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Sustainable Conjunctive Use of Surface and Ground Water: Modelling on the Basin Scale

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Abstract Farmers in the Indus basin, Pakistan have generally switched to groundwater for additional water supplies due to the irregular supply of irrigation water; currently over 50% of the agricultural land in the basin is at least partially irrigated by tube-wells. These wells pump fresh groundwater, which essentially is the result of massive leakage from irrigation canals into the originally saltwater aquifer since the inception of modern irrigation around 1870. Resalinization of the aquifer now threatens long-term prospects of this new groundwater resource. Since building new dams has become ever more complicated, water resources planning now focuses on sustainable conjunctive use of surface and ground waters. The paper evaluates the raising of the Mangla dam, its effects on long-term groundwater balance and waterlogging using an irrigation-economic model. It suggests guidelines to optimize the surface and sub-surface reservoirs by considering the farmers' action in response to government policies. Recently the Government of Pakistan decided to raise the height of the Mangla dam to substantially increase the storage capacity of the basin. This decision was based on basin-wide modelling of conjunctive use by using the General Algebraic Modelling System (GAMS)-based Indus Basin Model Revised (IBMR), which was updated for this purpose in 2000 and supplied with new data in 2002. The results of the analysis reinforced the decision to raise the dam height by 9 m instead of 12 m, which would increase water availability by 68% in the basin. One of the objectives of raising the dam height was to increase the sustainability of beneficial groundwater use in the basin by saving about 2 km³/a of groundwater abstractions.

Key words: GAMS, Groundwater, IBMR, Indus basin, Sustainable conjunctive use

1 INTRODUCTION

The availability of small pumps and well drilling technology during the last four decades has made large-scale agricultural developments possible in large water-scarce basins, such as the Indus basin, Pakistan. The fresh groundwater now available in the originally salty Indus basin groundwater system originates from massive leakage of irrigation canals and partially also irrigation return flow since surface water irrigation started around 1870. This leakage has become a freshwater resource in its own right, to such an extent that over 50% of the irrigated crops are now at least partially supplied with groundwater (Khan *et al.*, 2008). Therefore,

the leakage has created a groundwater storage which is now utilized in conjunction with the surface water storage behind large dams such as the Mangla dam. Given this situation, the emphasis of the water resources authorities and planners has shifted from development of new dams towards efficient utilization of the available water resources, particularly focusing on the potential of the large benefits to be gained from efficient, conjunctive use of surface and ground waters. Mara (1988) estimates that a 20% increase in agricultural output value is feasible in the Indus basin through efficient conjunctive use of surface and ground waters. Among other advantages, such combined use increases the sustainability of the overall irrigation

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system and enhances crop security, which, by itself, is a major incentive for private investments and increased agricultural output value.

The agro-based economy of Pakistan mainly depends on the Indus Basin irrigation system (Fig. 1). It accounts for about 21% of Pakistan's gross domestic product (GDP) and employs about 44% of its labour force. Pakistan measures about 80 million hectares (ha) of which 22 million ha are cultivated. Of this cultivated area 19.6 million ha are irrigated (Agricultural Statistics of Pakistan 2006–2007). Major crops are wheat, rice, cotton, maize and sugarcane, which together occupy about 63% of the total cropped area (Alam *et al.*, 2000).



Fig. 1 Indus basin network and Mangla dam (source: WAPDA).

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Between 1981 and 2007, wheat and rice production also increased proportionally to the population, which grew from 85 million to 160 million in the same period (Agricultural Statistics of Pakistan, 2006–2007). However, this agricultural production increased mostly because of the extra water that became available after the construction of the Mangla and Tarbela dams and the rapid growth of the number of groundwater pumping units, which increased to about 0.9 million in 2004 from 150.000 in 1975 (Pakistan Agricultural Machinery Census, 2004) throughout the basin.

Pakistan is running out of dam space owing to environmental concerns hampering or preventing construction of new dams and ongoing sedimentation of existing large reservoirs. Mangla reservoir, the second largest in the Indus basin has already lost 21% of its storage capacity due to sedimentation (National Engineering Services of Pakistan (Nespak, 2003).

The Indus Basin receives on average 172 km³/a of which 43 km³/a flows out into the ocean, and of which only about 13 km³/a are sufficient to maintain fisheries and sustain ecology (Bhatti *et al.*, 2009). Hence there is 30 km³/a potential.

Of the net inflow of 129 km³/a, 49 km³/a is used by crops (evapotranspiration from agricultural land). The remainder recharges the groundwater, either by leakage from canals (20 km³/a) or as irrigation surplus (60 km³/a). These estimates are based on WAPDA (Water and Power Development Authority) and Nespak (2009) databases.

MacDonald *et al.* (1990) estimated that 79% of the area in Punjab and 29% of that of Sind have groundwater that is suitable for irrigation. For these areas, conjunctive use of surface and subsurface reservoirs needs to be pursued much more systematically than in the past. The Indus Basin Model Revised (IBMR) is used as a quantitative tool to analyse the potential for improvements in the combined management of the available surface and ground waters on the basin scale.

The IBMR model was developed by the WAPDA of Pakistan and the World Bank since the mid-1970s. The model was intended to predict the impact of different projects on agricultural production. It can also be used to predict groundwater and salt flows, water logging, groundwater salinization and irrigation revenues. Mara and Duloy (1984) suggested that large gains in agricultural production and employment are possible, given more efficient policies as well as allocation and management of surface and ground waters. They presented some simulation results using the Indus Basin Model on an efficient conjunctive use for the irrigated agriculture of the Indus Basin, Pakistan.

They recommended enforcement of taxes and subsidies to control groundwater withdrawals. Ahmad and Kutcher (1992) used the IBMR to model the groundwater and salt flows in the Indus Basin. They estimated salt accumulation in the Punjab and Sind regions of Pakistan in both fresh and saline areas. They also analysed the causes of waterlogging and salinity in the Indus Basin, Pakistan. Leichenko and Wescoat (1993) used the IBMR to conduct climate impact assessment. They considered the potential environmental effects of climatic change and water development in the delta region of the Indus Basin, Pakistan. They evaluated the potential changes in river inflows, canal diversions and groundwater balance under a range of climate change and water development scenarios. In conclusion they formulated a national policy to restrict flows to the delta and suggested incorporation of climate impact assessment into water development planning. Hai (1995) used the IBMR to measure the impact of specific policy changes in cropping patterns, resource use, output levels, groundwater and salt balances by altering agricultural production technologies and resources. He concluded that sustainable agricultural production can be achieved through improvements in the level of resource use efficiency and careful monitoring of environmental issues. Rehman et al. (1997)





developed some insights regarding the agricultural production potential for Rechna Doab, Indus Basin, Pakistan. They used the Indus Basin Model and concluded that an integrated approach is required which should focus on the conjunctive management of surface and ground waters in combination with increasing agricultural productivity taking into account the deleterious effects of salinity so that increased crop yields can be achieved in а manner that supports sustainable irrigated agriculture. Jehangir et al. (2003) used the Indus Basin Model to assess the future net water requirements at the root zone level in Lower Chenab Canal (LCC) of the Indus Basin, Pakistan. They studied 13 different scenarios of canal reallocation to reduce the gap between net requirements and the total supplies in the irrigation system.

The rapid increase of groundwater irrigation over the last three decades has caused overexploitation of the fresh water stored in the aquifer underlying the Indus Basin. This is evidenced by increased widespread salinization of tube-wells, which endangers the future benefits of the conjunctive use of surface and ground waters. As reduction of these groundwater extractions was deemed necessary and given the dam-related problems described above, it was decided to raise the Mangla dam so that increased water demands could be met and corresponding over-exploitation of groundwater could be reduced.

The measure is the result of the analysis carried out by the simulation-optimization model IBMR, which was restructured and upgraded in the present study. Economic analysis was performed to find the best alternative of the dam raising options. The expansion of the dam is currently underway and is expected to be completed in 2010–2011. The model was also used to predict the groundwater balance and find optimal solutions for irrigation in the basin. To conclude, 2002 was taken as the base year, while simulations for different scenarios span the period 2002–2020.

2 INDUS BASIN MODEL REVISED 2.1 Model description

The IBMR is a large-scale mathematical model for the Indus Basin based on linear programming to maximize benefits and minimize cost. It is written in GAMS - General Algebraic Modelling System (www.gams.com) by using semi-analytical techniques. It consists of about ordinary differential and algebraic 2500 equations and has been used by the World Bank and WAPDA in various studies among which the left-bank outfall drain planning, on-farm water management, Kalabagh Dam design (Ahmad et al., 1990), and alternative salinity management projects (Rehman et al., 1997) are prominent (Ahmad and Kutcher, 1992).

The model divides the basin into nine agroclimatic zones (Fig. 2). These nine separate zone models are interlinked through a surface-storage and distribution model, which contains the entire system of river reaches, main canals, and groundwater storage, running with a monthly time-step over the reference period (Mara and Duloy, 1984). The model simulates recharge to and discharge from groundwater and estimates water balances of the groundwater and surface water reservoirs. The model aims at distributing the available water optimally for agriculture bearing in mind the groundwater storage and pumping capacity available in each zone. There are nine zone models, that are mapped (combined) into three province models, namely Punjab (containing four zone models: PMW, PCW, PSW, and PRW), Sind (containing four zone models: SCWN, SRWN, SCWS and SRWS), and NWFP (which is a single zone representing the whole province).

2.2 Concept and mathematical background

The IBMR model quantifies the water flows to the aquifer and computes the water budget for each of the nine zones. The groundwater balance can be written as:

$$\Delta S = R_r + R_c + R_w + R_p + R_i + R_i - D_e - D_d - D_i - D_x$$
(1)

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where ΔS is the net change in groundwater storage, R_r the recharge due to river seepage, R_c the recharge due to canal seepage, R_w the recharge from water courses and irrigation fields, R_p the recharge from precipitation, R_i the recharge from lateral flows from adjacent zones, R_{t} the recharge from tube-well operations, D_{e} the discharge from evaporation and transpiration, D_{d} the discharge from subsurface drainage, D_{t} the discharge by tube-wells, D_{x} the discharge from lateral flows to adjacent zones (Ahmad and Kutcher, 1992).



Fig. 2 IBMR agroclimatic zones of Indus basin (source: International Water Management Institute, Pakistan).

The method used in IBMR to estimate evaporation and transpiration is based on Gardner and Fireman (Ahmad and Kutcher, 1992) who estimate groundwater discharge D_e [L] as:

$$D_e = \frac{E \times 10.637}{H^{2.558}} \tag{2}$$

where *E* is evaporation [L] and *H* depth to the water table [L]. Because the zones are mostly separated by rivers, lateral movement between adjacent zones is negligible, i.e. only about 2% of the volume of annual groundwater recharge (Ahmad and Kutcher, 1992). IBMR computes the water table depth H_t [L] as

$$H_t = H_{t-1} + \frac{\Delta S}{A \times c} \tag{3}$$

where *A* is total area and *c* is the phreatic storage coefficient. The evaporation and the watertable depth are interrelated variables as shown by Eqs. (1), (2), and (3); and are computed iteratively. D_e is computed from Eq. (2) given H_{t-1} [L], which is then used to compute H_t from Eq. (3). The new estimate of D_e for the next iteration is made using the average of H_t and H_{t-1} . H_t is calculated again using Eq. (3) and this procedure is repeated until the convergence of H_t and D_e (Ahmad and Kutcher, 1992).

2.3 Model reformulation

The IBMR model was reformulated and upgraded in the current study. The reformulation includes water allocations in accordance with the Water Apportionment Accord 1991 (an agreement between provinces regarding distribution of water), multi-objective reservoir's operation and decision making, and Mangla dam raising aspects.

The updated IBMR represents hierarchical two-stage decision making – termed as multi-level programming. This formulation can be generalized as: the objective of decision making at the highest level (government) is to select a plan of action that optimizes its objective subject to rational reactions by the stakeholders at the lowest level, i.e. the farmers. The model contains nodes to distribute surface water according to the requirements of representative farms. The network is used to develop efficient water allocation schemes to optimize the regional use of available water resources. This necessitates knowledge of the water requirements of individual farms. Water use on the level of individual farms needs to be modelled, as farmers react without recognizing their individual impact on the (future) groundwater system and freshwater yields. Also, for this reason, the government should monitor the long-term consequences of water allocation schemes and investments (Bisschop et al., 1982) to ensure predictions keep up with actual developments in the water resource, water demand and actual water use. This multi-level structure of the IBMR model can mathematically be written in abstract form as follows:

$$Q_{21}z + Q_{22}x = d_2, \quad x \ge 0$$

$$\{ \underset{z \mid (x,j)}{\text{Minimize}} \quad k^T z + j^T z,$$

$$(4)$$

s.t.
$$Q_{11}z + Q_{12}x = d_1, \quad z \ge 0$$
 (5)

where x is a vector that can be thought of as a list of all parameters to be optimized at the top level such as water allocations; z is the response by stakeholders optimized for their short-term benefit; j is taxes and/or subsidies; d_2 and d_1 are vectors of available water resources at the highest and lowest levels, respectively; k is a vector of expenditure and prices; Q_{21} , Q_{22} , Q_{11} and Q_{12} are physical constraints and those due to policies of government and response of stakeholders at the top and bottom of the decision hierarchy. Eq. (4) is the objective function at the top level (i.e. government), which describes allocation of water with respect to the constraints as of Eq. (5); and Eq. (5) is the objective function at stakeholder level, which describes the demand of water by representative farms. Both have to be optimized in conjunction to maximize the economic value produced under the restrictions of available water

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resources and limitations of the distribution system, which now includes groundwater as an extra reservoir (Bisschop *et al.*, 1982).

2.4 Model inputs

The IBMR encompasses agriculture, irrigation, economics, and hydrology components. Therefore, the required data were obtained from various institutions such as the IRSA (Indus River System Authority), PMD (Pakistan Meteorological Department), NARC (National Agriculture Research Centre). PCRWR (Pakistan Council of Research in Water Resources), MINFAL (Ministry of Food, Agriculture and Livestock, Government of Pakistan), FBS (Federal Bureau of Statistics), PC GOP (Planning Commission, Government of Pakistan), WAPDA (Water and Power Development Authority), IWMI (International Water Management Institute), SOP (Survey of Pakistan), NESPAK (National Engineering Services of Pakistan), ASP (Agricultural Statistics of Pakistan) and then much data processing was carried out. The IBMR model was then used to simulate potential agricultural production and net economic benefits over the period 2002-2020, through optimization of water availability in surface and groundwater reservoirs (Alam, 2003).

3 RESULTS AND DISCUSSION

3.1 Economic appraisal

The model was used to determine the level of increase of the crest level of second largest dam in the Indus Basin, the Mangla dam (latitude 33° 8′ 32″ N and longitude 73° 38′ 40″ E). The analysis showed that raising the dam by 9 m and 12 m would increase water availability in the Indus Basin by 68% and 76%, respectively. The IBMR model has been used to determine the expected additional irrigation revenues. The cost of the 9- and 12-m raising alternatives was estimated at about US\$ 520 million and US\$

645 million, respectively, with annual operation and maintenance expenditure of about US \$ 3.1 million (Nespak, 2003). The final dam height increase decision was 9 m, which was based on the economic internal rate of return (EIRR) for the two dam levels and four different financial scenarios (Fig. 3). The actual groundwater use has increased EIRR of the 9-m dam height increase relative to the 12-m option because of the relatively low cost of surface storage and more direct benefits to the farmers. This has been a consequence of including groundwater in the IBMR model.

3.2 Groundwater balance

Table 1 depicts the net balance of the groundwater of the seven affected zones in the Indus Basin (Eq. (1)) for 2002 and the year 2020, with and without the increase in the height of the Mangla dam by 9 m. The year 2002 was a very dry year with large depletion of the groundwater volume due to intensive pumping. In contrast to this, year 2020 in the model simulations uses average weather conditions, so that the net volume taken from groundwater is less than 2002, despite increased demands. The table also compares the situation in 2020 with and without the increase of the height of the Mangla dam. The groundwater availability benefits all zones, except SRWN where the growth of the number of tube-wells outperforms the increased supply of irrigation water apart from the raised dam. The significant change appears in zone PSW, in which inflow would be increased by 4.3% and outflow decreased by 7.1% by 2020. To conclude, inflows would be increased by 1.1% and outflows decreased by 2.6% to the aquifer underlying the Indus Basin. In total, the increase of the dam height by 9 m is predicted to generate a saving of around 2 km³/a of groundwater, which by itself reduces the deterioration of the valuable groundwater resource caused by salinization and increase of the pumping cost.



Fig. 3 Economic internal rate of return- EIRR (%).

Table 1 Groundwater balance components (km³) in agroclimatic zones between 2002 and 2020 – with and without scenario of 9 m raising of the Mangla dam (Fig. 2 for zone description and spatial reference).

Scenarios	Components	PCW	PSW	PRW	SCWN	SRWN	SCWS	SRWS
Base case: 2002	Recharge	24.2	9.45	7.37	9.41	6.93	6.24	5.3
	Discharge	30.85	15.37	14.55	8.46	5.99	6.83	4.76
	GW balance	-6.66	-5.91	-7.18	0.94	0.94	-0.59	0.54
Without dam raising: 2020	Recharge	28.18	11.28	8.04	9.92	8.18	6.77	5.27
	Discharge	30.77	12.41	12.33	9.4	6.63	6.95	4.76
	GW balance	-2.59	-1.13	-4.29	0.52	1.55	-0.18	0.52
With dam raising: 2020	Recharge	28.09	11.77	7.99	9.93	8.11	7.35	5.38
	Discharge	29.65	11.53	11.42	9.26	6.94	7.29	4.76
	GW balance	-1.56	0.24	-3.43	0.67	1.16	0.05	0.62

3.3 Waterlogging

A positive groundwater balance signals a rising water table, providing a rough estimate of the magnitude and the change in waterlogging (Leichenko and Wescoat, 1993), a severe problem in the Indus Basin. A negative groundwater balance in 2002 in the zones PCW, PSW, PRW and SCWS suggests the risk of severe over-exploitation. These zones can be improved by raising the dam; the table indicates this for the zones PSW and SCWS. The performed study suggests as water management options: (1) to extract the groundwater from zones having a positive balance; and (2) to

restrict groundwater abstraction from the zones that are already over-pumped to increase their subsurface storage. These suggestions can of course only be realized with well-planned enforced pumping schedules at different spatial through taxes subsidies. scales and Implementation of such measures would take a number of years.

3.4 Optimization of irrigation under conjunctive use

The IBMR model was designed to use surface and ground waters conjunctively. It optimizes the surface and sub-surface stocks to maximize

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revenues, by evaluating the farmer's actions in response to government policies to allocate surface water and regulate or stimulate groundwater use. The country's water demands are projected to increase from 205 to 240 km³ between 2002 and 2020 (simulated demand as per the model, using growing population needs). Increase of surface water availability would decrease reliance on groundwater. The simulated surface and groundwater use as projected by the model (Figs. 4 and 5) predicts this for the coming years. Conserved groundwater can be used in future, increasing food security during dry periods. The model also depicts that basin outflow to the ocean will be reduced by about 14% by raising the dam, which is a net increase of available irrigation water (Fig. 6).

4 SUMMARY AND CONCLUSION

Pakistan must achieve extra water storage, because sedimentation has reduced the storage capacity of reservoirs in Pakistan by over 20%, while water demands are increasing. As development of new dams is very difficult owing to social, political and environmental concerns, enhancing the capacity of existing reservoirs is a good alternative, but cannot provide a complete solution. Conjunctive use with groundwater is necessary, thus utilizing the freshwater leakage into the naturally salt aquifer that has occurred and has taken place since the beginning of surface water irrigation around 1870. The EIRR analysis recommends to increase the height of the Mangla dam by 9 m. This increases its live storage capacity by 3.5 km³, which is about 68% of the current storage capacity (Nespak, 2003). The model predicts additional annual benefits of about US\$ 98 million by 2020 (Fig. 7). The groundwater balance indicates that overexploitation of groundwater in agro-climatic zones of Punjab would reduce significantly. Consequently, an extra saving of about 2 km³/a groundwater will enhance its future of utilization. The IBMR model is now a proven tool to optimize the use of Pakistan's water resources available from different sources in economic terms and suggests the policy guidelines. The IBMR-based techniques can generally be applied to the other irrigation systems operating in semi-arid and arid environments.



Fig. 4 Simulated surface water use (km³) trend under the conjunctive regime.



Fig. 5 Simulated ground water use (km³) trend benchmark requirements under the conjunctive regime.



Fig. 6 Outflow to sea (%) against benchmark require.



Fig. 7 Additional irrigation revenues (million US \$) due to dam raising.

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استفاده تلفیقی از آبهای سطحی و زیرزمینی: مدلسازی در مقیاس حوزه آبخیز

نويد علم و تئو اولستورن

چکیده بسیاری از کشاورزان در حوزه آبخیز رود سند در پاکستان به علت عرضه نامنظم آب آبیاری، برای تأمین آب مازاد به استفاده از آبهای زیرزمینی روی آوردهاند. در حال حاضر در بیش از ۵۰ درصد اراضی کشاورزی در حوزه آبخیز رودخانه سند حداقل بخشی از آبیاری با چاههای میلهای صورت میپذیرد. این چاهها آب زیرزمینی شیرین را پمپاژ میکنند که اساساً حاصل نفوذ عمده آب، پس از شروع آبیاری نوین در حدود سال ۱۸۷۰، از کانالهای آبیاری به آبخوان آب شوری است که از قبل در منطقه وجود داشته است. شور شدن دوباره أبخوان چشمانداز بلندمدت این منبع جدید آب زیرزمینی را تهدید میکند. بر همین اساس از زمانی که پیچیدگی حاکم بر مسئله احداث سدهای جدید بیشتر درک شد، برنامهریزی منابع آب بر استفاده تلفیقی از آبهای سطحی و زیرزمینی تمرکز کرده است. این مقاله با هدف ارزیابی اثرات افزایش ارتفاع سد Mangla بر تعادل بلندمدت آب زیرزمینی و برداشت آب با استفاده از یک مدل آبیاری اقتصادی می پردازد و در همین راستا دستورالعملهایی را برای بهینهسازی مخازن سطحی و زیرسطحی با توجه به عکسالعمل کشاورزان در مقابل سیاستهای دولت ارائه میکند. در سالیان اخیر دولت پاکستان تصمیم به بالا بردن ارتفاع سد Mangla برای افزایش قابل ملاحظه ظرفیت ذخیره در حوزه گرفت. این تصمیم براساس مدلسازی استفاده تلفیقی از آب در مقیاس حوزه آبخیز گرفته شد که از طریق بکارگیری مدل اصلاح شده حوزه سند (IBMR) و مبتنی بر سامانه مدلسازی جبری عمومی (GAMS) انجام شده است. مدل مذکور در سال ۲۰۰۰ برای همین هدف به روز شده و در سال ۲۰۰۲ با دادههای جدید ارائه شده است. نتایج تحلیلها بر افزایش ارتفاع سد تا ۹ متر به جای ۱۲ متر تأکید داشت که در دسترس بودن آب در حوزه رودخانه سند را تا ۶۸ درصد افزایش خواهد داد. یکی از گزینهها برای بالابردن ارتفاع سد افزایش پایداری استفاده از آبهای زیرزمینی در حوزه با ذخیره حدود ۲ کیلومتر مکعب بر سال از آبهای زیرزمینی می باشد که از طریق تعادل آبهای زیرزمینی شیرین با نفوذ از سیستم کانالی تحقق مییابد.

کلمات کلیدی: سامانه مدلسازی جبری عمومی، آبهای زیرزمینی، مدل اصلاح شده حوزه آبخیز رودخانه سند، حوزه آبخیز سند، استفاده تلفیقی پایدار