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An empirical analysis of the hydropower portfolio in Pakistan

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HIGHLIGHTS

- ► Pakistan has a hydropower potential of 60 GW distributed across 800 projects.
- ► Under-development projects will realize 36.7 GW of this potential by 2030.
- ► Project locations are skewed towards some sub-basins and provinces.
- ► Project sizes are very diverse and have quite limited private sector ownership.
- ► Gaps in data prevent proper risk assessment for Pakistan's hydropower development.

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ABSTRACT

The Indus Basin of Pakistan with 800 hydropower project sites and a feasible hydropower potential of 60 GW, 89% of which is undeveloped, is a complex system poised for large-scale changes in the future. Motivated by the need to understand future impacts of hydropower alternatives, this study conducted a multi-dimensional, empirical analysis of the full hydropower portfolio. The results show that the full portfolio spans multiple scales of capacity from mega (> 1000 MW) to micro (< 0.1 MW) projects with a skewed spatial distribution within the provinces, as well as among rivers and canals. Of the total feasible potential, 76% lies in two (out of six) administrative regions and 68% lies in two major rivers (out of more than 125 total channels). Once projects currently under implementation are commissioned, there would be a five-fold increase from a current installed capacity of 6720 MW to 36759 MW. It is recommended that the implementation and design decisions should carefully include spatial distribution and environmental considerations upfront. Furthermore, uncertainties in actual energy generation, and broader hydrological risks due to expected climate change effects should be included in the current planning of these systems that are to provide service over several decades into the future.

1. Introduction

Pakistan is undergoing massive demographic and economic changes (Kugelman and Hathaway, 2011). With a surging population estimated at over 175 million currently (UNPD, 2010) and projected to reach 236 million by 2030, increasing urbanization and expanding industrial base, the demand for energy and water is reaching new heights. The energy and water infrastructure has not kept pace, and currently the country faces severe energy and water shortages (Hathaway et al., 2007; EAC, 2009). In 2011, the average energy deficit between supply and demand stood at approximately 4,500 MW (see Fig. 1), and this shortage is expected to be aggravated in the future unless substantial mitigating initiatives are implemented quickly.

While some of this deficit can be reduced through improved demand management (EAC, 2009), loss reduction, and financial practices (NEPRA, 2011), it cannot be eliminated without increasing the installed electricity generation capacity in the country. Some recent quick-fix measures have included thermal power plants on a rental basis (ADB, 2010). However, for the long term this will be inefficient and insufficient.

For Pakistan, a country with significant water resources and limited fossil fuel reserves, there are strong economic incentives to deploy hydropower systems (Qazilbash, 2005). There are also growing international pressures, throughout the Hindu Kush-Himalayan (HKH) region, from Afghanistan to China, there is a "race to the top" for hydropower development. A number of new trans-border developments of water and power infrastructure by the upper riparians India and Afghanistan are precursors of potential new challenges regarding water supplies for Pakistan

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(World Bank, 2010). The issues are complex. For example, Pakistan raised objections to the design and operation of Baghlihar Dam, a run-of-river facility allowed under the Indus Waters Treaty subject to conditions including a limitation on minimum flows during reservoir filling (Lafitte, 2007; United Nations Treaty Series, 1960). In addition to design issues, Pakistani authorities claimed a loss of 2 million acre-feet (MAF) of water during the filling of Baghlihar Dam, data and losses questioned by India (Bengali, 2009). Dispute over another facility has been taken to the Permanent Court of Arbitration (2011). These developments further provide strategic impetus for enhancing the water storage and management infrastructure in the country.

In response to these pressures, a large number of storage and Run-of-River (RoR) hydropower schemes have been identified. Based on the projects that are under implementation, the total installed hydel capacity can be expected to potentially grow to 36,759 MW (PPIB, 2011) by the year 2030 (WAPDA, 2010). Given that the current installed hydel capacity on the Indus river system in Pakistan is 6,720 MW, this represents approximately a five-fold future increase.

Within this backdrop of development, it has become important to consider the potential, limits, and impacts of a progressively developed basin. This understanding is important since an upfront, portfolio-level assessment of the socio-economic, political and environmental impacts may allow for enhancing benefits (e.g., cost reduction, improved management, environmentally sensitive technical design), and averting negative effects. To date, this kind of analysis for the entire portfolio of hydropower projects has not been conducted for the Indus Basin, although some recent large projects have been subjected to individual detailed impact assessment (e.g. Ghazi Barotha Hydropower project (GBHP, 1994)).

This study serves as a first step towards constructing an understanding of future potential impacts of collective hydropower facilities. In this paper, we present an empirical analysis of the full portfolio (as currently identified) in Pakistan's Indus Basin and provide an assessment on the basis of size, sub-basin, administrative and organizational jurisdiction.

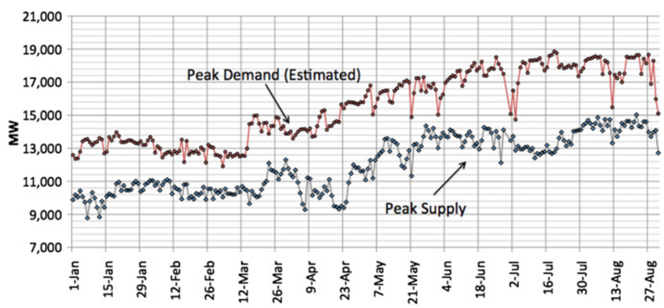

Fig. 1. Electricity supply and estimated demand (January–August 2011) in Pakistan. *Source*: (MoWP, 2011).

2. Sources of data: overview and comparison

In order to examine the full portfolio, we compiled data from five sources published between 2004 and 2011 (WAPDA, 2004, 2010; HPP-GTZ, 2005; PPIB, 2004, 2011). A comparison of the data revealed varying estimates of project capacities. A key change was in the estimated total feasible hydropower potential, that increased by 40% from 42,000 MW in a 2004 database (PPIB, 2004) to 60,000 MW in 2011 (PPIB, 2011). This increase is largely due to new sites being identified, as well as increases in estimated capacity of previously identified projects. Fig. 2(a) shows the maximum percent change in capacity estimates, based on data in

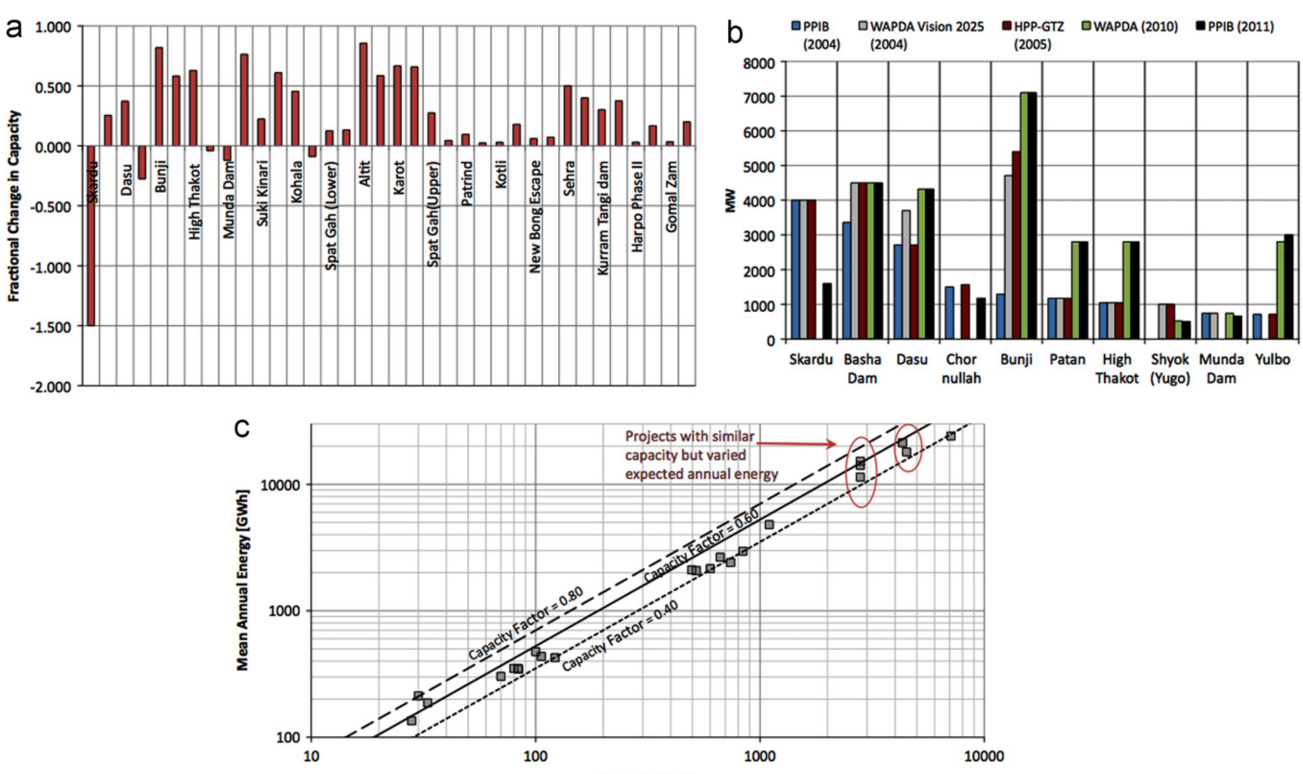

Fig. 2. (a) Fractional change in estimated hydropower capacity of various projects across different sources (WAPDA, 2004; WAPDA, 2010; HPP-GTZ, 2005; PPIB, 2004, 2011), (b) capacity comparison across selected large projects in different data sources and (c) projects with similar capacity, can have significantly different energy output. *Source*: (WAPDA, 2010).

(PPIB, 2011) and compared against data in documents from 2004 to 2010, for selected projects. It shows that for many projects the fractional increase is 40% or higher. Fig. 2(b) shows the capacity estimates (in MW) for a sub-set of the larger projects as reported in the different sources and arranged in decreasing order of capacity based on estimates provided in the earliest source used (PPIB, 2004). It can be noted from Fig. 2(b) that capacity estimates were revised upwards in later documents (with Skardu and Chor Nullah projects being the major exception).

This difference may be due to more accurate data becoming available over time, as well as increased technological efficiencies. There may also have been a shift in the reporting approach in which early sources reported average capacity estimates whereas later references reported maximum (peak) power generation estimates. This highlights an important issue that capacity estimates are an insufficient (though widely used) measure for project output description. Annual energy generation estimates should be provided for the full portfolio for a more complete evaluation of the options. Fig. 2(c) shows a sample of 23 projects (for which mean annual energy data was obtained from (WAPDA, 2010)). The red circles mark how a set of projects with the same capacity (shown along the *x*-axis) are expected to have a significantly different mean annual energy output (*y*-axis).

For the remainder of our analysis, we used data provided in (PPIB, 2011) except where noted, since it was the most comprehensive and the latest data source available.

3. Pakistan hydropower portfolio: analysis and results

The currently feasible hydropower portfolio in Pakistan's Indus Basin consists of 800 sites, spread across the regions of Khyber Pakhtunkhawa (KPK), Gilgit-Baltistan (GB), Azad Jammu and Kashmir (AJ&K), Punjab and Sindh. Of these sites, 134 have already been developed and are operational, 151 are under development, and the remaining 515 may be developed in the future. The 800 sites are located along more than 125 different rivers and streams and a number of different canals that are all connected to the Indus Basin Irrigation System (IBIS). The 800 sites have a collective potential of 59,794 MW of which 6720 MW, i.e., 11% of the total, has been realized. The on-going 151 different projects collectively comprise 30,039 MW of capacity that once installed will raise the total to 36,759 MW in the future (harnessing $\sim$61% of the total potential).

The on-going development, while large in magnitude, has a long time horizon for completion. Based on historical experience, as well as existing challenges, it is likely that a number of the projects currently designated as 'under implementation' may in reality take years (even decades) for commissioning. There is therefore currently ample opportunity for planners to chart and shape the course of hydropower development in the basin.

Note, that we use the term 'project' interchangeably with 'sites'. In a strict sense, the term 'project' is meaningful for sites that are under development or operational. However, in this work we use the term 'project' to also refer to sites that have only been identified for future potential development.

3.1. Scale and structure

Fig. 3(a) shows the capacity in MW, sorted in decreasing order, of all the feasible hydropower projects in the Indus Basin in Pakistan on a bar plot.

The *y*-axis of the figure is on a logarithmic scale, and it can be noted that the sizes (i.e. estimated capacity) run the full spectrum from thousands of megawatts to hundreds of kilowatts. The statistical median of the portfolio is 1 MW, mean is $\sim$75 MW and the standard deviation is 439 MW. Fig. 3(b) shows the capacity distribution (on a logarithmic *x*-axis).

We classify the projects using the terminology employed in (GoP, 2006a, 2006b) (and shown in Table 1). There is no universal standardized categorization of hydropower schemes (Egre and Milewski, 2002), and a variety of thresholds are used to classify projects as large, small, micro, mini etc. For this study, we used the classification found in most planning documents of hydropower projects in the Indus Basin and employed by the Alternative Energy Development Board of Pakistan.

As a whole, within this multi-scale portfolio, the mini-hydro systems dominate in extent (with 518 projects) whereas the large hydrosystems dominate in magnitude (accounting for 57,160 MW). Figs. 3(a) and (b) lay out the option space for hydropower systems in the Indus Basin. Determining what an optimal mix of large and small hydro may be from an economic and environmental sustainability perspective is an open question that merits detailed investigation.

Based on data in Fig. 3(b) and the collective capacity for each category (shown in Table 1), We note that while the 0.15–50 MW capacity range has three categories, all projects greater than 50 MW are simply lumped as Large Hydro. For planning and evaluation purposes, it would be useful to adopt additional categories within the $>$50 MW segment. We propose three possible additional categories to be introduced: medium hydro (50–499 MW), large hydro (500–1000 MW), and mega hydro ($>$1000 MW). One reason is that medium, large and mega hydro projects can be expected to have very different magnitudes of environmental and socio-economic impacts, across significantly different spatial and temporal scales.

3.2. Spatial distribution

The second dimension we considered, to characterize the overall system, was the spatial distribution of the portfolio. We analyzed the data based on the water channel (rivers and canals) boundary as well as political boundaries (defined by provinces and districts). An understanding of the spatial distribution – both within natural and socio-political boundaries – is relevant for distribution of costs and benefits, environmental impact assessment, as well as for identifying diversified options that can lend robustness (in power generation) to the collective system.

3.2.1. Projects on rivers

Our analysis in the riverine context was somewhat limited due to data gaps—348 projects did not have associated channel (river/stream) information specified in (PPIB, 2011). We constructed partial information using regional maps in (PPIB, 2011) for 253 of those projects, but were unable to gather data for 95 projects (with collective capacity of 494 MW in Gilgit-Baltistan). In the future, we hope to obtain a more complete set of geo-referenced project location data and will be able to increase the accuracy of this analysis.

Fig. 4(a) shows individual projects sites (marked with colored squares that indicate project status), on 106 different channels. The *y*-axis has a logarithmic scale and has dual units. For capacity data (individual squares and the solid black curve), the units are MW. For the total projects data (red curve with circles), the units are number of projects. The rivers have been ordered along the *x*-axis in the plot in decreasing order of total hydropower potential.

In aggregate terms, the Indus River main stem has the largest feasible hydropower potential (35,287 MW or 59% of the total) followed by Jhelum (5,469 MW or 9% of the total) which is a distant second largest.

While aggregate data is useful (and typically found in planning documents), the *distribution* of project sizes and number on each river sheds light on potential implications of the development.

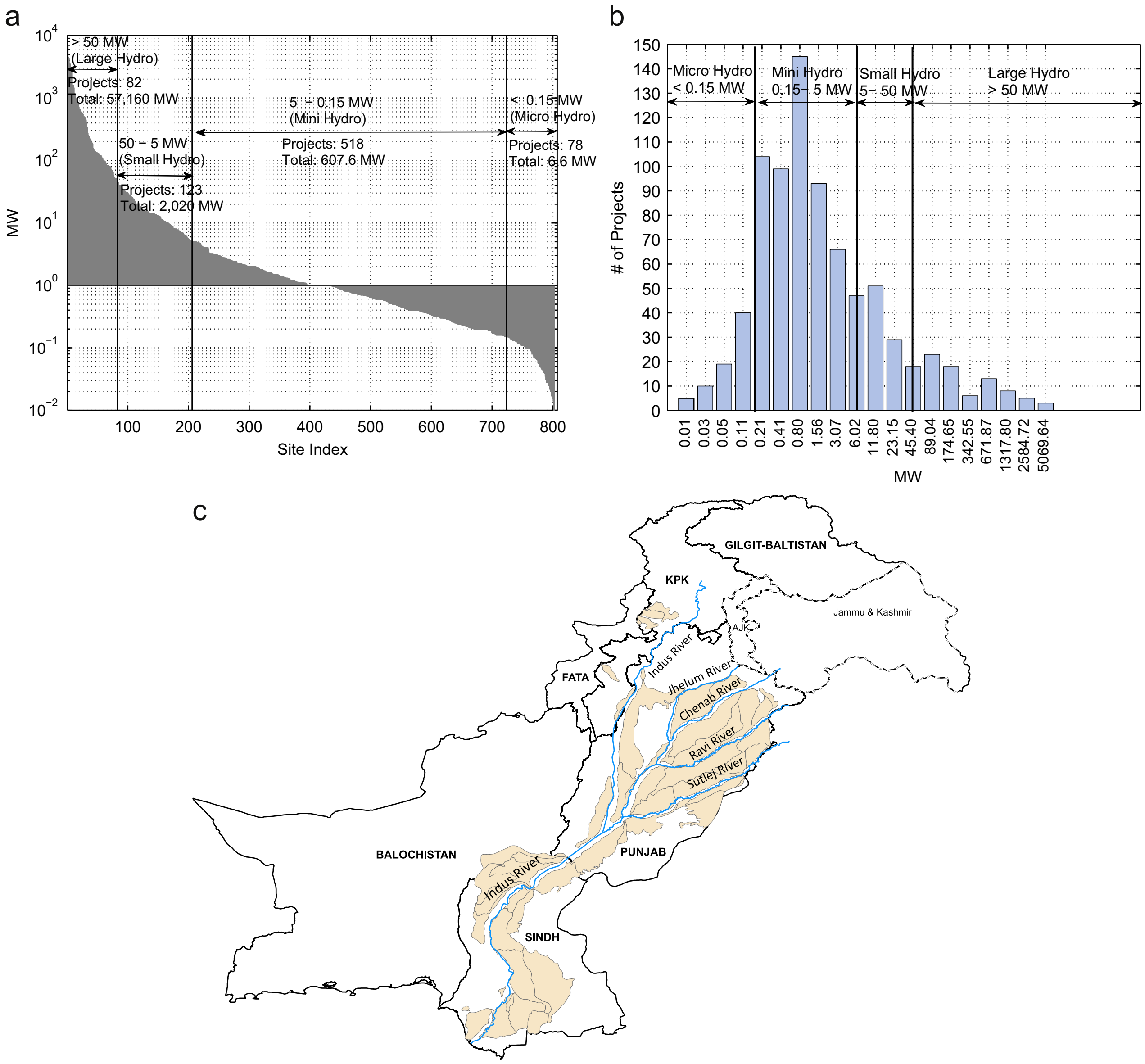

Fig. 3. (a) Hydropower portfolio in the Indus Basin, (b) Pakistan's hydropower portfolio capacity distribution and (c) five major rivers in Pakistan along with canal commands in the Indus Basin (shaded in yellow), and disputed territories. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Hydropower portfolio categorization and distribution.

Category	Cumulative capacity [MW]	Total # of projects	In operation		Under implementation	
			MW	# of Projects	MW	# of Projects
Micro hydro < 0.15 MW	6.62	79	1.93	20	0	0
Mini hydro: 0.15 MW—5 MW	607.6	518	89.44	97	158.5	66
Small hydro: 5 MW–50 MW	2020	123	196	13	719	42
Large hydro: > 50 MW	57,160	82	6433	6	29,162	43

From the projects on each channel on Fig. 4(a) (marked by squares), it can be noted that the Indus main stem hosts a full spectrum from micro hydro to mega hydro projects. The smallest identified sites have 100 kW estimated capacity (mostly RoR schemes in the Gilgit-Baltistan area) while the largest is the 7100 MW Bunji Dam project. It can also be noted that the distribution of project sizes is different on the rivers—some have a few large projects, while others have many small projects.

Fig. 4(b) shows a more detailed assessment of number of projects on the rivers. The solid red line indicates the total number of projects on each river and the median project capacity is shown with black triangles. The Indus river again ranks first with 54 projects, followed by the Bola Das River and Astore River with 15 projects each and so on. It can be noted that 68 channels have only a single project (or hydropower site). In these cases, the 'Median Project Capacity' is the exact project capacity—the

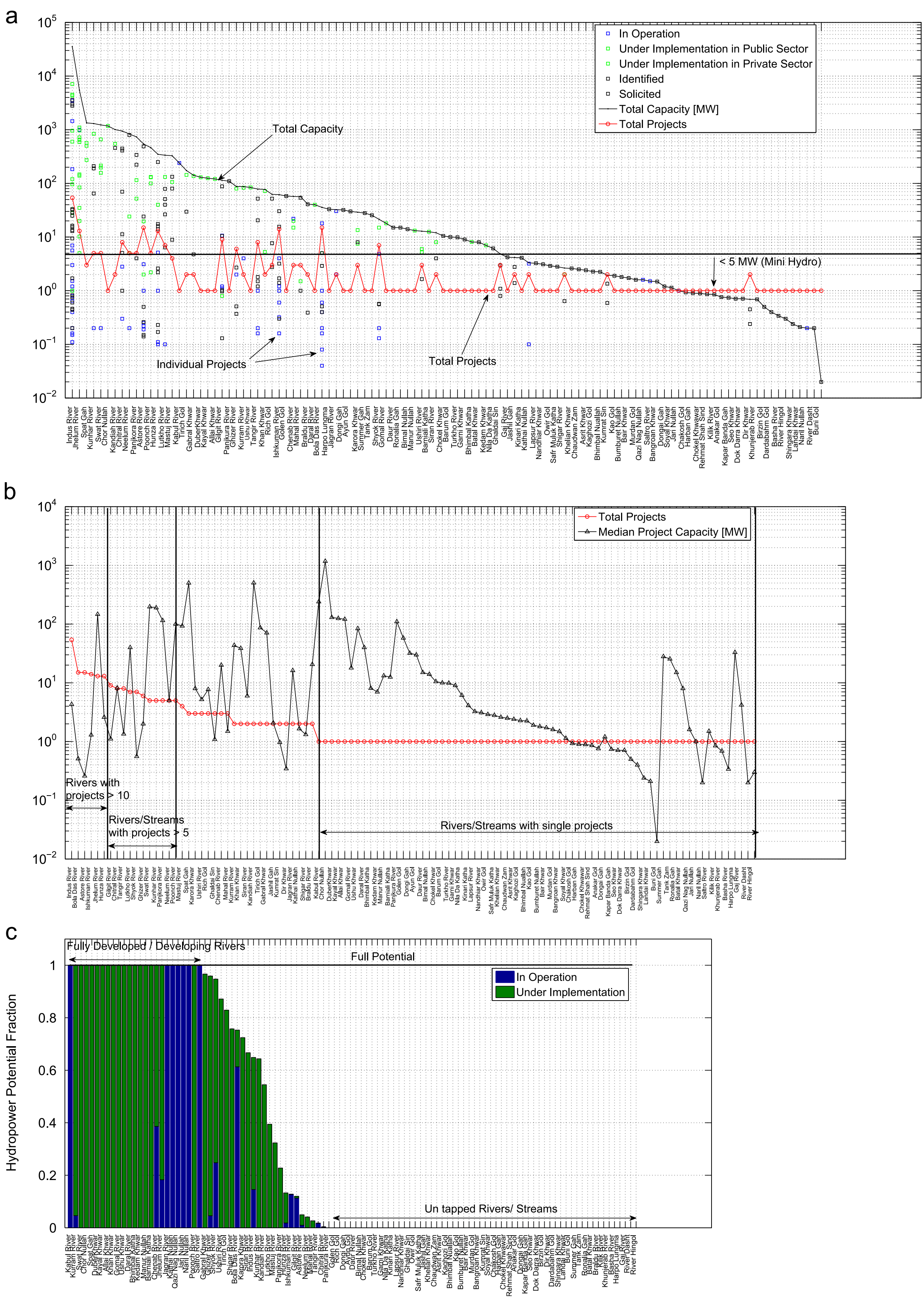

Fig. 4. (a) Hydropower projects on rivers and streams: channel wise distributions and total capacity, (b) rivers arranged in descending order by number of total projects and (c) extent of hydropower potential development on rivers.

median is only meaningful as a statistical measure for the cases where there are several projects. The median project capacity on the Indus is only 4.3 MW (due to the large number of small hydro schemes), And the mean is 653 MW with a standard deviation of 1,500 MW. The river Jhelum, with the second highest total hydropower potential, has a median of 147 MW. On the Jhelum, there are almost no small hydro schemes, and of its 13 total projects in Pakistan, 7 are greater than 500 MW each.

The number of projects on a river can serve as a crude proxy of the fragmentation that may result from development of hydropower (Nilsson et al., 2005; Moyle and Mount, 2007). River fragmentation – where sediment entrapment, fish migration obstacles, and other flow obstructions are created – is an important issue for large reservoir projects (Ziv et al., 2012). Most of the hydropower projects in the Indus system portfolio are run-of-river (RoR) schemes. Nonetheless, depending on the project size and system design, even RoR schemes can have significant flow diversions and storage (for meeting daily peaks and loads) (GBHP, 1994; PPIB, 2011).

At this level of analysis and characterization (wherein we did not have access to all project details, location along the river reach, distances between projects etc.), the total number of projects coupled with the inspection of project capacity distribution can provide first-order information that can be used for further investigation in the future. For instance, Fig. 4(b) shows that the rivers with comparatively large number of projects such as the Bola Das River, Ishkuman River, Tangir River have small median capacity, on the order of 1 MW, and an inspection of their projects (see Fig. 4(a)) indicates that all projects are small in size (with most less than 5 MW). These rivers, with a series of small hydro systems, may not get as careful an assessment since each individual project is small in size (and below the threshold requiring initial environmental assessment (GoP, 2006b)). However, if fragmentation issues, collection of several ponds for daily peaking, and other factors are considered, the cumulative impact of multiple projects may merit a closer review.

We also analyzed the level of development for each river by computing the total capacity of projects that are operational and are under implementation, and then comparing against the total feasible identified hydropower potential of that river (see Fig. 4(c)). A value of 1 indicates that the identified feasible potential on the river has been fully (100%) utilized. The blue segments indicate the extent at which the river is currently developed (operational projects), and the green segments show the on-going development fraction.

Fig. 4(c) shows that so far 7 channels have been fully tapped (i.e., their currently feasible total identified potential has been completely utilized): Kabul River, Jagran River, Kathai Nullah, Qazi Nag Nullah, Jari Nullah, Naril Nullah, and Saltro River. Once the currently on-going projects are completed, the Indus will be developed to 65% of its total identified potential (currently at 14.5%). Some of the other larger rivers such as river Jhelum (currently at 18%), Chenab (currently at 39%), Swat (currently at 0%), and Kurram (currently at 5%) will also all be fully tapped. It should be noted that once some of the missing and partial data of rivers is resolved (discussed in Section 3.2.1), this figure would be augmented.

In summary, some key statistics that emerge are that the Indus main stem has the largest potential at 59% of the total, with 54 projects—the largest number of projects than any other river in the system. Currently developed at 14.5% of its potential, it would be tapped to 65% once on-going projects are completed. The Jhelum is a distant second with 9% of the total potential, which would be tapped to 100% in the future. From an inspection of the on-going development, it is apparent that these two rivers will collectively form the backbone of hydro-electricity production for the national grid. These two already play a crucial role (with Tarbela dam on the Indus and Mangla on the Jhelum), and their role will further increase once on-going projects are commissioned. It is therefore important to consider scenarios where changes in inflows from historical levels (both increases as well as decreases) and social and environmental impacts are factored into the planning and design of the infrastructure.

3.2.2. Projects on canals

The Indus Basin hosts the world's largest contiguous network of irrigation canals (Shams ul Mulk, 2009). These irrigation canals, with significant flow volumes, host attractive potential for small hydropower generation. There are 303 sites on canals, of which 6 are located in KPK, 14 in Sindh, and the remaining 283 in Punjab province. The total hydropower potential on the canals system is 684 MW, which in aggregate terms is only 1.1% of the total potential (of 60 GW) in the basin. However, while it constitutes only 1% of the share, the small scale, distributed nature offers advantages of low upfront deployment costs, easier accessibility (which allows for cheaper maintenance and operation), and larger local population centers that can derive benefit from the generated electricity.

Fig. 5 shows the estimated hydropower capacity of individual project sites (marked with squares) on canals (sorted by descending order of total capacity). The canal names are shown (corresponding to the canal index numbers on the *x*-axis) in Table A.1 in the Appendix. The canal with highest total potential is Swat Canal in KPK with 121 MW (which is fully developed and operational). The second highest is Rohri Canal in Sindh with 109 MW—none of which has yet been developed.

Fig. 5 shows that most of the canal projects are below the mini-hydro threshold (of 5 MW), and therefore would be subject to less oversight and evaluation under current renewable energy development policy (GoP, 2006b) that exempts projects less than 5 MW from initial environmental evaluation. Second, while some canals have only a few sites, there are others that have up to 40 different sites identified. The collective impact of all of these deployed systems should be considered, and life-cycle costs and benefits be holistically assessed. Past experiences with stand-alone, unregulated systems serve as reminders that unintended and unwanted consequences can result (e.g., as evidenced by over-extraction of groundwater by off-grid tubewells (Briscoe and Qamar, 2005)).

3.2.3. Provincial distribution

The Indus Basin encompasses seven administrative regions in Pakistan: Khyber Pakhtunkhwa (KPK), the Federally Administered Tribal Areas, Gilgit-Baltistan (GB), Azad Jammu and Kashmir (AJ&K), Balochistan, Punjab, and Sindh. An analysis of the portfolio's distribution across these regions shows that KPK has the highest total potential ($\sim$25,000 MW), followed by Gilgit-Baltistan ($\sim$21,000 MW), Punjab ($\sim$7,300 MW), AJ&K ($\sim$6,500 MW), and finally Sindh ($\sim$193 MW).

Fig. 6 (a) shows the total capacity (black line), total number of projects (red line), as well as the capacity (bar plots) in terms of development status. Fig. 6(b) shows the province-wise capacity fractions by project status.

At the provincial scale, the role of private sector is found to be relatively pronounced in Punjab and in AJ&K. In GB and in KPK, the public sector has the largest role (given that most of the large projects are also located there and the private sector is only allowed participation in smaller projects). It is interesting to see that in terms of development level, AJ&K will have 86% of its feasible potential tapped once on-going activity is completed. KPK's level of development will be at $\sim$64%, Gilgit-Baltistan at 57% and Punjab at 47%. Note, however, that some of these data are contested, as when a dam has one abutment in one province and the other in a different province, which affects their relative shares of hydropower revenues.

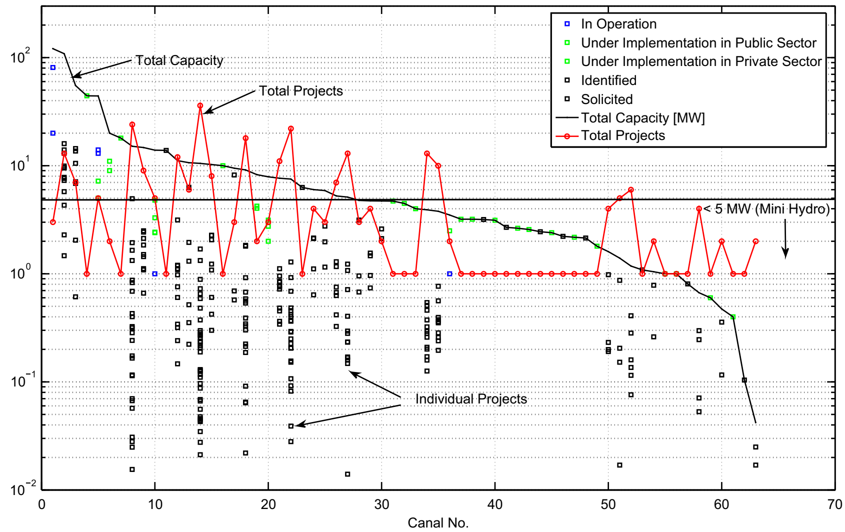

Fig. 5. Hydropower projects on canals.

Currently, based on operating projects, KPK has the largest installed capacity (at 3,849 MW) followed by Punjab (~1,700 MW) and AJ&K (~1,039 MW). GB's currently installed base is relatively small at 132 MW. This balance will change once projects under implementation are commissioned. The data shows that the total installed capacity in these regions will become 15,729 MW for KPK, 12,049 MW for GB, 5,533 for AJ&K, and 3,448 MW for Punjab. There will consequently be a shift in hydro-electricity production assets that are currently largely in KPK and Punjab to a more expanded role of KPK and a new important role for GB. KPK will host ~43% of the installed hydropower capacity followed by GB with 33% of the total installed capacity. Thus, while Punjab and Sindh are the largest end consumers of the waters of the Indus system (in their vast agricultural lands), KPK and GB will become the largest energy producers from this river system. The power production and water storage infrastructure will shift in aggregate measure to KPK and GB, while the water consumption and end-use base will continue to reside in Punjab and Sindh.

The provinces and regions are sub-divided into 120 smaller administrative 'districts' in Pakistan (IPG, 2012). Fig. 6(c) shows district-wise hydel capacity for river-based projects. The district data for canal projects was not available in (PPIB 2011). The spatial distribution, at the district scale, is greatly skewed. In the KPK area, the district with largest total potential is the Kandiah district, whereas Swabi district (where Tarbela dam is located) has the largest operational capacity. In Punjab, Mianwali district; in AJ&K, Muzaffarabad district, and in GB, Astore, Diamer and Skardu districts have large hydropower potential.

3.3. *Organizational context: hydropower agencies*

Hydropower projects are developed and operated by a number of different agencies in the country. Our analysis shows that there are 7 different agencies currently involved with water and power development, of which WAPDA is the federal/central agency and the rest are regional entities. An overview of these agencies is provided in Table 2.

We examined the extent and magnitude of the organizations' portfolios (based on operational projects), and how they will change due to projects that are under-implementation. Fig. 7(a) shows the distribution of projects in the jurisdiction of each agency. WAPDA oversees the large systems, whereas all the provincial agencies oversee smaller (< 50 MW) hydro systems. The PPIB, however, is engaged in coordinating some larger projects with private investors. It is interesting to note that based on currently operating and under implementation projects, the total capacity in the jurisdiction of the regional agencies, SHYDO, PPDB, AJ&K HEB and WAPD Giglit-Baltistan is similar (~400 MW total for each).

Fig. 7(b) shows a bubble plot, in which the location of the bubbles corresponds to the total capacity of projects in a particular status, and the size of the bubbles corresponds to the number of projects. The number of projects are also labeled inside the bubbles for clarity. We note that while WAPDA oversees the largest total capacity, the Water and Power Department-Gilgit Baltistan (WAPD) operates the largest number of individual projects/schemes. There is also a noticeable entrance of the private sector (mostly restricted to small scale hydro). The PPIB, PPDCL and PPDB are entities that relate with private producers. These agencies currently do not have operational systems; however, their role is expected to expand in the future (as can be seen by the green bubbles indicating under-implementation projects).

WAPDA currently manages 14 operating projects that have a collective capacity of 6461 MW. Once under-implementation projects are commissioned, it will have 34 hydropower facilities with a total capacity of 28,866 MW. This has important implications for institutional capability and organizational planning for the agency. Similar trends can be noted for SHYDO and AJ&K-HEB. In the case of Gilgit-Baltistan, the WAPD-Gilgit Baltistan is currently managing 98 small hydro systems with a total capacity of 132.7 MW. This portfolio will increase to 126 projects in the future with a more than doubling of the present total capacity to a new level of 381 MW. All of the public sector agencies need to plan upfront for this expansion so that they can effectively manage their expanded portfolios. Previous studies have noted the need for institutional reform and strengthening in Pakistan's water and power agencies (Briscoe and Qamar, 2005). These results highlight a related issue of the need for institutional readiness for significant portfolio expansions.

4. Mini-hydro systems

In the previous sections, we discussed results of our investigation from a technical, spatial and organizational perspective for the full portfolio. We now focus on a portion of the portfolio: the Mini Hydro (0.15–5 MW) segment. This subset of the portfolio is subject of great interest and development incentives (GoP, 2006a, 2006b; AEDB, 2006).

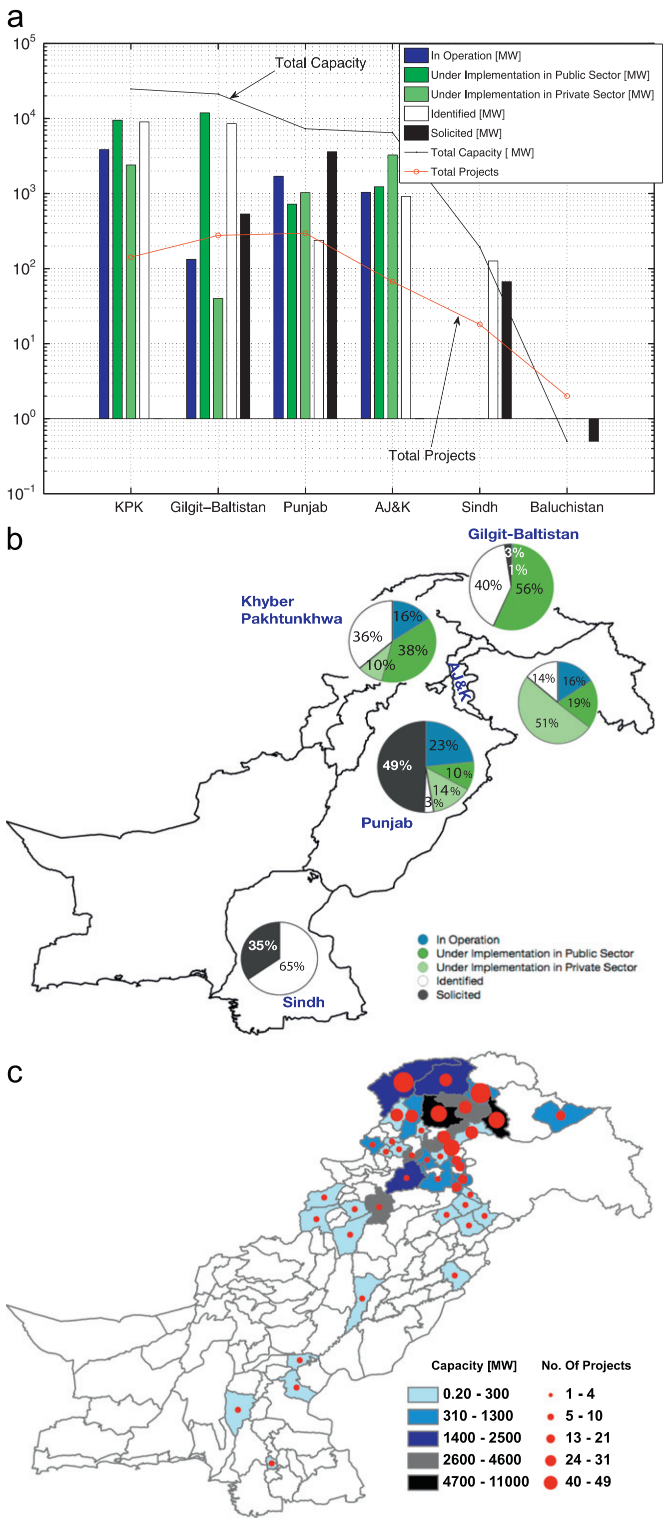

Fig. 6. (a) Total hydel capacity and projects by province/region, (b) project status fraction by province and (c) hydel capacity by district.

The common perceptions are that small hydro systems are beneficial from a variety of perspectives: they have low upfront costs, are suitable for private sector development (with additional benefits of local jobs, technical capacity creation, etc.), require minimal or no power transmission infrastructure (in fact their off-grid nature makes them ideal for deployment in rural and remote areas), and are environmentally benign (Varun and Bhat, 2009). Given the above considerations, the development of mini-hydro has accelerated in the northern mountainous areas (particularly in GB). The developments have in fact received awards, e.g. the Ashden energy award for small micro-hydro projects built by villages with support from private organizations (AKRSP, 2004). These developments have been actively encouraged, and in the Policy for Development of Renewable Energy for Power Generation drawn up in 2006, these projects have been given exemption from Initial Environmental Examination requirements (GoP, 2006b). In general, these efforts can be appreciated from an economic development perspective. However, the issue of large-scale use of small hydro has been raised (Abbasi and Abbasi, 2011), and it would be prudent to consider potential cumulative impacts upfront.

From the total mini-hydro capacity by province (shown in Fig. 8(a)), we can observe that while the Gilgit-Baltistan area is the major user of this class of hydropower systems, Punjab is currently making significant efforts in deploying these systems. There thus seems to be a diffusion of mini-hydro installations occurring from an original concentration in the remote mountainous regions of GB to the irrigation canals in the plains of Punjab. The impacts, if any, would therefore likely be different for the systems in these two different regions. For instance, it has been noted that micro-hydel has reduced deforestation and turf cutting for fuel (Hunzai, 2010) in Gilgit-Baltistan. In the case of agricultural lands of Punjab, these particular benefits will not be as applicable.

Fig. 8(b) shows – with very few blue segments in the bar plots that to date the canals have not been used for small-scale hydropower systems and there are only a small number of operational projects on canals. However, the green sections indicate the development activity currently undertaken by both the public and private sector. The role of the private sector (light green bars) can be especially noticed here.

Fig. 8(c) shows mini hydro projects on rivers (excluding data of river tributaries). The blue segments in the bar indicate that in some rivers, the projects are already operational (as also discussed previously), however there are some large green segments (corresponding to under-implementation projects) on a few rivers such as the Neelum, Mahl, Jhelum and Shigar rivers. Overall, a skewed distribution is also present here, wherein even in the micro-hydro category, a few rivers dominate in terms of total sites as well as capacity.

5. Summary and discussion

This study has attempted to create a systems-level understanding of the currently known feasible hydropower portfolio in Pakistan's Indus Basin. By situating the portfolio in its structural (size), natural (sub-basin), administrative (provincial districts), and organizational contexts, we have drawn out important insights relevant for strategic planning and policy. This quantitative analysis is essential for understanding potential collective energy benefits, environmental impacts, social and political implications, and capacity building and restructuring of public sector agencies; and it has largely been neglected from the debate surrounding hydropower development in Pakistan.

In regards to the structure of the portfolio, we find a multi-scale system that provides a continuous spectrum of options ranging from mega (> 1000 MW) to micro (< 0.15 MW) projects. The size distribution however is skewed in which of the 800 projects, only 82 (or 10%) belong to the > 50 MW category. This 10% of the portfolio, however, in terms of collective capacity (at 57.16 GW) accounts for 95% of the total feasible potential (of 60 GW) in the basin. Small and micro-hydro systems, both across rivers and the massive canal network that forms a unique and characteristic feature of the basin, collectively form a very small piece of the pie offering only ~2,600 MW in total. For energy starved Pakistan, this 2,600 MW,

Table 2
Water and power development agencies in Pakistan.

Name	Year established	Description/Role
Water and Power Development Authority (WAPDA)	1958	WAPDA was established with a broad mandate of water and power infrastructure development for irrigation, water supply, drainage and flood-control, power generation, transmission and distribution of power. Currently, it is focused on the development, operation and maintenance of all major hydropower projects in the public sector.
Sarhad Hydel Development Organization (SHYDO)	1993	SHYDO, established by the provincial government of KPK, is responsible for identifying and developing the hydropower potential in the province.
Private Power and Infrastructure Board (PPIB)	1994	PPIB was established to facilitate power generation in the private sector. It currently serves as the focal contact on behalf of the federal government for private investors in development of hydropower.
Punjab Power Development Board (PPDB)	1995	PPDB has the mandate to implement power generation projects in the private sector, in the province of Punjab, through the utilization of the water resources of canals/rivers (and other indigenous resources e.g. oil, gas, and coal) (PPGB, 2006).
Punjab Power Development Company Ltd. (PPDCL)		PPDCL is a corporate body, owned by the Government of Punjab, and established under the Company Ordinance 1984, in the energy department of the province.
AJ&K Hydroelectric Board (AJ&K HEB)	1989	The Government of Azad Jammu and Kashmir established its Hydro Electric Board to plan and to undertake development of identified hydro potential in the region. One of its key priorities is the development of the region's hydro potential through participation of the private sector. Large, public sector projects in the region are implemented by AJKHEB and WAPDA (PPIB 2011).
Water and Power Department (WAPD), Gilgit-Baltistan		Its mandate includes development of small and medium hydel stations, as well as development and maintenance of local transmission lines (GWAPD, 2012).

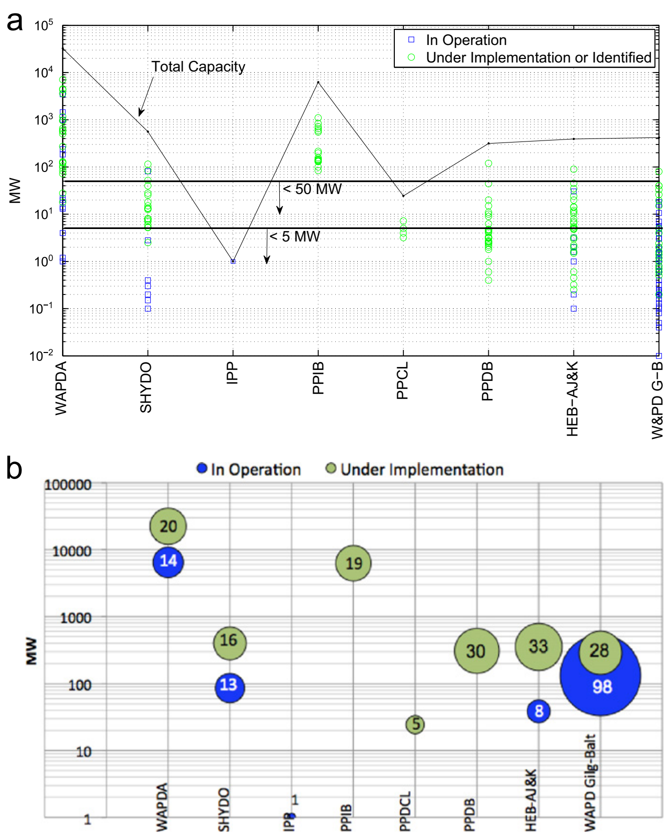

Fig. 7. (a) Projects and total capacity under jurisdiction of water and power agencies, (b) magnitude and extent of agencies' portfolios.

running on free flowing waters instead of expensive fossil fuel would still be a useful addition. Its dispersed nature and in most cases lack of connectivity to the national grid would mean that the energy benefits from this part of the portfolio would be localized. At the national level, however, while the direct energy benefits would be small or non-existent, indirect benefits may materialize through demand for turbines and other equipment that may be domestically manufactured, skilled labor for maintenance, etc.

Within the riverine and canal boundaries, we found that the Indus main stem plays an out-sized role in terms of total feasible hydropower potential across the spectrum of the portfolio. Its main stem hosts the most projects (54) as compared to any other river, accounts for 59% of the total portfolio potential (with 35.2 GW) and has projects across the spectrum from micro to large hydro. The Indus for millennia has cradled human civilizations in its basin with its flowing waters and rich sedimentary deposits that enable large scale agriculture. It appears that in the near future it will assume an increasingly crucial role in satisfying the growing hunger for energy as well.

Within canals, the relatively larger options have already been developed (such as in the Swat Canal), and the ones remaining to be exploited are largely in the micro-hydro category. The direct energy benefits will be small (only 684 MW or 1% of the total portfolio), and their location in densely populated plains of Punjab may provide only small marginal benefits. In remote, sparsely populated mountainous areas of Gilgit-Baltistan the riverine micro-hydro has provided significant benefits, but the benefits in the context of Punjab may well be different. In dense populations with high localized energy demand, as in the case in Punjab, larger systems may provide economies of scale and more cost effective energy options. A full life cycle analysis, and evaluation of direct and in-direct benefits should be conducted. A key aspect of the canal portfolio is that there is significant activity from the private sector which may be an important indirect benefit of developing this segment of the portfolio.

In regards to distribution of the feasible portfolio among provinces and districts, there is again a skewed distribution in which two regions Khyber Pakhtunkhwa and Gilgit-Baltistan collectively host 76% (~46 GW) of the total 60 GW potential. Once the dust settles on currently under-development projects, AJ&K is expected to have almost maxed out its potential (85% will be utilized), but others will retain almost half for future exploitation. The results also predict a future shifting of the power generation system from currently being based in KPK and Punjab to a further enhanced role of KPK and a new important role for Gilgit-Baltistan (that will host 43% and 33% respectively of the total expected installed capacity). Thus while the irrigation benefits of the Indus waters will continue to be largely derived from the vast plains of Punjab and Sindh, the benefits due to energy production systems can be expected to infuse in KPK and Gilgit-Baltistan. Recent reports have already begun to indicate such trends, for instance the newly inaugurated 36 MW Daral Khwar hydroproject (to be completed in three years) is expected to generate annual revenue of Rs. 1 billion (~ > USD 10 million) for KPK (The News, 2012).

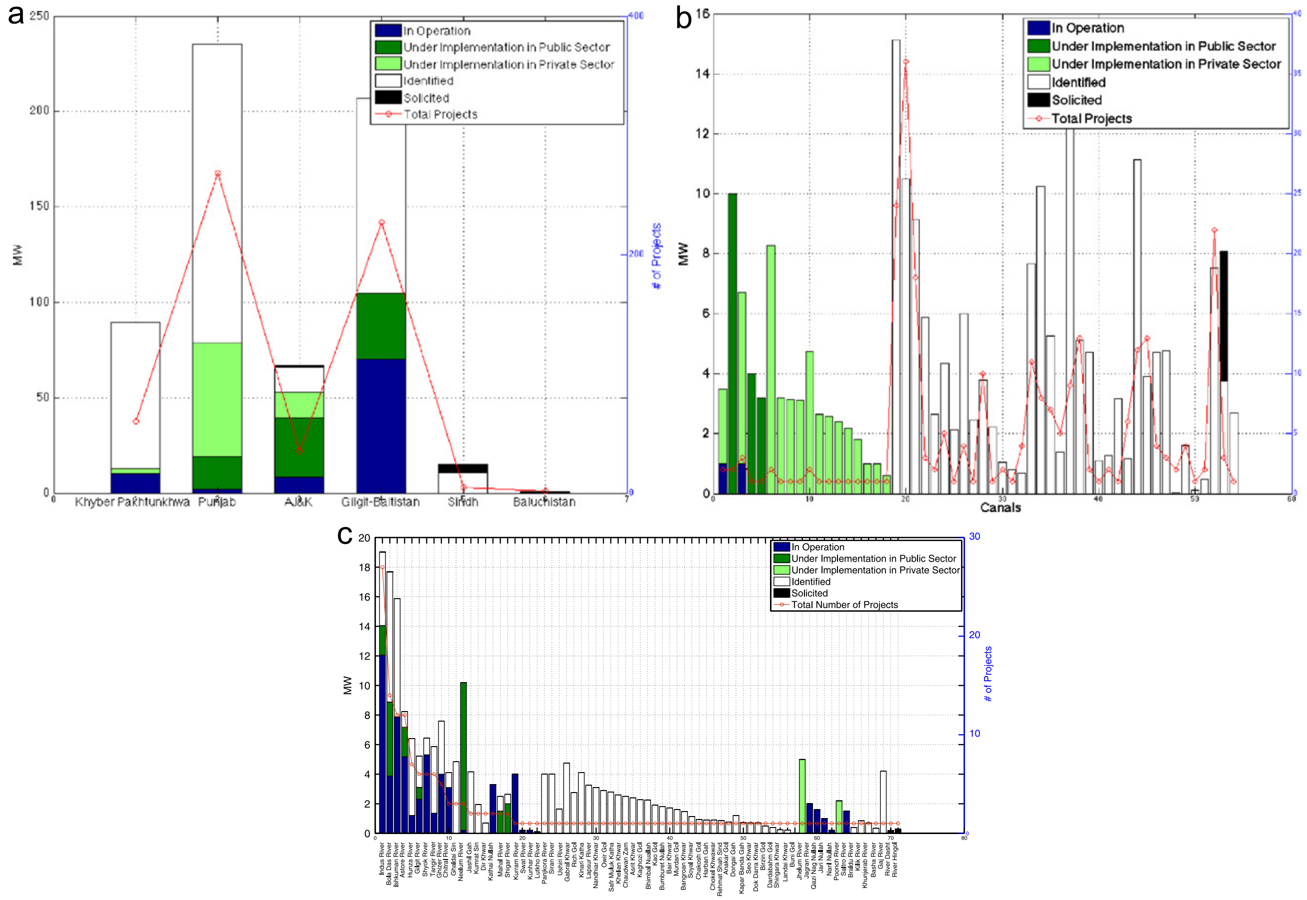

Fig. 8. (a) Mini-hydro by total capacity and number of projects on a regional and status basis, (b) mini hydro on canals by total capacity, total number of projects and status and (c) mini hydro projects on rivers.

An analysis of the organizational dimension reveals a significant future expansion in portfolio for almost all the agencies along with entrance of new entities created to promote involvement of the private sector. We find that WAPDA and SHYDO will more than double their existing portfolios in number of projects (from 14 to 34 and from 13 to 29 respectively), whereas HEB-AJ&K portfolio will increase five times (from 8 to a total of 41 projects). The nature and size of the projects varies across the agencies, in which the large projects are in the domain of the federal level agency WAPDA, whereas the smaller (< 50 MW) projects are in the jurisdictions of the regional/provincial agencies. This doubling and trebling of the portfolios needs expedient planning ranging from expansion of personnel, technical and managerial capacity, to streamlining of procedures for continued effective management.

6. Recommendations and future work

In the previous sections we discussed our analysis and reported key observations regarding the proposed hydropower development in Pakistan. In this section, we outline key recommendations relevant for future policy-making and action.

6.1. Create open-access information sources

A first-order policy problem, in regards to effective deployment of hydropower projects in Pakistan, is lack of complete, coherent, and publicly accessible information. This lack of visibility, along with the urgent need for generation and use of smart knowledge has been highlighted in the past (Briscoe and Qamar, 2005). The discussions in Section 2 (regarding varying capacity specifications), and in Section 3 (regarding incomplete sub-basin and river reach data) illustrate the dearth of complete and consistent data that can be readily and independently used for analysis. We highly recommend that information repositories (maintained by public agencies) be created that provide access to up-to-date, reliable and digitally usable data.

The development of hydropower in Pakistan is not only a technical issue, but also a political challenge. To bring the projects online, a large number of constituencies will have to be mobilized, accommodated, and satisfied over a period of time. However, if the system benefits are not as promised, or if the system development costs are much higher than estimated, this can become a seedbed for political discord and governance upheaval. We think it is of the utmost importance for Pakistan's policymakers and their international supporters to commission independent collection of data, and its analysis, for Pakistan's hydropower system; and to make the full range of hydropower alternatives, as well as the costs and benefits of hydropower development publicly available. If Pakistan is to seriously embark on a journey towards solving its energy problems, and if hydropower is going to be a real option instead of a vague hope, we think this is an essential policy step.

6.2. Internalize environmental costs

An initial review of available documents shows that economic considerations are the primary and perhaps only factor in project ranking and prioritization (GTZ-HPP; Haq, 2009; ADB, 2010) for Indus Basin project planning. While economic feasibility should always be a key necessary factor, it should not be the only one. In some instances, multi-criteria analytical approaches have been used (GTZ-HPP), however all the criteria have been related to cost. For instance, Table 3 shows the criteria and scoring weights (developed over several experts workshops) used for ranking 38 undeveloped run-of-river hydropower sites (GTZ-HPP).

Note that the location accessibility criterion was motivated by cost and investor attractiveness. In a number of reports and studies we find the issue of recognition of wider environmental and ecological ramifications of the basin's development being raised (HPP, 2004; Klimpt et al., 2002; Wescoat et al., 2000). However, to date environmental considerations remain confined to project-level impact assessments conducted mostly to service the requirements of donor agencies. For sustainable development of the basin, there needs to be a real and genuine shift in planning and implementation in which economic feasibility includes environmental costs.

Table 3
Criteria for ranking 38 undeveloped Run-of-River hydropower sites—Source (GTZ-HPP).

No.	Criterion	Weight (%)
1	Cost of energy [$/kWh]	40
2	Mean annual energy generated [kWh]	25
3	Availability of reliable hydrological data[a]	15
4	Distance to nearest grid/load center [km]	10
5	Location accessibility	10

[a] Data reliability was measured by length of hydrological record available.

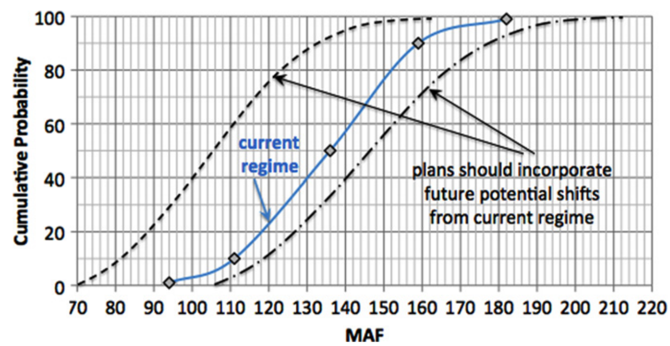

Fig. 9. Cumulative probability distribution of inflow in the western rivers during the Kharif (summer) cropping season (solid blue curve) and notional shifts in future (dashed black curves). Source: (Shams ul Mulk, 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6.3. *Plan and design for uncertainty*

The infrastructure investments needed for some key reservoir projects are currently estimated at $35 billion (EAC, 2009). Significant capital investments will also be made by the private sector in developing some of the smaller projects in the basin. As large monetary resources are committed, it is important to ensure that the eventual value obtained over the life of the systems is not adversely affected by future uncertainties. Planning and designing systems in the Indus river system based on historical norms may at best lead to missed opportunities and in the worst case to grave failures if predictions regarding variation in runoff volumes are realized.

In general, hydrological and seismological risks are particularly relevant for hydropower system planning in that basin. The hydrological risks stem from year to year variability in flows. Fig. 9 shows the cumulative probability function of inflows in western rivers of the Indus system based on historical data (solid blue line). How this curve may shape up in the future as a result of climate change is a difficult question to answer—nonetheless a very important one to consider. Recent studies have indicated that the basin is one of the most vulnerable ones in the world to climate change (Immerzeel et al., 2010).

Future shifts from historical norms are important to consider both for design guidelines (to prevent system failure such as from increased magnitudes of floods and droughts) as well as for strategic planning for storage and power generation. The unprecedented flood of 2010 in Pakistan, with estimated losses of $10 billion and 3000 MW of electric power capacity affected, serve to highlight this issue (NFRP, 2011). The historic 2010 flood, caused partial damage to both large (Ghazi Barotha, Chashma, Gomal Zam, Jinnah and Neelum–Jhelum) hydel power plants, as well as 81 micro hydropower stations. Additionally, 3233 km of transmission and distribution lines were also affected. As projects are being developed, there should be careful attention to changed climatic patterns under which the new systems may need to operate.

Related to hydrological uncertainty is the variability in actual energy production that should be factored in. Power benefits vary during dry and wet cycles, whereas for appraisal the average generation is used. Experience with Tarbela (currently the largest hydropower facility and storage dam in Pakistan) has shown that significant variations, that were not originally expected, can occur. The predicted output was considered to be broadly stable from year to year, however it has been variable in actual practice due to a variety of reasons (HPP, 2004). Planners should include consideration of this aspect in comparing and prioritizing projects. Note, that seasonal and monthly variations are expected in the snow-fed Indus river system, but the significant shifts around the expected monthly energy output have lead to energy shortages.

In a related aspect, we also find more emphasis (in planning documents) on project capacity rather than expected energy generation. For a large portfolio with several options, factoring in the energy production (instead of capacity) should be the more important measure.

In addition to better understanding the hydrological risks (at the portfolio level), seismological risks also need to be factored in since they can have significant impact in the upper Indus Basin. The historic earthquake of 2005 in the AJ&K region, and large dam failures in other basins highlight that traditional seismological safety margins need to be re-examined (Ali, 2007; Kazi, 2009).

Some of the risks can be mitigated through strategic diversification of the hydropower assets (on a sub-basin and regional basis). A diversified portfolio, as well as flexible engineering approaches (De Neufville and Scholtes, 2011), can help reduce downside risks as well as increase up-side potential. Some measures can include enhanced safety provisions, as well as provisions for up-rating capacity in the future if changed flow regimes provide opportunities for additional power generation.

Furthermore, international hydropower development and markets may provide important options for ensuring sustained energy supplies. While it may be difficult to imagine in the current geopolitical context, regional power grids and markets may develop in future decades, and it seems prudent to anticipate that possibility. Precedents, positive and mixed or problematic, are available in other basins of South Asia, e.g., between Nepal, India and Bhutan. Propositions of a South-Asian energy grid have been floated (Obaidullah, 2010), and there are reported plans for electricity trading between India and Pakistan (Tribune, 2011).

6.4. *Understand the costs and benefits of hydropower alternatives within Pakistan's overall electric power and energy portfolio*

In this paper, we have tried to understand Pakistan's hydropower development options, and have highlighted several gaps in the available data that prevent us from better understanding of the costs and benefits of the proposed system. However, our analysis, albeit essential, is only a component of a much larger analysis that is needed to understand options for meeting Pakistan's energy needs. For instance, to properly situate the costs and benefits of the hydropower system within the country's energy portfolio (e.g. to compare it against energy import options), we need to understand how to manage the demand and distribution side of the energy equation more deeply. We also need to understand the social and political feasibility of developing different energy options. For instance, if power losses due to inefficiency (NEPRA, 2011) or theft remain high, the total cost of system losses would become intolerably high with the projected population increase. The current power sector in Pakistan faces significant issues of revolving debt owed by different power producers, consumers and suppliers to each other (NEPRA, 2011), and if persistent over the long term, can severely impede development of hydropower projects.

It is also not clear whether the face-value of Pakistan's hydropower potential (60 GW) as usually quoted, or costs which have been estimated, represent the realizable hydropower potential or costs. For instance, issues with provincial royalties for energy (natural gas and copper for Balochistan, Tarbela for KP) (Qureshi, 2007) and the political opposition to projects (e.g., Kalabagh dam) makes it difficult to ascertain which of the on-paper projects will actually be developed. Furthermore, the uncertain security situation in certain areas can escalate the development costs, as well as create problems if they are not managed well politically (e.g. sabotage of natural gas pipelines) (Muneer and Asif, 2007).

In summary, we have analyzed one aspect of the energy problem, the hydropower system, in detail. There needs to be much more concerted investment into data collection, reporting, and analysis before specific policy choices and trade-offs can be evaluated.

In regards to future research, important next steps (based on availability of data) will include incorporation of cost in our analysis, and development of evaluation frameworks for ranking and prioritization of projects. Traditionally, projects are evaluated on economic metrics (monetary cost-benefit analysis, expected return-on-investment (EROI), etc.) There is now growing recognition of expanding the evaluation basis to include environmental costs that may accrue and to use more sophisticated probabilistic evaluation approaches (instead of deterministic estimates) for cases where there are significant uncertainties. In the case of the Indus Basin, degradation of its delta from past developments (TD, 2000), risks from climate change (GoP, 2010) and trans-boundary developments serve to increase the importance of enhanced evaluation approaches.

7. Conclusions

This study sheds new light on the hydropower portfolio of Pakistan, and lays the groundwork for future advanced assessments. While the focus of this work has been on the hydropower supply, we are acutely conscious of the role of demand management, loss reduction, and power sector reforms more broadly, which cut across electric power supply technologies. We have concentrated on the relative efficiency of hydropower supply alternatives vis-à-vis the full array of power distribution and demand efficiency alternatives.

For Pakistan, with its growing energy demand along with availability of water resources, development of its portion of the Indus Basin for hydropower is a necessity. There is continued (albeit slow) progress on various large projects such as on the 4500 MW Diamer-Bhasha Dam project initiated in October, 2011; and the funding agreement with the World Bank for the 4320 MW Dasu Hydropower project (Tribune, 2012) etc. However, the seemingly large level of on-going and planned development would still be insufficient for meeting the country's future needs (Qazilbash, 2005). The current plans would put per capita capacity in Pakistan at approximately 0.15 KW/person in 2030 (assuming 230 million people in 2030). This would make the per capita consumption in 2030 less than the current energy consumption in most sub-Saharan countries (which is between 0.3–1.6 KW/person (WEC, 2012)). The hydropower development plans, therefore, need to be revised to harness more of the 60 GW potential in the coming decades. The question for planning is thus not of *if* rather of *which* systems should be deployed and *how*, so that the collective system is sensitive to the environment, providing important societal needs, and responsive to future change. Given the upfront large capital expenditure required in installing these systems, the options need to be strategically considered to ensure the long-term sustainability, profitability, and continuity of the total system.

While the details of our work have been focused on Pakistan's hydropower portfolio, this work is more generally an illustrative example of a multi-dimensional, systems-level analysis of the hydropower portfolio in a largely under-developed basin. Currently, there is significant untapped hydropower potential in many basins in Africa, Latin America and Asia (Bartle, 2002). Policy makers engaged in planning similar developments in such basins can use this analytical blue-print for obtaining insights regarding possible strategy options that would not be visible from an individual project-centric approach, or an approach that is biased either toward portfolios of large or small projects.

Acknowledgment

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Appendix

See Table A1 below.

Table A1
Canal names (sorted in descending order of total hydropower potential).

Rank	Canal name	Rank	Canal name
1	'Swat canal'	33	'Lower Bari Doab canal'
2	'Rohri canal'	34	'Ravi/ Sidhnai Sidhnai canal'
3	'Chenab/Marala Marala Ravi link canal'	35	'Chenab/Trimmu Rangpur canal'
4	'C.J. link canal'	36	'Machai canal'

Table A1 (*continued*)

Rank	Canal name	Rank	Canal name
5	'Upper Chenab canal'	37	'Pak Pattan canal'
6	'B.S. link-1 canal'	38	'Gujrat Branch canal'
7	'Pehur high level canal'	39	'Ravi/ Balloki B.S. main link'
8	'Chenab/Khanki lower Chenab canal'	40	'Thal canal'
9	'Jhelum/Mangla upper Jhelum canal'	41	'Nara canal'
10	'L.B.D.C'	42	'Muzaffargarh canal'
11	'Indus/Chashma Chashma Jhelum link canal'	43	'Upper Gogera'
12	'Ravi/ Balloki lower Bari Doab Canal'	44	'Chenab/Trimmu Haveli canal'
13	'Chenab/Panjnad Panjnad canal'	45	'Lower Chenab canal'
14	'Chenab/Khanki Upper Gogera branch'	46	'Chenab/Trimmu Trimmu-Sidhnai link canal'
15	'Indus/Taunsa D.G. Khan canal'	47	'Pakpattan'
16	'T.P. link canal'	48	'Chenab/Qadirabad lower Chenab canal feeder'
17	'Ravi/ Balloki B.S. link II'	49	'Jhang branch'
18	'Chenab/Marala B.R.B.D link canal'	50	'Sutlej/Sulemanki eastern Saddiqia canal'
19	'TP link canal'	51	'Jhelum/Mangla Gujrat Branch Canal'
20	'B.R.B.D link canal'	52	'Ravi/ Balloki Depalpur canal'
21	'Indus/Jinnah Thal main line lower canal'	53	'Ravi/ Balloki B.S. link I'
22	'Sutlej/Sulemanki Pak Pattan canal'	54	'Indus/Chashma Chashma right bank canal'
23	'Bambanwala upper Chenab canal'	55	'Lower Jhelum canal'
24	'Chenab/Qadirabad Qadirabad Balloki link canal'	56	'Jhang Branch canal'
25	'Chenab/Marala Chenab/upper Chenab canal'	57	'Indus/Chashma Chasma Jhelum link canal'
26	'Indus/Taunsa Muzaffargrah canal'	58	'Indus/Jinnah Thal canal'
27	'Jhelum/Rasul lower Jhelum canal'	59	'Koranga Fazaal shah feeder'
28	'Sutlej/Islam Mailsi canal'	60	'Sutlej/Sulemanki P.I link'
29	'Sutlej/Islam Bahawal canal'	61	'8-R distributary RD 6+000'
30	'Jhelum/Rasul Rasul Qadirabad link'	62	'Sutlej/Sulemanki Fordhwah canal'
31	'Abbasia canal'	63	'Sutlej/Islam Qaimpur canal'
32	'S.M.B link'		

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