016b) also explored the number of consecutive intervals that a given canal remains closed, and made the case that from an individual farmer’s perspective, experiencing closure of a canal for consecutive intervals may appear inequitable irrespective of the fact that a manager might report the Gini is minimum. The INEQ-LP operated 78% of canals such that they were only closed for 1 interval and operated on the subsequent interval. However in the operations plan prepared by the INEQ-LP model; 19% of canals remained closed for two consecutive intervals; 1% of canals remained closed for three consecutive intervals; and, 1% of canals remained closed for four consecutive intervals! In Table 3 it can be seen that there are no canals closed consecutively for two intervals. Although Table 3 does not report the results for all the intervals in the interest of brevity, in fact none of the canals were closed for more than one consecutive interval.

The INEQ-LP+ model does not explicitly use logical groups of canals. Therefore in Table 3 in any interval there are implicitly two groups of canals; those canals that are closed; and, those canals that are operational (DPR = 10 + 10%). From Table 1, the canals with short name HL, FC and HR are all co-located at running distance 86,961m and therefore it would logical to group these canals together and either operate all three or, not operate all three. Table 3, interval #3 shows that the INEQ-LP+ decides to close HL and FC but to operate HR at a DPR of 1.03. Such an operational plan could cause social problems as farms linked to the canals HL and FC will not receive water whereas adjacent farms linked to the canal HR will receive water. Although a manager might offer the explanation that there isn’t sufficient water and this operation is in the interest of minimizing inequity – the retort is likely to be “*so why is my neighbour getting water and I am not?”*

Figure 4 shows the cumulative depth of application and the canal capacity to examine whether the INEQ-LP+ model is biased in favour of larger canals or smaller canals. The sample size is rather low (17) for this statistical analysis. With that caveat, the low R2 value indicates that the linear model is a poor fit. The *p*-value of the independent variable CanalCapacity indicates that canal capacity is in an insignificant explanatory variable of depth of application. This is also confirmed by the negative adjusted R2. Rather the constant is the significant explanatory variable. This is intuitive since the end-of-season Gini reported in Table 3 is 1.11% which indicates that by the end of the season, all canals have received an average depth 450.06mm with a range of 36mm. This suggests what little inequity there is as reported by the Gini of 1.11% is not biased towards larger canals or smaller canals.

Figure 5a, 5b and 5c shows the Gini of the cumulative depth of irrigation for the summer 2014, winter 2014-15 and summer 2015 crop seasons respectively. The figures show results from the INEQ-LP+ model and compares this with the INEQ-LP. The INEQ-LP+ model improves on the INEQ-LP model (reduced Gini) for every interval of the crop season. The results for winter 2014-15 presented in Figure 5b, are similar with the inequity lower than that of the INEQ-LP model throughout the crop season. In Figure 5b the inequity shows an increase in inequity towards the middle of the crop season. During these intervals of the crop season, canals are typically closed for annual maintenance and there is only low residual flow in the secondary canal. The default case of the LP-INEQ+ model is to prohibit spillage, hence this low flow must be allocated to one or more of the tertiary canals. As there is a high allocation cost associated with operating a canal outside of the operational range, invariably low flows are allocated to small canals in order to achieve a DPR within the operational range. Hence when flows are low, only small canals are operated and larger canals remain closed which in turn increases inequity. Towards the end of the winter 2014-15 crop season when canals are reopened and more regular flow in the secondary canal is available, the model reduces the inequity and the end of season inequity with the INEQ-LP+ model is very low. Figure 5c reports the results from the INEQ-LP+ model applied to the summer 2015 crop season and again the inequity in each interval is less than the INEQ-LP model with an end-of-season of just 0.72%. Hence the results show a consistent improvement over all the three seasons reported.

Table 4 compares the first interval and end-of-season Gini for the various canal operations planners with the LP-INEQ+ model. The LP-INEQ+ model is able to achieve better equity at both the beginning and end of the season and over all the three seasons reported. All models report an equal or better end-of-season inequity than the observed data. One reason for the observed inequity is due to the state of disrepair of many of the canals. Where a canal is silted, an operator cannot release the required discharge without risking overtopping/breaching of the canal. Where a canal has scoured an operator has to release an excessive discharge to ensure the water surface elevation is sufficiently high enough that the water can flow onto the adjacent fields through the canal turnouts. This in turn causes operational inequity. There is also anecdotal evidence of deliberate surcharging of canals for various reasons.

### Sensitivity to Permissible Spillage

Table 5 reports the results if spillage is permitted for a range of values of the permissible spillage coefficient as as defined in (17). Table 5 presents the results from the the INEQ-LP+ model applied to the Summer 2014 crop season data with the default operational range of +10% DPR . When the permissible spillage coefficient is set at 5% (up to 5% spillage is permitted), for the first interval the model opts not to allow any spillage, rather the model allocates all the available flows to the tertiary canals as this minimizes inequity - the objective of the model. Hence the Gini is insensitive to the spillage coefficient for the first interval. In the interest of brevity, the results for each interval are not reported in Table 5, however for certain intervals the model does take advantage of the permissible spillage. When the permissible spillage coefficient is et at 5%, the end-of-season spillage estimated using (18) is 1.94% which is less than the permissible spillage, again implying the model even when allowed to spill water will prefer to allocate water as this minimizes inequity. For the range of spillage coefficient reported in Table 5, the relationship between the Gini and spillage is non-monotonic and therefore simplistic conclusions such as increasing the permissible spillage coefficient improves equity cannot be made.

### Sensitivity to Operational Range

The default operational range for the allocation function is +10%. In this section, the operational range is varied from (+5% to +15%) and the sensitivity of solutions to operational range is reported in Figure 6. These results are again for the summer 2014 crop season and with default permissible spillage coefficient of 0%. In the interest of clarity, only results for the first interval and end-of-season are reported. The Gini for the first interval is sensitive to the operational range and the function is generally monotonic i.e. the Gini decreases if operational range is increased. The end-of-season Gini is largely independent of operational range. This contrasts with the sensitivity to permissible spillage. If inequity in the early intervals of a crop season is of concern the planner may choose to increase the operational range in the earlier intervals of the crop season and then decrease the operational range towards the end of the crop season.

# Conclusions and Recommendations

This research presents a linear programme, the LP-INEQ+ model, to develop canal operations plans. The LP-INEQ+ minimizes inequity explicitly and allows canals to be operated within a range of capacity or to be closed altogether. The results show a considerable improvement with inequity as measured by the Gini showing a marked decrease both at the beginning of the crop season and at the end of the crop season. Furthermore, the LP-INEQ+ model avoids closing canals for consecutive intervals. The LP-INEQ+ model can allow for spillage, however in general little is to be gained by allowing spillage. The LP-INEQ+ model defines an operational range as the narrow range around canal capacity. Increasing the operational range does improve equity, particularly in the earlier intervals of the crop-season and this gives the planner options if the inequity is too high or above acceptable limits.

The LP-INEQ+ does not explicitly group canals, in practice it is sometimes necessary to group canals for example; to minimize the operational costs; for social reasons; or, because the number of regulation structures is limited. These constraints are context and site specific and would need further investigation when applying the LP-INEQ+ model. The LP-INEQ+ model is limited to water delivered through canals and does not consider groundwater, which the literature shows can contribute substantially towards crop water requirements in many *warabandi* managed irrigation systems. Further work could explore whether access to groundwater exacerbates or mitigates inequity and whether a canal operations planner would need to account for groundwater when minimizing inequity.

The LP-INEQ+ model is a viable engineering decision support tool to prepare canal operations plans and, this is demonstrated through an engineering application in the next section. The LP-INEQ+ model is technically a more sophisticated method of producing a canal operations plan as compared to the existing practice. For many irrigation agencies, particularly in developing countries, there are significant institutional and capacity building challenges that would need to be overcome before this engineering research can become engineering practice.

# Engineering Application

To demonstrate the engineering application of this research, the LP-INEQ+ model is used to develop a canal operations plans for Hakra Branch for the summer 2107 and winter 2017-18 crop seasons. For both these crop seasons a 7 day interval is used running through from Saturday to Friday which coincides with the *warabandi* schedule issued at the farm level. Therefore there are there are a total of 26 intervals in each crop season. The available discharge in the secondary canal of Hakra Branch is estimated from the 2005-2016 averages and subtracting the rated discharge of all canal turnouts located along the Hakra Branch and also subtracting another 10% for conveyance and distribution losses. For the purposes of this engineering application, the default permissible spillage coefficient (0%) and default operational range (+10%) are used. The flood channel canal (short name FC) remains closed during the winter season, hence the winter canal plan is for 16 canals as opposed to the 17 canals operated during the summer season.

Table 6 shows the discharge at which each canal should be operated for each of the intervals of the summer 2017 crop season. Table 6 only shows intervals 1,2,3 and 26 in the interest of brevity. The Gini for the first interval is 9.27%. The end-of-season Gini is 0.81%, i.e. by the end of the season there is very little inequity in the allocation of water amongst the tertiary canals.

Table 7 shows the discharge at which each tertiary canal should be operated for each of the intervals of the winter 2017-18 crop season. In the interest of brevity, Table 7 only shows intervals 1,2,3 and 26. The Gini for the first interval of the winter 2017-18 is 10.09% and the end-of-season Gini is 0.82%.

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# Notation

= area irrigated by canal *n*;

= allocation cost for canal *n* during interval *τ* ;

= average cumulative depth of water delivered by all canals up to and including current interval ;

= cumulative depth of water delivered by canal *n* up to and including current interval ;

= cumulative depth of water delivered by canal *m* up to and including current interval ;

= delivery performance ratio for canal *n* for the interval *t*;

*G* = Gini index; *xi*= variable of interest for the *i*th member in the population;

= Gini-index up to and including current interval ;

*M*= large positive constant;

*n* = index representing canal;

*N* = size of the population (number of canals in the operations plan);

*p* = index representing a breakpoint in the allocation cost function;

= discharge allocated to the canal *n*  in interval *t*; and, = capacity of the canal *n*;

= net discharge in the secondary canal in interval *t*;

= duration of interval *t*;

= end-of-season spillage for a crop season;

= spillage in interval *t*;

*t* = index representing interval;

= average of the variable of interest for the population;

*xj* = variable of interest for the *j*th member in the population;

= *x* coordinate of the allocation function for canal *n* at the breakpoint *p* for the interval *t*;

= *y*-coordinate of the allocation function for canal *n* at the breakpoint *p* for the interval *t*;

= objective function of the LP-INEQ+ model up to and including interval *τ*;

= minimum of the objective function of the LP-INEQ+ model up to and including interval *τ*;

= permissible spillage coefficient;

= weight for canal *n* at breakpoint *p* for the interval *t*; and,

= current interval.

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# **Tables**

TABLE 1. Tertiary canals of Hakra Branch Canal

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TABLE 5: Sensitivity to the permissible spillage coefficient (Summer 2014)

TABLE 6: Canal operations plan for the summer 2017 crop season

TABLE 7: Canal operations plan for the winter 2017-18 crop season

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| TABLE 1. Tertiary canals of Hakra Branch Canal | | | | | | | |
| # | Canal name | | Running distance  (m) | Bank | Capacity  (m3 s-1) | Area  irrigated  (ha) | Capacity per unit area  (Ls-1ha-1) |
|  | Long | Short |
| 1 | Baku Shah Distributary | BS | 10,058 | Left | 0.17 | 609 | 0.279 |
| 2 | Sundar Distributary | 1R | 18,653 | Right | 0.54 | 2,009 | 0.269 |
| 3 | Dunga Bunga Distributary | 2R | 22,661 | Right | 0.62 | 2,147 | 0.289 |
| 4 | Mubarik Distributary | 1L | 25,526 | Left | 2.35 | 6,917 | 0.340 |
| 5 | Khatan Distributary | 3R | 27,354 | Right | 9.99 | 29,443 | 0.339 |
| 6 | Haroonabad Distributary | 4R | 27,354 | Right | 6.40 | 17,586 | 0.364 |
| 7 | Bhagsen Distributary | 5R | 43,798 | Right | 1.02 | 3,713 | 0.275 |
| 8 | Mamun Distributary | 6R | 50,229 | Right | 15.46 | 41,205 | 0.375 |
| 9 | Mianwala Distributary | 2L | 50,229 | Left | 0.54 | 1,769 | 0.305 |
| 10 | Khichiwala Distributary | 7R | 56,903 | Right | 7.73 | 21,795 | 0.355 |
| 11 | Malkir Distributary | 3L | 59,656 | Left | 0.28 | 703 | 0.398 |
| 12 | Kamrani Distributary | 4L | 68,577 | Left | 0.25 | 682 | 0.367 |
| 13 | Josar Distributary | 8R | 69,872 | Right | 0.68 | 2,573 | 0.264 |
| 14 | Sardrewala Distributary | 9R | 77,486 | Right | 5.97 | 19,909 | 0.300 |
| 15 | Hakra Left Distributary | HL | 86,961 | Left | 0.65 | 2,418 | 0.269 |
| 16 | Flood Channel Distributary | FC | 86,961 | Centre | 2.07 | 6,684 | 0.310 |
| 17 | Hakra Right Distributary | HR | 86,961 | Right | 14.44 | **42,894** | 0.337 |
| TOTAL | | | | | | 203,057 |  |
| GINI | | | | | |  | 7.28% |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| TABLE 2. A comparison of the various canal operations planner model characteristics | | | | |
| Characteristic | LP-DPR | NLP-DPR | LP-INEQ | LP-INEQ+ |
| Reference | Anwar et al (2016a) | | Anwar et al (2016b) | - |
| Decision variable DPR | Binary 0, 1 only | 0 to 1 (incl.) | Binary 0, 1 only | 0 to ∞ |
| Objective function | Dual | Single | Dual | Dual |
| Objective function | Maximize DPR &  minimize spillage | Maximize DPR | Minimize spillage &  inequity | Minimize inequity & allocation cost |
| Priority in objective function | Maximize DPR | - | Minimize spillage | Minimize allocation cost |
| Permissible spillage | 0 to 1 incl. | 0 | 0 to 1 incl. | 0 to 1 incl. |
| Model | Linear | Non-linear | Linear | Linear |
| Solution | Global opt. | Local opt. | Global opt. | Global opt. |

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| TABLE 3. Results for summer 2014 crop season (LP-INEQ+ model) | | | | | | | | | |
| Tertiary canal  short name | Interval number and from – to dates) | | | | | | | | |
| #1 | #2 | #3 | #4 | #5 - #22 | | | | #23 |
| Apr-18 to Apr-25 | Apr-26 to May-03 | May-04 to May-11 | May-12 to May19 | ..  .. | ..  .. | ..  .. | ..  .. | Oct-11 to Oct-18 |
| BS | 1.09 | 1.02 | ***0.00*** | 1.09 | … | … | … | … | 1.08 |
| 1R | 1.10 | 1.10 | ***0.00*** | 1.10 | … | … | … | … | 1.10 |
| 2R | 1.05 | 0.98 | ***0.00*** | 1.05 | … | … | … | … | 1.04 |
| 1L | 0.90 | 0.90 | ***0.00*** | 0.90 | … | … | … | … | 1.00 |
| 3R | 0.90 | 0.90 | ***0.00*** | 0.90 | … | … | … | … | 1.03 |
| 4R | 0.90 | 0.90 | ***0.00*** | 0.90 | … | … | … | … | 1.10 |
| 5R | 1.10 | 1.05 | ***0.00*** | 1.10 | … | … | … | … | 1.10 |
| 6R | 0.90 | 0.00 | 1.10 | 0.90 | … | … | … | … | 0.90 |
| 2L | 1.00 | 0.93 | ***0.00*** | 1.00 | … | … | … | … | 0.92 |
| 7R | 0.00 | 1.10 | 0.90 | ***0.00*** | … | … | … | … | 1.10 |
| 3L | 0.90 | 0.90 | ***0.00*** | 0.90 | … | … | … | … | 0.90 |
| 4L | 0.90 | 0.90 | ***0.00*** | 0.90 | … | … | … | … | 0.90 |
| 8R | 1.10 | 1.10 | ***0.00*** | 1.10 | … | … | … | … | 1.10 |
| 9R | 1.02 | 0.94 | ***0.00*** | 1.02 | … | … | … | … | ***0.00*** |
| HL | 1.10 | 1.09 | ***0.00*** | 1.10 | … | … | … | … | 1.10 |
| FC | 0.99 | 0.92 | ***0.00*** | 0.99 | … | … | … | … | 0.90 |
| HR | 0.91 | 0.90 | 1.03 | 0.91 | … | … | … | … | 0.91 |
| Gini (%) | 8.62 | 6.88 | 6.58 | 5.11 | … | … | … | … | 1.11 |
| Gini depth (%) | 8.62 | 10.54 | 83.37 | 3.18 | … | … | … | … | 11.74 |
| Spillage (%) | 0.00 | 0.00 | 0.00 | 0.00 | … | … | … | … | 0.00 |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| TABLE 4. A comparison of the various models and actual canal operation plans | | | | | | | |
| Season | Interval | Performance indicator | Observed data | LP-DPR | NLP-DPR | LP-INEQ | LP-INEQ+ |
| Summer 2014 | First interval | Gini (%) | 29.02 | 13.17 | 12.07 | 29.21 | 8.62 |
| Spillage (%) | 0 | 4.00 | 0 | 0.02 | 0 |
| End-of-season | Gini (%) | 14.28 | 7.44 | 7.23 | 9.30 | 1.11 |
| Average spillage (%) | 0 | 6.29 | 0 | 0.03 | 0 |
|  | | | | | | | |
| Winter 2014-15 | First interval | Gini (%) | 42.76 | 25.42 | 65.90 | 76.44 | 14.98 |
| Spillage (%) | 0 | 14.62 | 0 | 0.02 | 0 |
| End-of-season | Gini (%) | 23.12 | 19.85 | 13.06 | 9.15 | 1.83 |
| Average spillage (%) | 0 | 4.65 | 0 | 0.11 | 0 |
|  | | | | | | | |
| Summer 2015 | First interval | Gini (%) | 44.41 | 24.06 | 19.96 | 23.87 | 14.45 |
| Spillage (%) | 0 | 13.53 | 0 | 0.04 | 0 |
| End-of-season | Gini (%) | 21.19 | 9.46 | 7.56 | 5.33 | 1.07 |
| Average spillage (%) | 0 | 6.12 | 0 | 0.02 | 0 |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| TABLE 5: Sensitivity to the permissible spillage coefficient (Summer 2014) | | | | | | | |
| Interval | Performance Indicator | Permissible spillage coefficient | | | | | |
| 0% | 1% | 2% | 3% | 4% | 5% |
| First interval | Gini (%) | 8.62 | 8.62 | 8.62 | 8.62 | 8.62 | 8.62 |
| Spillage (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
|  | | | | | | | |
| End-of-season | Gini (%) | 1.11 | 0.56 | 0.76 | 0.73 | 0.72 | 0.48 |
| Spillage (%) | 0.00 | 0.40 | 0.96 | 1.28 | 1.35 | 1.94 |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| TABLE 6: Canal operations plan for the summer 2017 crop season | | | | | | | | |
| Canal short name | Capacity (m3s-1) | Interval 1 | Interval 2 | Interval 3 | … | … | … | Interval 26 |
| Apr., 15 017 | Apr., 22 2017 | Apr., 29 2017 |  |  |  | Oct., 07 2017 |
| to | to | to | to |
| Apr., 21 2017 | Apr., 28, 2017 | May., 05 2017 | Oct., 13 2017 |
| BS | 0.17 | 0.18 | 0.18 | 0.15 |  |  |  | 0.15 |
| 1R | 0.54 | 0.59 | 0.59 | 0.50 |  |  |  | 0.54 |
| 2R | 0.62 | 0.63 | 0.63 | 0.56 |  |  |  | 0.56 |
| 1L | 2.35 | 2.12 | 2.12 | 2.12 |  |  |  | 2.12 |
| 3R | 10.0 | 9.00 | 9.00 | 9.00 |  |  |  | ***0.00*** |
| 4R | 6.40 | 5.76 | 5.76 | ***0.00*** |  |  |  | 7.04 |
| 5R | 1.02 | 1.09 | 1.09 | 0.93 |  |  |  | 0.98 |
| 6R | 15.46 | ***0.00*** | 13.91 | 13.91 |  |  |  | 16.91 |
| 2L | 0.54 | 0.52 | 0.52 | 0.48 |  |  |  | 0.48 |
| 7R | 7.73 | 6.96 | 6.96 | 6.96 |  |  |  | 7.08 |
| 3L | 0.28 | 0.25 | 0.25 | ***0.00*** |  |  |  | 0.29 |
| 4L | 0.25 | 0.23 | 0.23 | ***0.00*** |  |  |  | 0.23 |
| 8R | 0.68 | 0.75 | 0.75 | 0.66 |  |  |  | 0.69 |
| 9R | 5.97 | 5.38 | 5.88 | 5.38 |  |  |  | 6.33 |
| HL | 0.65 | 0.71 | 0.71 | 0.61 |  |  |  | 0.64 |
| FC | 2.07 | 1.95 | 1.97 | 1.86 |  |  |  | 1.86 |
| HR | 14.44 | 13.00 | ***0.00*** | 14.63 |  |  |  | ***0.00*** |
| Gini | | 9.27% | 8.06% | 6.27% |  |  |  | 0.81% |
| Est. net discharge (m3s-1) | | 49.09 | 50.55 | 57.76 |  |  |  | 45.9 |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| TABLE 7: Canal operations plan for the winter 2017-18 crop season | | | | | | | | |
| Canal short name | Capacity (m3s-1) | Interval 1 | Interval 2 | Interval 3 | … | … | … | Interval 26 |
| Oct., 14 2017 | Oct., 21 2017 | Oct., 28 2017 |  |  |  | Apr., 07 2018 |
| to | to | to | to |
| Oct., 20 2017 | Oct., 27 2017 | Nov., 03 2017 | Apr., 13 2018 |
| BS | 0.17 | 0.17 | ***0.00*** | 0.19 |  |  |  | ***0.00*** |
| 1R | 0.54 | 0.58 | ***0.00*** | 0.59 |  |  |  | ***0.00*** |
| 2R | 0.62 | 0.62 | ***0.00*** | 0.68 |  |  |  | ***0.00*** |
| 1L | 2.35 | 2.12 | ***0.00*** | 2.51 |  |  |  | ***0.00*** |
| 3R | 10.00 | 9.00 | ***0.00*** | 11.00 |  |  |  | 9.00 |
| 4R | 6.40 | 5.76 | ***0.00*** | 6.82 |  |  |  | 5.76 |
| 5R | 1.02 | 1.06 | ***0.00*** | 1.12 |  |  |  | ***0.00*** |
| 6R | 15.46 | ***0.00*** | 17.01 | ***0.00*** |  |  |  | 15.19 |
| 2L | 0.54 | 0.51 | ***0.00*** | 0.56 |  |  |  | ***0.00*** |
| 7R | 7.73 | 6.96 | ***0.00*** | 8.50 |  |  |  | ***0.00*** |
| 3L | 0.28 | 0.25 | ***0.00*** | 0.25 |  |  |  | ***0.00*** |
| 4L | 0.25 | 0.23 | ***0.00*** | 0.23 |  |  |  | ***0.00*** |
| 8R | 0.68 | 0.74 | ***0.00*** | 0.75 |  |  |  | ***0.00*** |
| 9R | 5.97 | 5.38 | ***0.00*** | 6.57 |  |  |  | ***0.00*** |
| HL | 0.65 | 0.69 | ***0.00*** | 0.72 |  |  |  | ***0.00*** |
| HR | 14.44 | 13.00 | 14.53 | ***0.00*** |  |  |  | 13.27 |
| Gini | | 10.09% | 10.67% | 6.19% |  |  |  | 0.82% |
| Est. net discharge (m3s-1) | | 47.05 | 31.53 | 40.49 |  |  |  | 43.22 |

# Figures

FIGURE 1: Canal command area of Hakra Branch Canal, Punjab, Pakistan

FIGURE 2: Allocation cost function

FIGURE 3: The lambda method

FIGURE 4: Cumulative depth of irrigation and canal capacity

FIGURE 5. Gini of cumulative depth of irrigation

a. Summer 2014 crop season

b. Winter 2014-15 crop season

c. Summer 2015 crop season

FIGURE 6: Sensitivity to operational range

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| FIGURE 1: Canal command area of Hakra Branch Canal, Punjab, Pakistan |

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| FIGURE 2: Allocation cost function |

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| 0  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.00  0.10  0.20  0.30  0.40  0.50  0.60  0.70  0.80  0.90  1.00  Allocation cost  Delivery performance ratio  1  (X  1  ,Y  1  )  2 (X  2  ,Y  2  )  3  (X  3  ,Y  3  )  4  (X  4  ,Y  4  )  dpr  \*  = 0.70  Coordinates of breakpoints  (X  1  , Y  1  ) = (0.00, 0.00)  (X  2  , Y  2  ) = (0.30, 0.30)  (X  3  , Y  3  ) = (0.50, 0.10)  (X  4  , Y  4  ) = (1.00, 0.60)  dpr  \*\*  = 0.50 |
| FIGURE 3: The lambda method |

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| FIGURE 4: Cumulative depth of irrigation and canal capacity |

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| 1. Summer 2014 crop season |
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| 1. Winter 2014-15 crop season |
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| 1. Summer 2015 crop season |
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| Figure 5:. Gini of cumulative depth of irrigation |

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| Figure 6: Sensitivity to operational range |

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