Agricultural water allocation efficiency in a developing country canal irrigation system

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ONLINE APPENDIX

Appendix 1: Supplementary figures

Figure A.1. *Overhead view of the Hakra Branch Canal with three secondary channels (in yellow) and outlet locations (light blue dots)*

Figure A.2. *A typical Hakra Branch Canal distributary channel (secondary canal) with direction of flow indicated*

Figure A.3. *A typical outlet structure on a Hakra Branch Canal distributary. Outlet draws water from the distributary channel. The size of the actual transmission structure (e.g. a pipe) is under ten inches with a designed discharge capacity under 10 cubic feet per second*

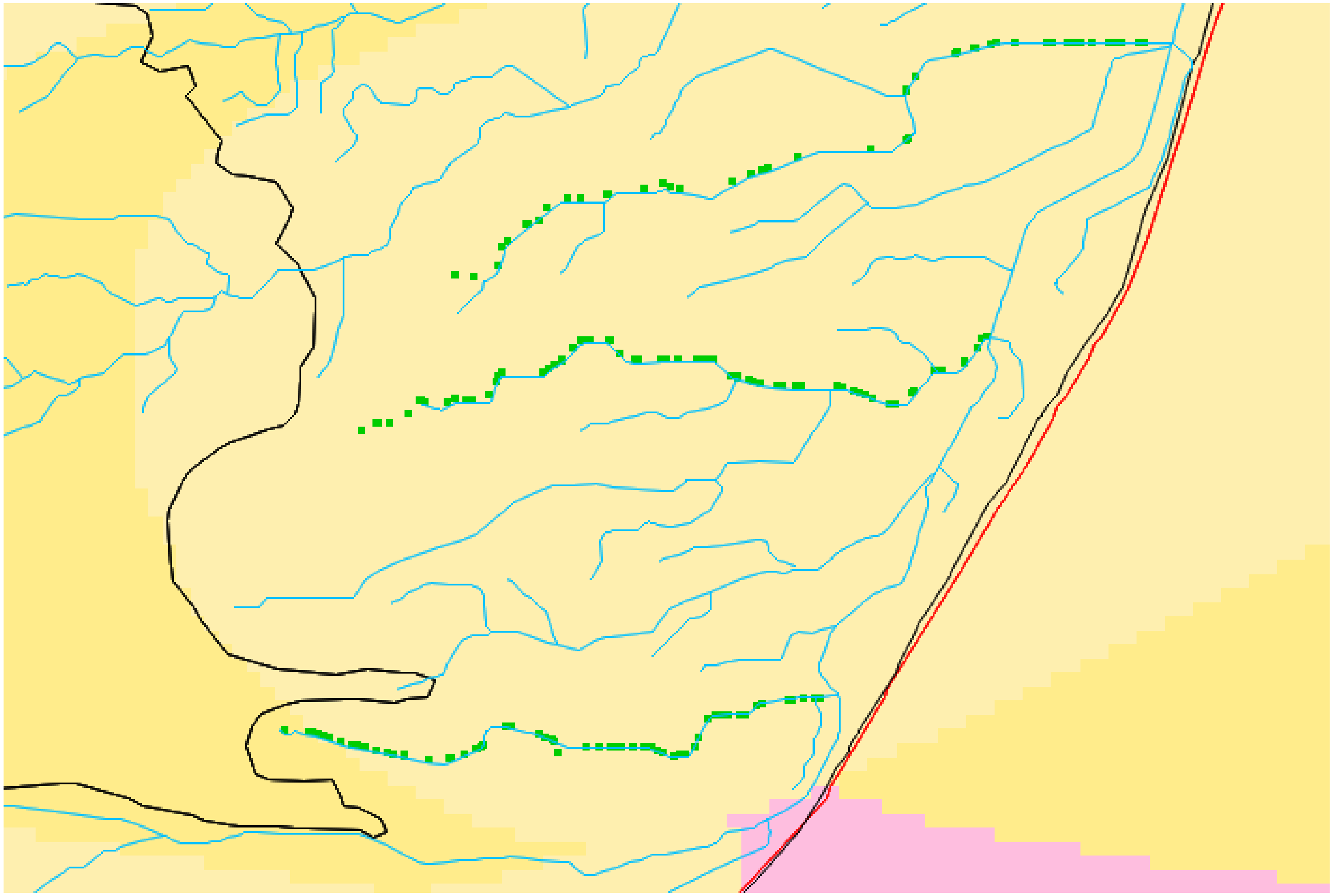


Figure A.4. *This figure shows the soil type in the studied irrigation canal area. As can be seen, the soil type is homogenous across the study site*

Figure key: (1) Blue Lines indicate major canal arteries including distributaries; (2) Green Dots indicate points where measurements were made; (3) Black Lines indicate administrative borders; (4) Red Line indicates international border; and (5) Pale Yellow indicates Calcisol soil type (darker yellow indicate sand dunes, while the magenta indicates Solanchak soil type).

Appendix 2: Supplementary Tables

Table A.1. *Summary statistics*

Variable	Mean	Std. Dev.	Min	Max
Number of members in household?	9.48	5.76	2.00	40.00
Number of Adults (18+ years)?	6.08	3.70	2.00	25.00
Number of household members that work?	2.50	1.67	1.00	15.00
How many years of formal education has the respondent had?	3.29	2.13	0.00	8.00
How many a year of formal education has the female head of HH had?	1.49	2.10	0.00	8.00
Have sons received any formal education?	0.96	0.19	0.00	1.00
Have daughters received any formal education?	0.95	0.22	0.00	1.00
How many years have you been managing farms?	18.38	11.05	1.00	64.00
How many years have you been involved in agriculture?	28.63	12.60	1.00	60.00
Have you had any contact with agricultural extension services?	0.44	0.50	0.00	1.00
Are you involved in livestock production?	0.93	0.26	0.00	1.00
Formal sector loans?	0.21	0.41	0.00	1.00
Determine what to grow in the winter based on summer outcomes?	0.48	0.50	0.00	1.00
Land inherited?	0.98	0.13	0.00	1.00
Planted Area (acres)	8.73	10.32	1.00	102.00
Land Value (Rs.)	6,345,649.00	7,106,878.00	0.00	91,200,000.00
Canal Water Feet/Acre	6.33	6.52	0.00	43.33
Net Revenue (Rs.)/Acre	15,599.24	16,414.34	-17,816.67	88,923.76

Table A.2. *Full set of specifications testing traditional and new measures of farmer water use*

VARIABLES	(1) Net Revenue	(2) Net Revenue	(3) Net Revenue	(4) Net Revenue	(5) Net Revenue	(6) Net Revenue	(7) Net Revenue	(8) Net Revenue
Turns Received	3,273**	2,664						
	(1,384)	(1,767)						
Turns Received^2	-6.952	41.85						
	(81.70)	(109.2)						
Turn Time			0.118	-0.0322				
			(0.271)	(0.312)				
Turn Time^2			5.86e-06	6.39×10^{-6}				
			(5.77e-06)	(5.77×10^{-6})				
Total Depth					689.7	1,181		
					(498.8)	(2,360)		
Total Depth^2					10.45	-19.96		
					(17.76)	(328.1)		
Measured Canal Water							1,819***	1,817***
							(384.6)	(454.0)
Measured Canal Water^2							-30.15***	-30.59**
							(11.17)	(12.28)
Observations	339	339	339	339	339	339	339	339
R-squared	0.095	0.199	0.033	0.131	0.068	0.184	0.152	0.244
Controls	NO	YES	NO	YES	NO	YES	NO	YES

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05.

Table A.3. *Table 3 specification (4) shown with full list of control variables*

VARIABLES	Net Revenue
Measured Canal Water	1,817***
	(454.0)
Measured Canal Water^2	-30.59**
	(12.28)
Control Variables	
Groundwater EC	6.915*
	(3.552)
Groundwater EC^2	-0.00106**
	(0.000516)
Planted Area	134.6
	(92.70)
Primary Head	-360.1
	(2,103)
Primary Tail	-3,122
	(2,246)
Number of members in household?	-110.6
	(258.1)
Number of Adults (18+ years)?	-56.38
	(567.5)
Number of household members that work?	1,817***
	(682.2)
How many years of formal education has the respondent had?	-118.3
	(507.7)
How many a year of formal education has the female head of HH had?	602.2
	(560.0)
Have sons received any formal education?	-4,907
	(4,082)
Have daughters received any formal education?	2,821
	(3,585)
How many years have you been managing farms?	-147.1
	(133.4)
How many years have you been involved in agriculture?	-79.29
	(114.6)
Have you had any contact with agricultural extension services?	-530.9
	(2,073)
Are you involved in livestock production?	5,315**
	(2,327)
Do you have formal sector loans?	3,016
	(2,926)
Do you determine what to grow in winter?	-3,361
	(2,043)
Land inherited	5,794
	(4,386)

Note: *** p<0.01, ** p<0.05, * p<0.1

Table A.4. *Table 2 specification (4) with full set of control variables and addition of indicator variable to signify pump ownership and borehole depth*

VARIABLES	Net Revenue
Measured Canal Water	1,775***
	(458.3)
Measured Canal Water^2	-29.70**
	(12.38)
Own groundwater Pump	-2,072
	(1,845)
Controls	YES

Note: *** p<0.01, ** p<0.05.

Table A.5. *Demonstrating exogeneity of canal water to farmer characteristics*

VARIABLES	(1) HH Size	(2) Adults	(3) Working Members	(4) Head of HH Education	(5) Sons Educated	(6) Daughters Educated	(7) Management Experience (years)	(8) Overall Agricultural Experience (years)	(9) Contact With Agricultural Extension	(10) Formal Sector Loans	(11) Winter Crop Based on Summer Outcomes	(12) Land Inherited (1 = yes)
CanalWater/Acre	-0.00935	-0.00461	0.0127	-0.00174	0.000696	0.000322	0.0230	-0.217*	0.00388	-0.000675	-0.00550	0.000579
	(0.0381)	(0.0242)	(0.0119)	(0.0158)	(0.000625)	(0.00161)	(0.119)	(0.119)	(0.00413)	(0.00339)	(0.00370)	(0.000634)
Observations	339	339	339	339	339	339	339	339	339	339	339	339
R-squared	0.000	0.000	0.002	0.000	0.001	0.000	0.000	0.013	0.003	0.000	0.005	0.001

Notes: Robust standard errors in parentheses. * p<0.1

Table A.6. *Demonstrating exogeneity of canal water to farmer characteristics*

VARIABLES	CanalWater/Acre
HHSize	-0.0421
	(0.116)
Adults	-0.0554
	(0.176)
WorkingMembers	0.364
	(0.297)
HeadOfHHEducation	-0.108
	(0.174)
SonsEducated	1.310
	(1.246)
DaughtersEducated	-0.303
	(1.796)
ManagementExperience(years)	0.110*
	(0.0591)
OverallAgriculturalExperience(years)	-0.129***
	(0.0448)
ContactWithAgriculturalExtension	0.895
	(0.881)
FormalSectorLoans	0.0575
	(1.024)
WinterCropBasedOnSummerOutcomes	-1.184
	(0.872)
LandInherited (1 = yes)	2.701
	(1.868)
Observations	339
R-squared	0.058

Notes: Robust standard errors in parentheses. *** p<0.01, * p<0.1.
$F(12, 321) = 1.46$

Table A.7. *All specifications from table 2 with full set of control variables and addition of variables for pump power and well depth*

VARIABLES	(1) Net Revenue	(2) Net Revenue	(3) Net Revenue	(4) Net Revenue
a. Farmer recall				
Turns Received	4,043*			
	(2,189)			
Turns Received^2	-186.4			
	(200.9)			
Turn Time		-0.0737		
		(0.304)		
Turn Time^2		4.15e-06		
		(6.88e-06)		
Perceived Depth			218.8	
			(2,397)	
Perceived Depth^2			113.7	
			(327.4)	
b. Measured water use				
Measured Canal Water				1,597***
				(455.6)
Measured Canal Water^2				-25.26**
				(12.06)
Borehole Depth	8.371	3.517	5.369	-3.628
	(29.55)	(29.73)	(29.54)	(27.56)
Pump Power	89.55	114.9	106.8	69.07
	(114.1)	(118.1)	(117.4)	(108.5)
Observations	317	317	317	317
R-squared	0.185	0.155	0.159	0.261

Notes: In each specification the dependent variable is farmer net revenue. The independent variables are farmer reported measures of canal water and their squared term. Specification (1) uses farmer reported turns received and its square. Specification (2) uses farmer reported turn time and its square. Specification (3) uses farmer reported depth applied and its square. Specification (4) uses the improved measure of canal water delivered and its square All specifications include a vector of controls, as specified in table A.2 (a). Additionally, this table contains two additional variables on the right hand side, namely bore hole depth and pump power. The sample size is smaller (317) rather than the full sample (339) since these results select into a subset of farmers with groundwater pumps. Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

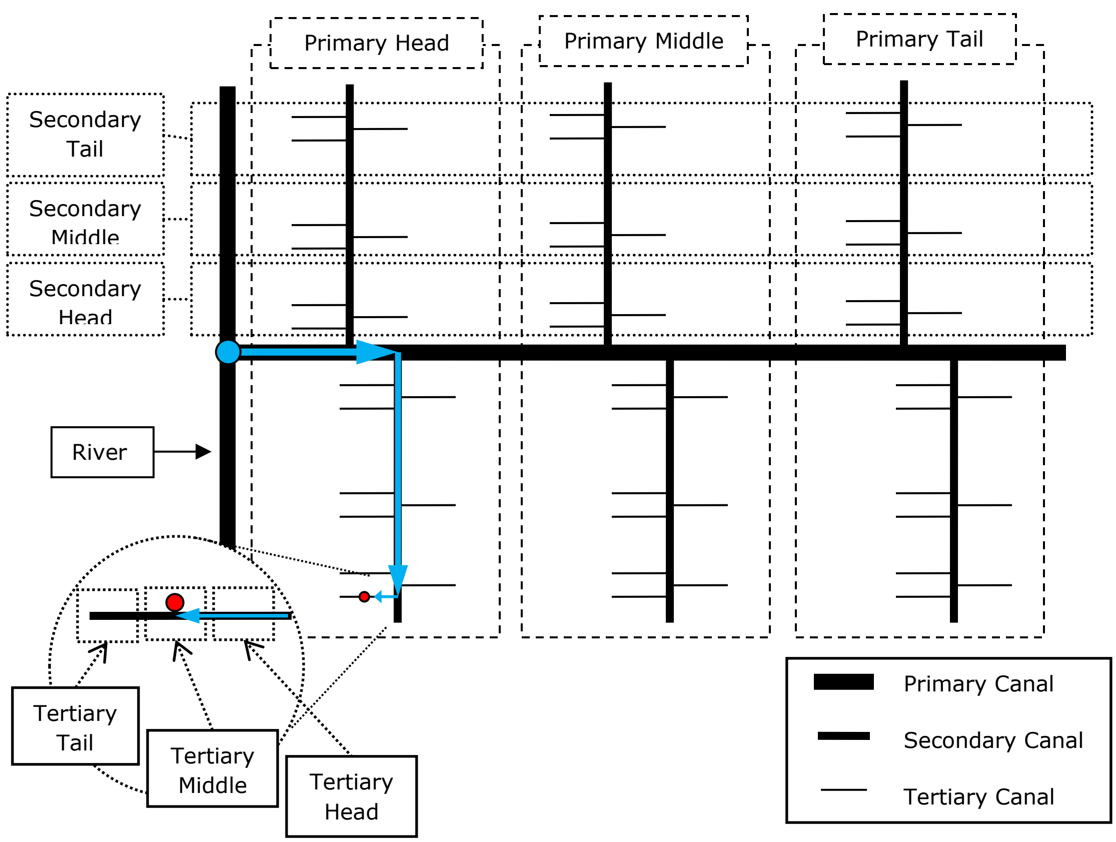
Table A.8. *Net revenue regression with improved water measures with and without conveyance loss*

VARIABLES	(1) Net Revenue	(2) Net Revenue	(3) Net Revenue	(4) Net Revenue	(5) Net Revenue
Measured Canal Water	1,816***	1,012***	1,007***	1,097***	1,092***
	(452.8)	(241.8)	(240.2)	(262.5)	(260.1)
Measured Canal Water^2	-30.39**	-9.342***	-9.115***	-10.89***	-10.69***
	(12.24)	(3.430)	(3.331)	(3.998)	(3.900)
Controls	YES	YES	YES	YES	YES
Adjustment for canal losses	NO	YES	YES	YES	YES
Adjustment Method	.	1	2	3	4
Observations	339	337	337	337	337
R-squared	0.244	0.254	0.258	0.256	0.258

In each specification the dependent variable is farmer net revenue and the independent variables are canal water per acre delivered and controls. Specification (1) is identical to specification (4) in table 2, while specifications (2), (3), (4) and (5) adjust the volume of water delivered upward to account for channel losses using four slightly different formulas (as discussed in the appendix 3). Robust standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Appendix 3: Conveyance Efficiency

One of the key hydrologic parameters of interest to this study is the delivery efficiency of water in the irrigation canal system, referred to as conveyance efficiency (CE). The figure below clarifies what exactly is being sought. Farmers are spread across the head, middle and tails of the primary, secondary and tertiary levels of the canal command. Let's say that one of the farmers selected in our sample is indicated by the red dot. Water travels to a farmer (blue arrows) from the very head of the system (blue dot) to the farmer's field. Thus, CE is the water that actually reaches a farmer's field gate. What we want to estimate is the volume of water lost on the unit as it makes its way from the blue dot to the red dot.



Essentially, what is required is a basic hydrologic model of the canal system that includes CE as a model parameter. Secondary and tertiary canal segments in the Hakra Branch Canal have already been studied to determine CE using the inflow-outflow method to determine channel losses (Khan *et al*., 1999). Measuring loss using the inflow-outflow method requires careful measurement of flow at predetermined points in the canal and also requires calibration of all intermediate outflow structures (outlets on a distributary and farm gates on a watercourse). Primary canal segments have not been measured this way in any known study for Pakistan and specifically for the Hakra Canal System. However, discharge data for a long period of time is available and can be used to develop an estimate for CE.

Ideally, what we would like is for there to be a channel segment specific CE term. That is, for each identifiable reach of the Hakra canal system, we can specify CE for each unit of distance travelled by water. At this stage (barring being able to go out and do an inflow-outflow study or another relevant field experiment), there is essentially one plan available to us. First, we will estimate the inter-distributary conveyance loss and intra-distributary conveyance loss using historic discharge data. For the tertiary canal segments, no historic discharge data is available and therefore we will rely on Khan *et al.*'s estimates of CE and transplant them for the segments of interest to us.

Primary Channel CE Estimates (Canal Head to Tail)

To estimate inter-distributary CE we need to develop a basic relation between CE and various channel segments using discharge data.[1] The idea is fairly simple; let's start at the level of the Hakra Branch Canal itself (the main stem from which the distributaries of interest, i.e. 3R, 6R and 9R, offtake).

The dataset used was all discharge data in the concerned distributaries from March 2006

[1] In all calculations, the average discharge was calculated for a given offtaking point for the summer period (May 1st to 30th October) for a period of 5 years (2006 to 2011).

up to November 2011.[2] In essence, we can rely on the simple idea of mass balance, i.e. canal input should equal output unless there is loss. The idea relies on having complete data on input discharge and all off-taking discharge.

Thus at the primary level, i.e. the main stem of the Hakra canal, we should find that,

$$\overline{q_{Loss}} = \frac{\sum_t^T \left(Q_t^{HB} - \sum_i^N Q_{ti}\right)}{\sum_t^T \left(Q_t^{HB}\right)},$$

where $\overline{q_{Loss}}$ is average percentage loss, Q_t^{HB} is discharge at the Hakra Branch head at time t, Q_{ti} is discharge in distributory i at time t. This loss term applies to the entire length of the Hakra Branch and if we assume a linear relationship we can attribute a percentage loss to each foot of length. With this, we calculate loss of discharge up to the heads of the three distributaries of interest as:

Distributory	**Percentage Loss in Discharge**
3R	0.089258
6R	0.163897
9R	0.252836

Secondary Channel CE Estimates (Distributory Head to Tail)

For secondary canals, the simple method above does not apply since we do not have discharge at the head of off-taking outlets. What we do have instead is the discharge at the head of minor canals that offtake from distributaries which can be used to get a rough guide to conveyance efficiency in the secondary channels of interest.

The distributaries in Hakra Branch Canal have a total of 23 offtaking minor canals. This allows us to relate distributory distances to discharge at offtaking minor canals. We know the CCA, actual discharge and water allowance (the budgeted discharge) at each of these points (i.e.,

[2] The basic dataset provides canal name, date of record, discharge, capacity at head and culturable command area. The dataset is not ready to use as is and requires considerable cleaning, augmentation and completion.

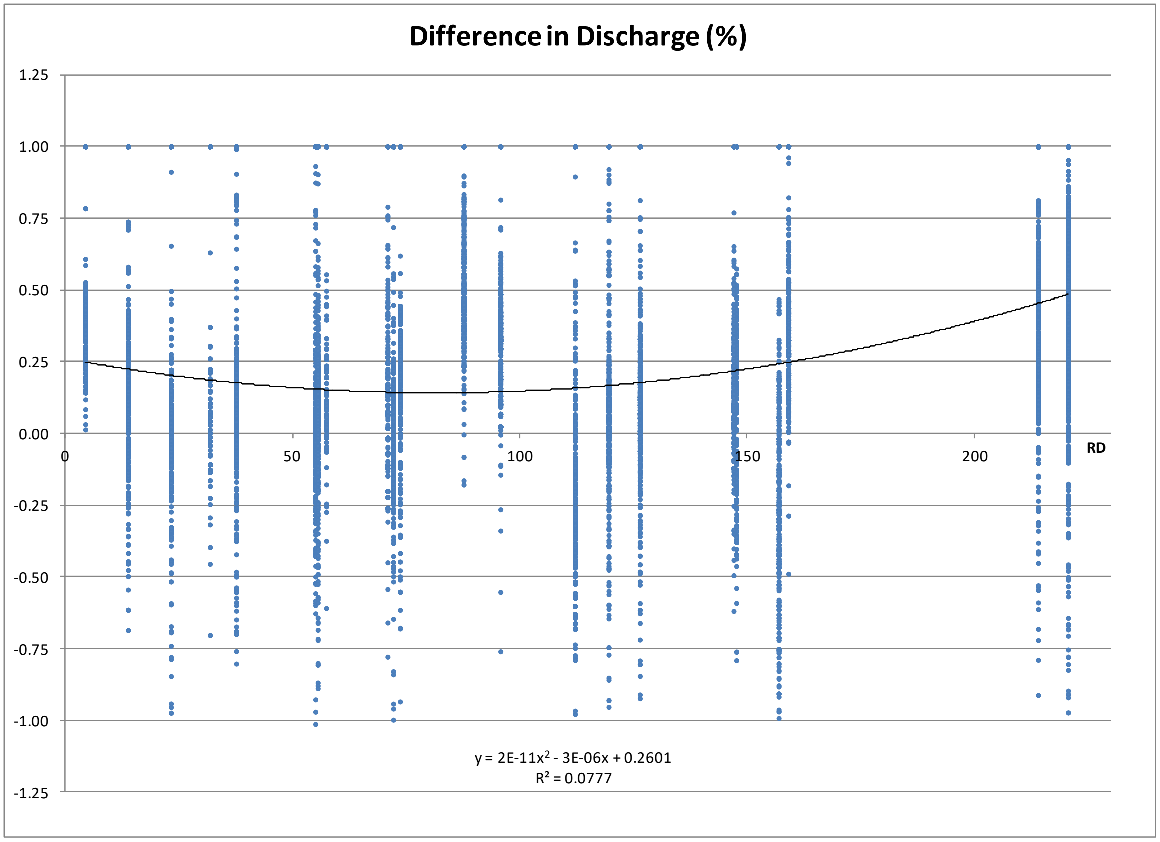
for both the distributaries and minor canals). To start with, we might consider the difference, D_{diff}, between the actual discharge per unit CCA at the head of a distributory, D_{head}, and the actual discharge per unit CCA at a given minor canal, D_i (we normalize by CCA so that the quantities being differenced are comparable),

$$D_{diff} = D_d - D_i.$$

If this difference is positive, we can assume that there has been some loss between. As a first cut, the discharge per unit CCA should be roughly the same at both points. If there is a difference in discharge per unit CCA between the two points, we can assume that the lost quantity can be attributed to conveyance losses. Using this method, the following was calculated:

$$d_{it}^{diff} = \frac{D_{dt} - D_{it}}{D_{dt}}.$$

This gives a percentage loss per observation. Using this, we can relate distance from the head of a distributory to the head of a given minor canal observation; a second order polynomial relation is displayed in the graph below.



The second order polynomial relation between conveyance loss and distance is

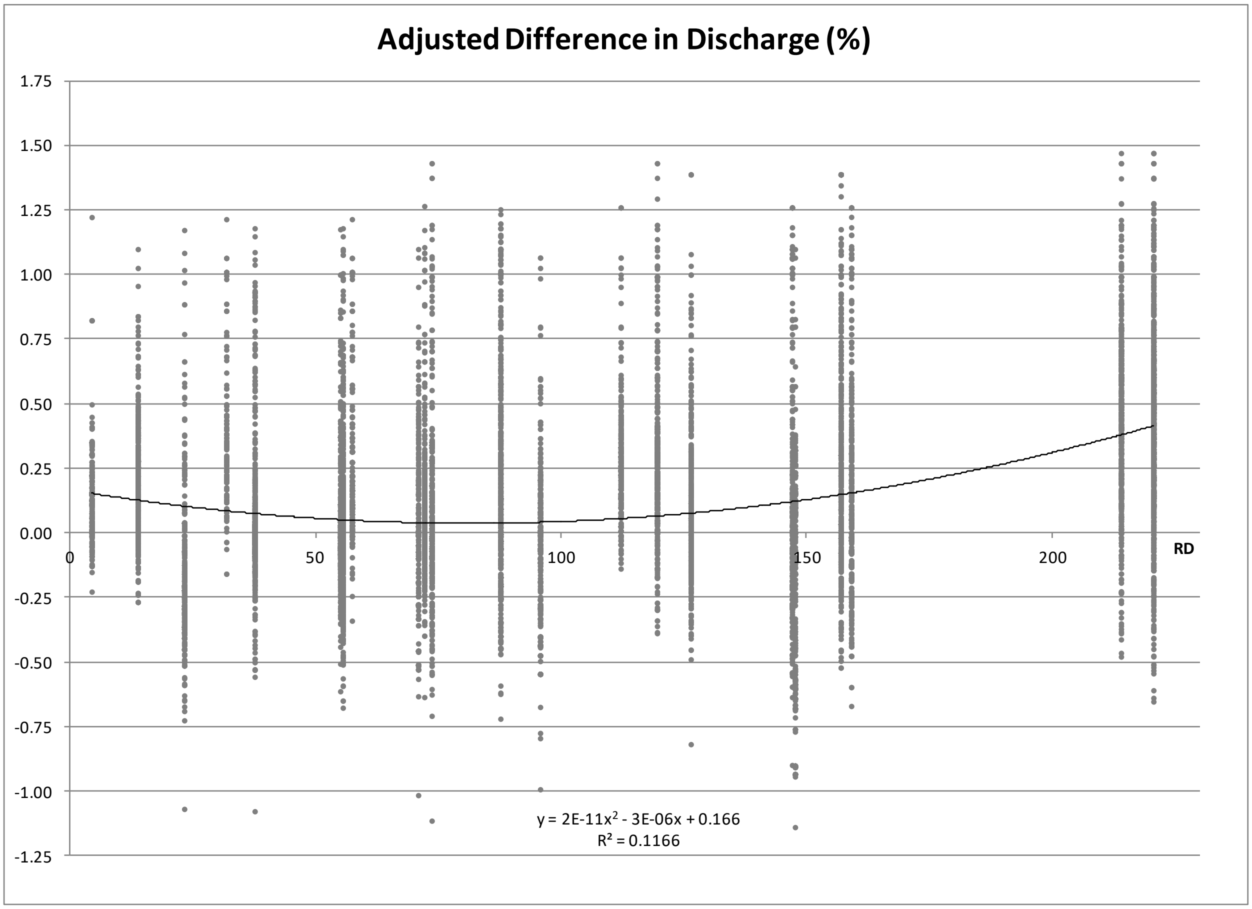
$$l = 0.00000000002d^2 - 0.000003d + 0.2601,$$

where l is percentage loss and d is distance in feet from the head of the channel segment.

An alternative method is as follows. It could be that the different minor canals may be assessed differently, i.e. the water allowance may be different for different distributaries. A channel's command area is assessed by the irrigation department and is based on some presumed crop mix (once set these usually do not change). Thus, what we are really after is the difference between the ratio of actual discharge per unit CCA, D_{dt}, to assessed discharge per unit CCA, A_{dt}, at the head of the distributory and the ratio of actual discharge per unit CCA, D_{it}, to assessed discharge per unit CCA, A_{it}, at a given minor canal head,

$$r_{it}^{diff} = \frac{D_{dt}}{A_{dt}} - \frac{D_{it}}{A_{it}}.$$

Using this data, the following relation emerges (again, using a second order polynomial).



The second order polynomial relation between conveyance loss and distance, using adjusted discharge difference, is

$$l = 0.00000000002d^2 - 0.000003d + 0.1660.$$

How do these estimates compare to some existing work?

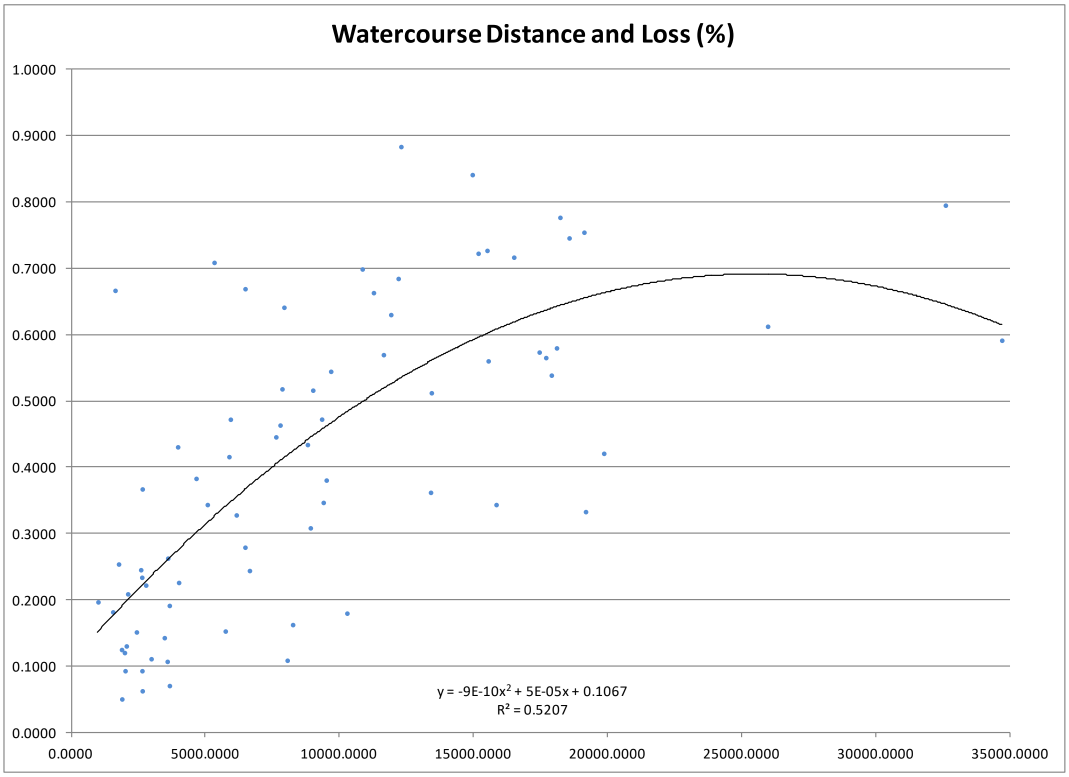
The estimates from the two models we have generated are not far off from the admittedly old estimates of conveyance loss shown in the table below. There really is no good way to judge how well our estimation does. Given the adjusted difference in discharge estimation makes an additional correction, we will choose it.

Study	Distributary	Length	Reference Loss	Adjusted Difference in Discharge Estimate	Difference in Discharge Estimate
Khan et al. (1999)	3R	162300	0.15	0.21	0.30
Cheema *et al*. (1999)	4R	112050	0.17	0.08	0.18

Tertiary channel CE estimates (outlet head to tail)

For tertiary channels, we do not have any historic discharge data, therefore we will have to rely on some existing estimate. Using Khan *et al.*'s study, we can derive a simple relation for watercourse CE. The study being referred to has average (over time) loss percentage for a set of watercourses across the Hakra Branch Canal. It provides loss percentage for the head, middle and tail of the watercourses selected.[3] We can use these to develop a simple relation between loss and distance (much like we did for primary and secondary canals). Using data from tables 20 and 21 from Khan *et al.*'s study, we develop the following relation.

[3] Basic data can be found in Khan *et al*.'s study and must be extracted and augmented.



The second order polynomial relation is

$$l = -0.0000000009d^2 + 0.00005d + 0.1067,$$

where l is percentage loss and d is distance in feet from the head of the channel segment.

References

Cheema, M.A., Z.I. Mirza, M. Ul Hassan, and D. Bandaragoda (1997), 'Socio-economic baseline survey for a pilot project on water users organizations in the Hakra 4-R Distributary Command Area', IWMI Pakistan Report R-037, International Irrigation Management Institute, Lahore, Pakistan.

Khan, A.H., P.W. Vehmeyer, A.P. Reichert, M.S. Ejaz, I.M. Kalwij, and G.V. Skogerboe (1999), 'Water supply and water balance studies for the Fordwah Eastern Sadiqia South Project Area', IWMI Pakistan Report R-088, International Water Management Institute, Lahore,

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