Article

Free Discharge of Subsurface Drainage Effluent: An Alternate Design of the Surface Drain System in Pakistan

Muhammad Ali Imran [1], Jinlan Xu [1], Muhammad Sultan [2,*], Redmond R. Shamshiri [3,*], Naveed Ahmed [4], Qaiser Javed [5], Hafiz Muhammad Asfahan [2], Yasir Latif [6], Muhammad Usman [7] and Riaz Ahmad [8]

1 School of Environmental and Municipal Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China; maimran@xauat.edu.cn (M.A.I.); xujinlan@xauat.edu.cn (J.X.)
2 Department of Agricultural Engineering, Bahauddin Zakariya University, Multan 60800, Pakistan; hmasfahan@gmail.com
3 Department of Engineering for Crop Production, Leibniz Institute for Agricultural Engineering and Bioeconomy, 14469 Potsdam-Bornim, Germany
4 Key Laboratory of Mountain Surface Process and Ecological Regulations, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China; naveedahmed@imde.ac.cn
5 School of the Environment and Safety Engineering, Jiangsu University, Zhenjiang 212013, China; qjaved@ujs.edu.cn
6 Institute of Computer Sciences, Czech Academy of Sciences, 18200 Prague, Czech Republic; latif@cs.cas.cz
7 Institute for Water Resources and Water Supply, Hamburg University of Technology, Am Schwarzenberg-Campus 3, 20173 Hamburg, Germany; muhammad.usman@tuhh.de
8 College of Engineering, Nanjing Agricultural University, Nanjing 210031, China; riaz@cau.edu.cn
* Correspondence: muhammadsultan@bzu.edu.pk (M.S.); rshamshiri@atb-potsdam.de (R.R.S.); Tel.: +92-333-6108888 (M.S.)

Abstract: In Pakistan, many subsurface (SS) drainage projects were launched by the Salinity Control and Reclamation Project (SCARP) to deal with twin problems (waterlogging and salinity). In some cases, sump pumps were installed for the disposal of SS effluent into surface drainage channels. Presently, sump pumps have become dysfunctional due to social and financial constraints. This study evaluates the alternate design of the Paharang drainage system that could permit the discharge of the SS drainage system in the response of gravity. The proposed design was completed after many successive trials in terms of lowering the bed level and decreasing the channel bed slope. Interconnected MS-Excel worksheets were developed to design the L-section and X-section. Design continuity of the drainage system was achieved by ensuring the bed and water levels of the receiving drain were lower than the outfalling drain. The drain cross-section was set within the present row with a few changes on the service roadside. The channel side slope was taken as 1:1.5 and the spoil bank inner and outer slopes were kept as 1:2 for the entire design. The earthwork was calculated in terms of excavation for lowering the bed level and increasing the drain section to place the excavated materials in a specific manner. The study showed that modification in the design of the Paharang drainage system is technically admissible and allows for the continuous discharge of SS drainage effluent from the area.

Keywords: surface drain system; design; drainage effluent; Pakistan

1. Introduction

Waterlogging and salinization issues (typically referred to as twin problems) elevate due to seepage from unlined canals, flooding of inferior quality groundwater, and practicing poor techniques for irrigating the land [1,2]. Because of the aforementioned twin problem, a significant proportion of the crop yield decreases in waterlogged areas worldwide due to the uplifting of anaerobic conditions and the growth of hydrophilic weeds, which develop nutrient deficiency in the root zone [3–5].

Unfortunately, in Pakistan along the Indus Basin Flood Plains (IBFP), approximately 7 million hectares (ha) of the land are affected by waterlogging and salinization. Nearly

half of the waterlogged area (~3 million ha) is located in Punjab, mainly responsible for regulating ~90% of the country's food chain [1,2,6]. This might be due to this area comprising the largest irrigation structure run by gravity, which is regrettably unlined. However, the unlined system contributes a significant portion of groundwater replenishment by seepage, which is the second most crucial freshwater source. However, in some areas of Pakistan, the groundwater level is already close to the soil bed, especially the areas close to the IBFP. This leads to the conversion of precious fertile land into toxic saline unculturable land. Some of the problems associated with waterlogging and salinity in the farms and lands of Pakistan are demonstrated in Figure 1. However, keeping in mind that various efforts and approaches have been actively employed to eliminate the twin evils. For instance, management practices related to soil and crop [7] drainage networks in either the surface or subsurface [8–11] and raising the soil bed [12–14]. A significant improvement has been documented in the literature due to the consideration of management practices, as mentioned earlier [8–11].

Figure 1. Example of farm and land problems associated with waterlogging and salinity in Pakistan showing: (**a**) improper control of waterlogging and salinity in low-lying areas of Sindh, (**b**) the reduction of essential nutrients including N, P, and K, and an increase of minerals such as Fe and Mn in the soil, and (**c,d**) the mismanagement of surface water resources and salinity causing water with the total dissolved solids (TDS) over 1500 in the Thatta and Sindh districts. (Source: Adaptive AgroTech Consultancy).

Similarly, the government of Pakistan (GOP) initiated mega-projects, such as the Salinity Control and Reclamation Project (SCARP) wells between the 1960s and 2000s, whereby the vast number of tubewells (vertical drainage system) were installed to maintain the sustainable groundwater table for crops [15]. The purpose of SCARP tubewells was to lower the water table, leaching the salts by intensified irrigation, and to ensure the comfort zone for crop production [16,17] by simply pumping the water from the ground and disposing of it into a well-lined drainage channel. From here, the gravity force was employed for conveying the water into nearby streams. It was reported that about 8 million ha of land were reclaimed at a cost of USD 2 billion [18]. However, later, it was recognized that SCARP tubewells were not a promising option due to the massive operational costs, maintenance costs, and the country's socioeconomic instability. An alternative option preferred by farmers is the privatization of tubewells to obtain good-quality shallow groundwater [1,18].

Another sustainable solution for reclaiming the wetlands is developing surface or subsurface drainage structures for carrying away the water from the waterlogged areas. In this regard, the World Bank releases the funds to line the water conveying channels, particularly watercourses and farmers' field channels, for enhancement of the culturable land [2,19]. Surface or subsurface drains merely collect the water below the root zone through collectors/laterals and drain it to nearby sumps or reservoirs. The sumps or reservoirs are constructed deep below the surface or subsurface channels in order to carry a significant amount of water. When the sumps get filled, they are emptied by employing a pumping unit to pump the water from the sumps or reservoirs and outfalls into the surface drains, usually constructed bottom-up from the subsurface drains. In this regard, subsurface drains and laterals work as water collecting entities from waterlogged areas, whereas pumping units and surface drains operate as water conveying entities from one locality to another locality [3,20–22]. Fourth Drainage Project (FDP) is one of the leading

projects of the World Bank's twin evil removal initiative, which was installed in Faisalabad. In this regard, the literature documented a significant improvement of groundwater quality and reclamation of salinity from the agriculturable land [23,24]. However, electricity shortfalls and extensive pumping make it dysfunctional overall. Therefore, researchers need to further explore alternative options that could be energy-efficient and economical. In order to do so, there would be technical modifications required on the FDP site. It could be done by redesigning the surface drains and employing gravity for conveying the water from the sumps to the surface drains. Alternatively, the latest techniques of GIS and geophysics have been considered for selecting suitable basins with freshwater aquifers for the formation of an efficient exploration strategy [2]. However, redesigning the surface drainage network still seems necessary.As such, various design parameters need to be taken into account, including permissible velocity, side slope, and bedslope. Permissible velocity for clear and muddy water was calculated by Fortier et al. [25] at 0.45 and 0.75 m/s, respectively. Ritzema et al. [26] stated that for fine sand and loam, the velocity ranges from 0.1 to 0.3 m/s and from 0.3 to 0.6 m/s, respectively. The government of Pakistan (GOP, 1993) [27,28] concluded that for fine sand, the maximum velocity is 0.45 m/s, and for sand and sandy loam the maximum velocity is 0.75 m/s. Deshmukh et al. [29] concluded that the time required for water to flow from a section of channel (time of flow) and the flow velocity can be affected by a resectioning of the drain, and overland flow time can be increased by raising the cross-section of the drain. The side slope should be checked for stability against erosiveness, under wet conditions, and against the sudden lowering of water levels on the cessation of flows. Steep side slopes are desirable to save excavation as well as the land area occupied. However, the steeper side slope can only be used in cohesive and well-aggregated soils or where bank protection is provided. The GOP (1993) [27] have recommended following side slope ratios also called horizontal to vertical distance (H:V) for sand, loam, and clay, which are 3:1, 2:1, and 1:1, respectively. According to the 1984 United States Bureau of Reclamation (USBR) [30] guide, the value of Manning's roughness coefficient 'n' lies between 0.025 and0.030. The value of Manning's roughness coefficient 'n' reflects the net effect of all factors causing the reduction of flow. As a general guide, berm width is taken as twice the channel depth with a minimum of 5 to 10 feet. Tipton and Kalmbach et al. [31–33] recommended a berm width of 4, 6, and 10 feet for channels having a design depth (D) of <4, 4–6, and >6 feet, respectively. The minimum berm width is taken equal to the drain design depth (D) or the depth of cut (H). The berm may be increased when higher velocities tend to enlarge the section, or the drain passes through marshy or unstable soils.

At present, the subsurface drains outfall their effluent into the sump via drainage collector pipes, from which water is pumped and carried through shallow surface disposal channels, and ultimately outfalls into surface drains. Lackey K. A. [34] reported that pumping stations involve a complex balancing of several critical priorities, including reliable long-term service, operations and maintenance considerations, capital cost, and constructability. An investigation of the current situation reveals that pumping units, electricity transmission lines, transformer devices, and other instrumentation have been pilfered, and that there is a shortage of budget and electricity for operating such systems. Okarwy et al. [35] also investigated the impact of shallow surface drainage, rather than a conventional design. The design is more economical and adoptable for economically unstable countries such as Pakistan because it excludes the requirement of sump and pump accessories.

In the present study, we proposed a redesigned consideration for the Paharang drainage network that could receive drainage effluents under the gravity flow from sumps to surface drains. The idea is to lower down the beds of surface drains from the corresponding sump beds to develop the hydraulic gradient. In this regard, active surface drain beds are excavated further to achieve the prerequisite depth, so that drainage collectors directly dispose the collected water (via perforated pores) from waterlogged areas into the surface drains under the action of gravity. In addition, the study also determines

the additional design requirements for the surface drains' cross-section and subsurface drainage units. In order to achieve the subsurface gravity flow, the modified bed level of surface drains was set below the drainage collector. The required surface drain bed level is achieved by deepening the existing bed level and/or decreasing the bed slope. The proposed design was completed after many successive trials. Interconnected MS-Excel worksheets were developed to optimize and redesign the L-section and the X-section of the proposed approach.

2. Data and Methods

2.1. Study Area

The Paharang drainage network (PDN) lies in the southwestern part of Faisalabad city (longitude 73°05′1.68″ to 73°11′27.27″ N Latitude 31°34′38.50″ to 31°42′00″ E). It has a drainage area of 560 km^2. The project area contains a wide range of coarse to medium soil textures. It has an overall length of 63 km (39.15 miles). The uniform slope of 1:5000, which is generally prevalent in the area, was adopted from the source to the receiving body, the Chakbandi main drain. Moreover, eight branch/tributary drains contribute to the main drain. Figure 2 demonstrates the map and schematic of the FDP and the PDN, respectively. Existing blueprints of the PDN, which include maps, L-sections, X-sections, sump pumps along the collector's outfall, discharge in drains, hydraulic structures, water table depth, and soil type along the drain, were collected from the Punjab Irrigation Department (PID) in Faisalabad.

2.2. Computation of Required Bed Level

To discharge SS outflow into the surface drain network by the action of gravity, it is mandatory to maintain a downward slope between the SS and the surface drainage channels. It is merely done by lowering the bed of the surface drain from the level of the SS drainage collector pipe. Elevation of the SS drainage collector pipe at the surface drain (EL_C) is calculated as:

$$EL_c = CL - (D \times S) \tag{1}$$

where D is the distance from the sump to the surface drain; S is the slope of the collector drain, and CL is the existing SS drainage collector level at sump. EL_C is calculated to determine the required bed level of the surface drain. The minimum water level in the surface drain is calculated as:

$$WL_{LF} = EL_C - SF \tag{2}$$

$$BL_{RV} = WL_{LF} - d_{LF} \tag{3}$$

where WL_{LF} is low-flow water level (minimum level) in the surface drain; SF is the safe margin (0.3 to 0.5 m); BL_{RV} is the revised drain bed level, and d_{LF} is the flow depth at low flow. The existing and proposed design of the drain section, along with the water level for both the high/maximum (WL_{HF}) and low/minimum (WL_{LF}) flow conditions, are described in Figure 3. An extended SS drainage collector pipe receives water from the existing SS drainage network and directly disposes of into the surface drain.

All the sumps have the potential to operate with the proposed extended drainage collector pipe facility to outflow the SS water into the surface drainage channel because of gravity. Drainage collector pipes discharge SS water freely when the surface drain is operating at a low/minimum flow. However, this free outfall is hampered temporarily when the water level in the surface drain reaches the level of the drainage collector pipe, particularly during a storm or a high-level surface runoff. In turn, the drainage collector pipe ceases to dispose of the SS outflow into the surface drainage for a few hours/days. A self-closing valve/lid is thus mounted at the outlet of the drainage collector pipe to block/stop the backward flow of the surface drain water into the conventional sump via the drainage collector pipe.
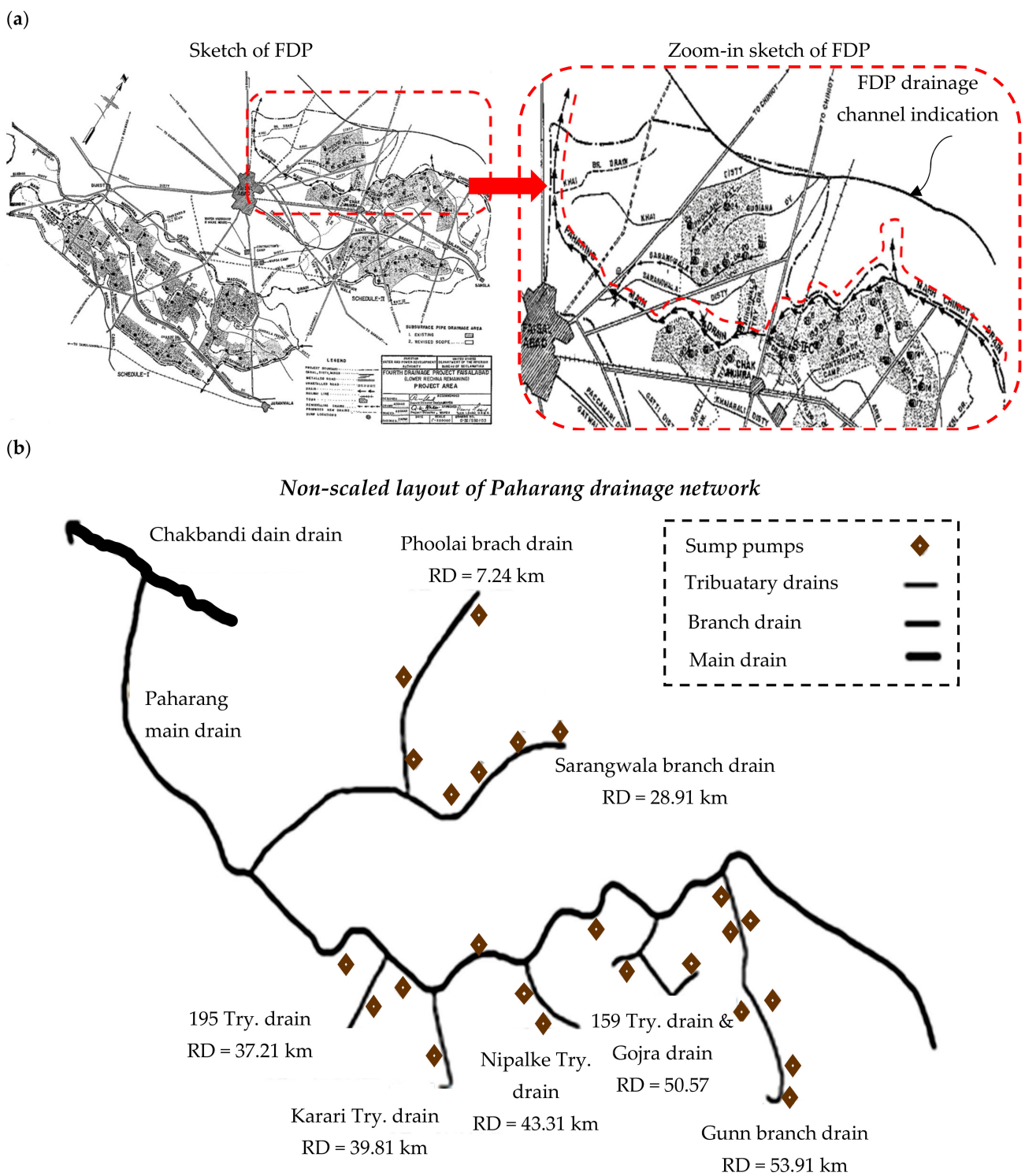
(**a**)

(**b**)

Figure 2. (**a**) Layout map of the Fourth Drainage Project (FDP), and (**b**) non-scaled layout of drainage and location of sump pumps in the Paharang drainage network (PDN).
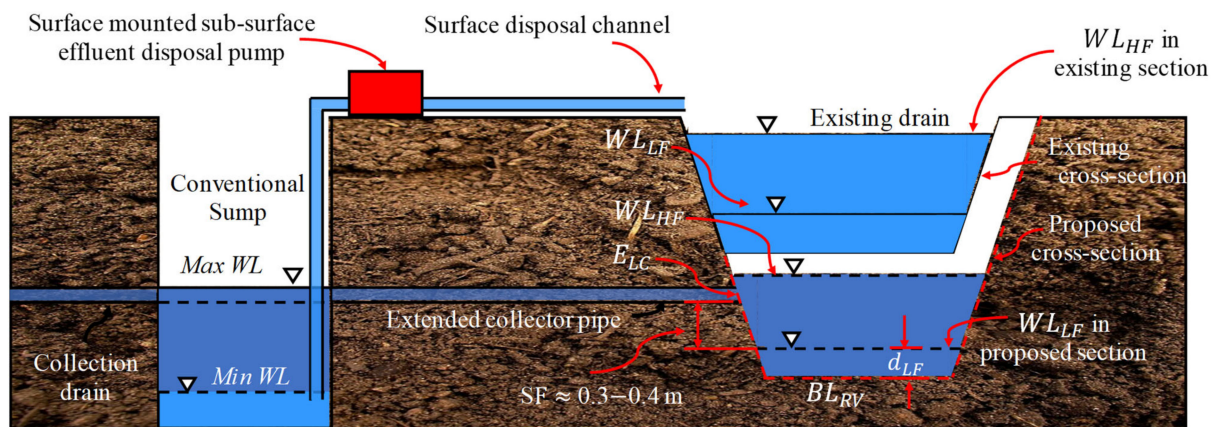
Figure 3. Schematic arrangement of extended pipe collector from sump to surface drain.

2.3. Redesign of Surface Drain L-Section

To ensure the gravity flow of SS effluent; surface drainage channels needed to be redesigned; lowering the surface drain bed and water level by 1 to 2 m. This was achieved by changing the existing bed slope of drains S_1:1 (H:V) to a smaller value S_2:1 ($S_2 > S_1$) by such an extent that the requisite bed level was achieved over the selected distance D, as shown in Figure 4.

$$\Delta BL_B = EB_{LB} - \frac{D}{(S_2 - S_1)} \qquad (4)$$

$$BL_B = BL_A + \frac{D}{S_2} \qquad (5)$$

where BL_A and BL_B are bed levels at A and B, respectively, D is the distance from point A to point B, EB_{LB} is the existing bed level at B, and ΔBL_B is the change in the bed level at B. The slope beyond point B may be either kept the same as the existing slope or changed to accomplish further lowering. This was repeated until the bed level of all main/branch/tributary drains was achieved as required at all the collector outfall locations.
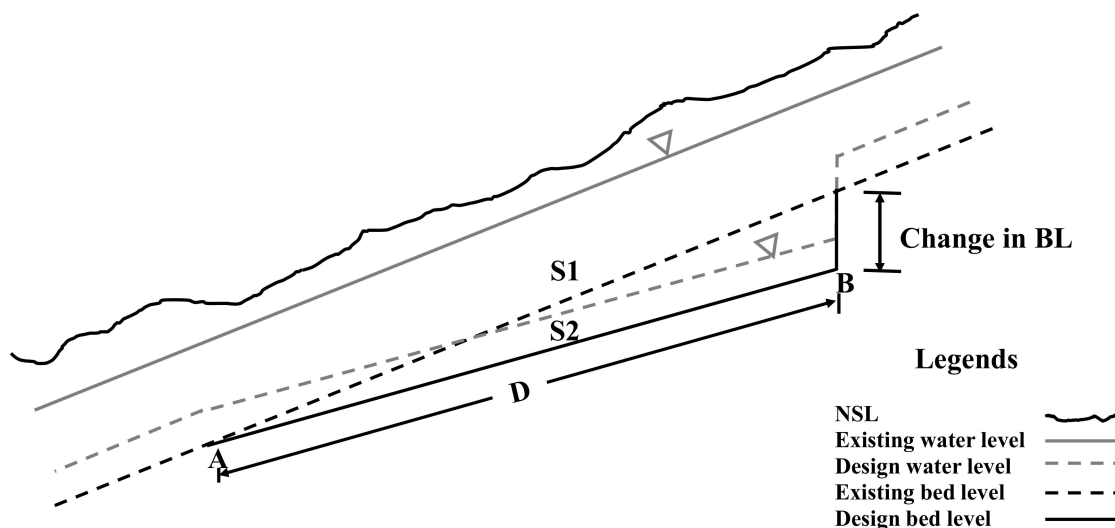

Figure 4. Typical schematic diagram of longitudinal section.

2.4. Flow Section Design

Manning's formula was used to redesign the cross-section of the proposed drains using the existing drains roughness coefficient (n) and side slope values. The drain cross-section at low flow and high flow was achieved by changing the values of bed width (B), and revised bed slope (S_2). The point where the bed slope of the surface drainage channel changes is represented as point A in Figure 4. A compromise design was achieved for all main, branch, and tributary drains and all their reaches by endorsing the prime efforts on the redesigning of the bed level of the Paharang main drain (surface drain). The simultaneous design was carried out using the Excel workbook. Interconnected worksheets were designed for each main, branch, or tributary drain. During the redesign, the drain top width was taken as a design constraint, such that the row for the revised cross-section is not varied too much from the existing row of the drain.

2.5. Flow Section Design

Design continuity of the outfalling drain (i.e., branch drain) and receiving drain (i.e., main drain) was ensured by employing the following conditions:

$$BL_O \geq BL_R \text{ and } WL_{LFO} \geq WL_{LFR} \text{ and } WL_{HFO} \geq WL_{HFR}$$

where BL is the bed level and WL is the water level. The subscripts O and R stand for the outfalling and receiving drains, respectively, whilst LFO and HFR stand for the low flow in the outfalling drains and the high flow in the receiving drains, respectively.

3. Results and Discussion

3.1. Required Bed Lowering and Design Continuity

Extended SS drainage collector pipe levels were calculated with slope ranges between 0.0007 and 0.0013. Low-flow depth was measured anddepends upon the corresponding channel section. Figure 4 shows that the outfall levels of the proposed extended drainage collector pipes are well below the existing bed level. Hence, it was required to lower the bed level of the surface drainage channel from 2.29 to 4.1 m, which includes the level of the extended drainage collector pipe, depth of discharge, and safe margin for the free disposal of the sumps effluent. Overall, 11 out of 24 reaches of the surface drainage channels were required to lower the bed level by about 3 m or more from the outfall of extended drainage collector pipe.

The required bed level of the surface drain (main drain) depends upon outfall levels of the SS drainage pipe collectors as well as the outfall levels of branch drains. Contrastingly, the bed levels of the branch and tributary drains depend upon the SS drainage pipe collector levels and their outfall, the bed level of the surface drain (main drain), and the receiving body. Thus, the selection of any parameter for the upstream drain affects the design parameters of all other higher-/lower-order surface, branch, and tributary drains accordingly. This requirement was resolved by many successive trials. The results of the final selected trial are presented in Table 1.

Table 1. Design continuity of the Paharang main drain.

Drain	RD (km)	BL_O (m)	BL_R (m)	WL_{HFO} (m)	WL_{HFR} (m)	WL_{LFO} (m)	WL_{LFR} (m)
Sarangwala Branch	28.91	178.5	178.2	180.6	180.6	179.7	179.2
195 Try. Drain	37.21	181.7	180.4	183.1	182.7	182.0	181.2
Karari Try. Drain	39.81	181.6	180.7	183.2	183.1	181.9	181.7
NIPALKE Try.	43.31	181.5	181.1	183.8	183.5	182.3	182.0
159 Try. Drain	50.57	184.0	182.8	184.8	183.5	184.5	183.6
Gojra Drain	50.57	184.0	182.8	184.7	184.5	184.3	183.6
Gunna Branch	53.91	183.5	183.2	184.7	184.4	184.2	184.0

3.2. Redesigned Longitudinal Sections

The whole length of the Paharang main drain was divided into 17 reaches, in which 7 branches/tributary drains and 4 SS drainage pipe collectors were directly outfalling into the main drain. Based on the proposed configuration of the longitudinal section, this needed to be redesigned. In the first trial, it was ensured that the bed level of the main drain remained lower than the outfall levels of the extended drainage collector pipes. From this trial, it was observed that the bed level of Paharang main drain at the outfalling point was lower than the receiving Chakbandi main drain, which resulted in non-uniformity and free flow of the hydraulic structure. Alternatively, it seemed that the design did not need any alteration up to the reduced distance (RD) of 7.16 km because there was no interconnected branch/tributary drain and no drainage pipe collector outfall. Another significant purpose to keep the section as per the existing design was the large aqueduct of Waghwal (Jhang BC and Mudhuana) laid in this section at the RD of 7.097 km. Undoubtedly, lowering the bed level of the aqueduct could be too expensive and problematic. In the second trial, the bed level of the main drain was started lower from the RD of 7.160 km. However, at the bed slope of 1:5000, the required level could not be achieved; also, it was not possible to increase the depth more than the downstream portion, as the bed level was lowered more than the first reach. In the third trial, from the reach at the RD of 7.160 to the RD of 53.950 km, the channel bed slope was decreased up to 1:8000. The required bed level was achieved, but the capacity to carry the discharge of the channel reduced as the bed slope decreased. Therefore, the channel bed width was increased to pass the design discharge. The complete proposed design of Paharang main drain along with existing design are described in Figure 5. All sumps can outfall at gravity flow during the low-flow conditions and the reach-wise design of the parameters with low-flow water levels are given in Table 2.
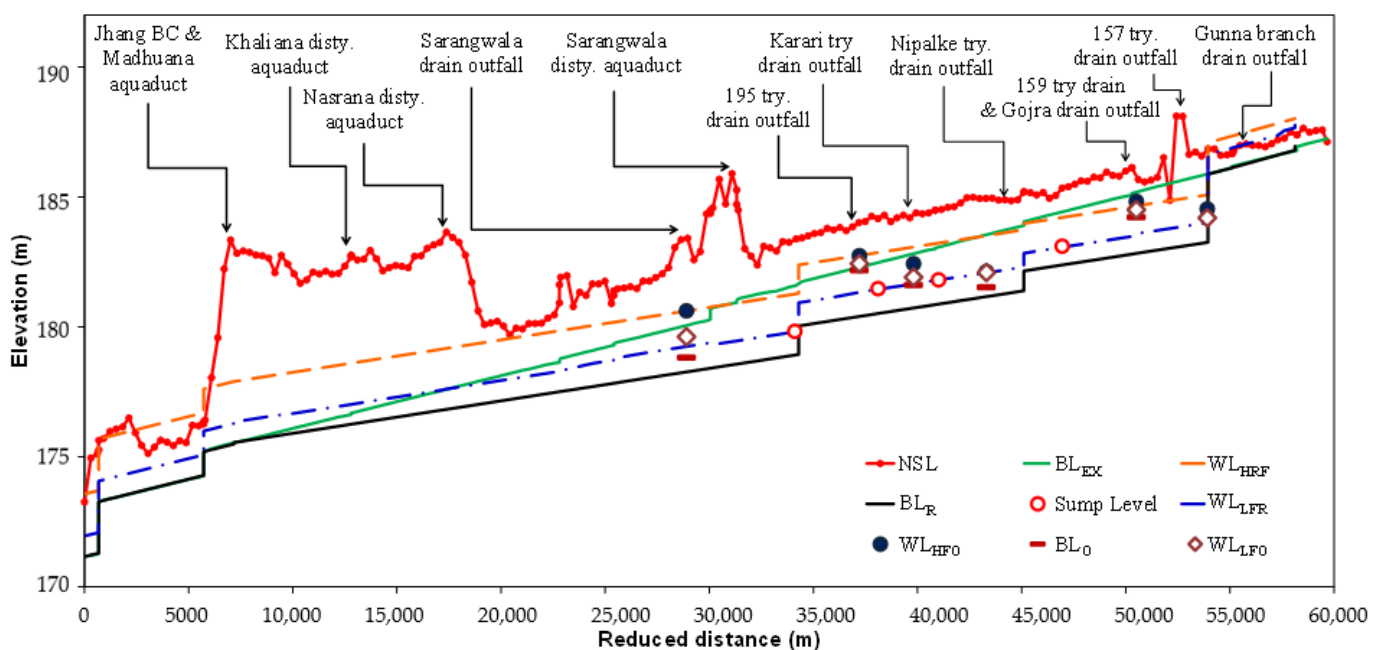

Figure 5. Proposed L-section of the Paharang main drain.

<div align="center">Table 2. Reach-wise design for Paharang main drain.</div>

Reach (km)	B (m)	dHF (m)	BS H:1V	V (m/s)	High Q (m³/s)	dLF (m)	Low Q (m³/s)
0–7.16	11.28	7.9	5000	0.52	18.58	0.74	2.72
7.16–9.14	15.1	7.7	8000	0.42	18.39	0.74	2.69
9.14–12.80	14.32	7.7	8000	0.42	17.50	0.76	2.60
12.80–17.04	14.02	7.7	8000	0.42	17.16	0.77	2.58
17.04–22.55	13.72	7.7	8000	0.41	16.82	0.78	2.58
22.55–25.42	10.82	7.7	8000	0.40	13.59	0.90	2.55
25.42–30.05	9.30	7.7	8000	0.40	11.92	0.98	2.49
30.05–31.09	7.77	7.7	8000	0.39	10.25	0.88	1.81
31.09–34.14	7.62	7.7	8000	0.38	10.08	0.89	1.81
34.14–40.84	5.33	7.7	8000	0.36	7.61	0.93	1.38
40.84–45.11	4.72	7.7	8000	0.36	6.96	0.91	1.22
45.11–50.29	4.72	6	8000	0.32	4.30	0.68	0.74
50.29–53.95	3.66	6	8000	0.30	3.57	0.68	0.57
53.95–57.30	6.10	4	4500	0.35	3.40	0.76	0.57
57.30–58.12	4.57	4	4500	0.34	2.63	0.87	0.57
58.12–59.65	3.05	3.5	4500	0.30	1.47	0.87	0.57

3.3. Redesigned Cross-Section

There were six sites selected randomly to represent the different reach of length for showing the existing and proposed design of the cross-section of the Paharang main drain, presented in Figure 6. In the proposed design, the right bank of the channel was kept as the same design in most of the reaches, because it would be difficult and expensive to shift the service road and dowel. Therefore, the left side of the channel was used to increase the bed width, because extra berm width was available on the left side for future extension. However, for some reaches after the RD of 34.140 km, it became necessary to shift the dowel and service road to maintain the berm width required for the proposed design. However, there was no paved service road in these reaches. In the typical cross-section design of both the main and sub drains, the side slope of the channel was used at 1:1.5, and for the spoil bank, 1:2 inner and outer bank slope was used. In the plots of the cross-section channel (Figure 6), the side slope may not look perfect because of the unequal horizontal and vertical scaling, but in the whole design, its value was taken as 1:1.5.

In the remodeled section from the RD of 7.160 km to the RD of 53.950 km, a mild channel slope of 1:8000 was used, which reduced the discharge capacity of the drain. Therefore, passing the design discharge at the mild bed slope required a larger channel section. Channel capacity can be increased by increasing depth and bed width. Depth was increased to attain the required bed level. Thus, keeping in mind the relation of $B/d = 2$, the bed width was increased to increase the discharge capacity of the drain. As the bed width increased, the top width also increased. At the start of the tail side, increase in the top width was managed with extra width available for future extension. However, in the next section towards the head side, the extra berm was not enough. Therefore, an additional row was required for the proposed design. Similarly, the bed level difference was also increasing from tail to head, which caused an increase in the row. Important features for the proposed design cross-sections presented in the Table 3.
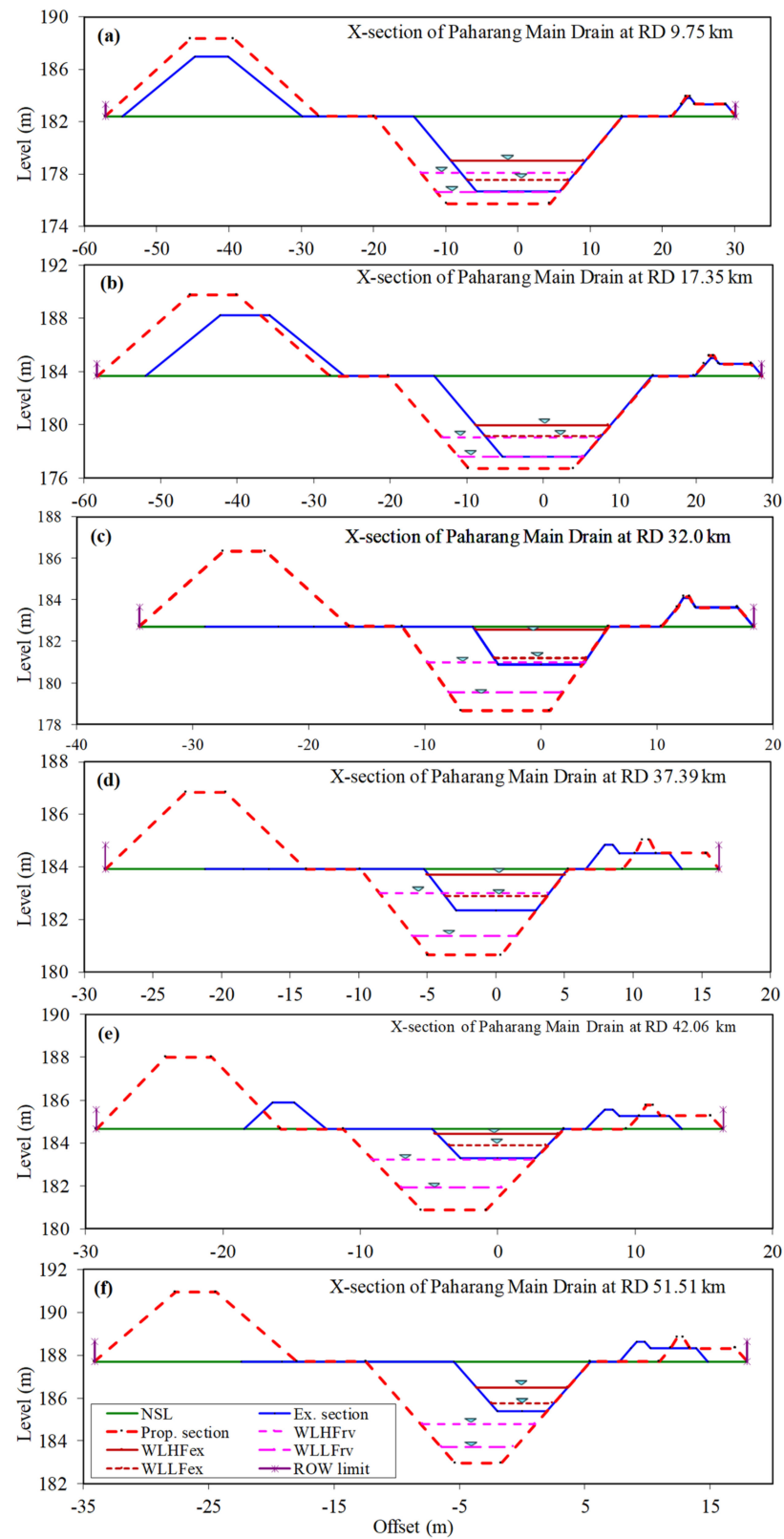
Figure 6. Cross-section design of (**a**) relative distance (RD) of 9.750 km, (**b**) RD of 17.350 km, (**c**) RD of 32.000 km, (**d**) RD of 37.390 km, (**e**) RD of 42.060 km, and (**f**) RD of 51.510 km on the Paharang main drain.

Table 3. Features of design cross-section of the Paharang main drain.

RD (km)	NSL (m)	Existing Bed Level (m)	Design Bed Level (m)	WLHF$_{RV}$ (m)	WLLF$_{RV}$ (m)	WLHF$_{EX}$ (m)	WLHF$_{EX}$ (m)	Additional ROW (m)	
								Left	Right
7.62	182.91	175.98	175.47	177.82	176.39	178.32	177.07	0	0
9.75	182.41	176.65	175.73	178.08	179.68	179.0	177.54	2.34	0
13.72	182.93	177.08	176.23	178.58	177.13	179.43	177.64	3.59	0
17.35	183.65	177.59	176.69	179.04	177.60	179.94	179.15	60.32	0
19.81	180.21	178.15	176.99	179.34	177.60	179.88	179.17	6.34	0
26.82	181.75	179.62	178.15	180.35	178.98	181.08	181.06	1.06	0
32.00	182.71	180.89	178.65	181.0	189.05	182.56	181.19	4.09	0
37.39	183.91	182.34	180.64	182.99	178.17	183.69	182.90	7.27	2.68
42.06	184.65	183.29	180.87	183.22	181.36	184.41	183.86	10.77	2.99
49.07	185.95	184.91	182.66	184.49	18.32	185.82	185.21	13.85	0
51.51	187.69	185.39	182.95	184.78	183.71	186.49	185.76	11.69	10.3

To lower the bed level and redesign the cross-section of the PDN, it was necessary to calculate the earthwork in terms of excavation, and to dump the excavated materials in a specific manner. For the proposed design, 1435 m^3 and 1030 m^3 of earthwork were required for the Paharang main drain and its branch/tributary drain, respectively.

3.4. Modification in Hydraulic Structures

Mainly, there are three types of hydraulic structures along the main drain that are bridges, aqueducts, and water coarse crossings. Because of the excavation, in terms of lowering the bed level of the drain, the stability of the structure reduces as the foundations of the supporting piers are exposed. To protect the structure and foundation's stability, one must either increase the depth of the foundation by providing a pad (expensive solution) or line the section around the structure to increase the stability and remove the risk of erosion. Both solutions can be adopted, as the proposed L-section design of the main drain shows that the change in bed level is increasing towards the source point. Thus, the proposed design can be divided in two sections at the RD of 25.910 km; at this point, the difference between the existing and proposed bed levels was 1.57 m. In this section, the exposure of the foundation was less, so the section was lined around the structure. In the second section after the RD of 25.910 km, the bed level difference was more. Therefore, the foundation depth can be increased by providing a pad below the foundation, as shown schematically in Figure 7 (left). There were three aqueducts lying in the redesigned section of the Paharang main drain. Table 4 describes the details of the changes made with respect to the bed level. In the cross-section design at the proposed bed level, the top width increases because of an increase in the bed width. Therefore, it causes an increase in aqueduct length and change in bed level and water level that are explained by the schematic, proposed design of the aqueduct in Figure 7 (right).
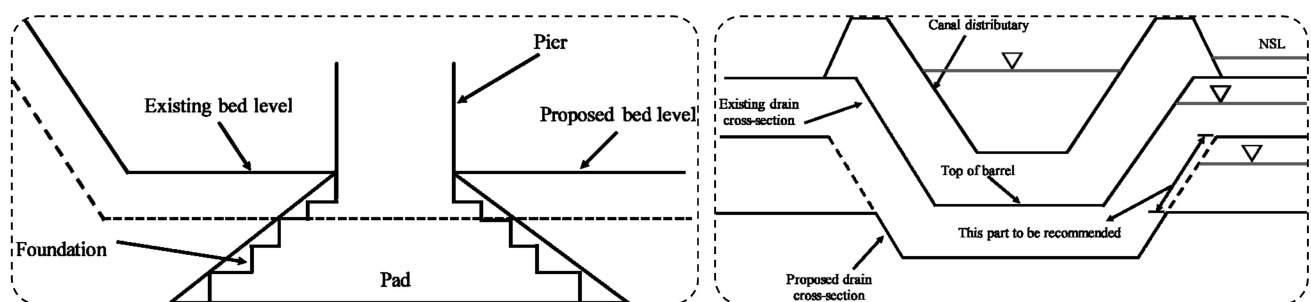

Figure 7. Schematic diagram of the pad design (**left**) and the aqueduct with the proposed design (**right**).

Table 4. Difference in design bed level (DBL) of the aqueduct.

Name	RD (km)	Existing DBL (m)	Proposed DBL (m)	Difference in DBL (m)
Aquaduct of Khaliana	12.809	176.68	176.26	0.43
Aquaduct of Nasrana	17.034	177.52	176.78	0.74
Aquaduct of Sarangwala Disty.	31.320	180.93	178.56	2.36

4. Conclusions

An alternate design of the Paharang drainage system was evaluated that can receive gravitation discharge of subsurface drainage effluent. A model based on Microsoft Excel was developed to complete the design. The proposed design was achieved by lowering the bed level and decreasing the drain bed slope. As the bed level and low-flow water level of the surface drain become lower than the subsurface drainage collector pipes, the water can discharge freely into the surface drain under gravity at all times. The present constraints related to budget, electricity, law and order, theft of sump pump parts, etc. would thus become irrelevant. Therefore, the subsurface drainage system can operate uninterrupted throughout the year. The cost related to operating the pumping unit in terms of electricity/fuel, required labor, and maintenance can also be reduced. The redesign of the Paharang main drain to admit free flow may be adopted after further economic and structural analysis. In the future, subsurface drainage projects should be designed to ensure gravity outflow into surface drains by deepening the flow section of surface drains.

References

1. Qureshi, A.S.; McCornick, P.G.; Qadir, M.; Aslam, Z. Managing salinity and waterlogging in the Indus Basin of Pakistan. *Agric. Water Manag.* **2008**, *95*, 1–10. [CrossRef]
2. Qureshi, A.S. Groundwater Governance in Pakistan: From Colossal Development to Neglected Management. *Water* **2020**, *12*, 3017. [CrossRef]
3. Cannell, R.Q.; Belford, R.K.; Gales, K.; Dennis, C.W.; Prew, R.D. Effects of waterlogging at different stages of development on the growth and yield of winter wheat. *J. Sci. Food Agric.* **1980**, *31*, 117–132. [CrossRef]
4. Liu, H.; Li, M.; Zheng, X.; Wang, Y.; Anwar, S. Surface Salinization of Soil under Mulched. *Water* **2020**, *12*, 3031. [CrossRef]
5. Mdrpk, D. *Operation Updates Report Pakistan: Monsoon Floods*; IFRC: Islamabad, Pakistan, 2020; pp. 1–21. Available online: https://reliefweb.int/sites/reliefweb.int/files/resources/MDRPK019du1.pdf (accessed on 9 March 2021).
6. Hocking, P.J.; Reicosky, D.C.; Meyer, W.S. Effects of intermittent waterlogging on the mineral nutrition of cotton. *Plant Soil* **1987**, *101*, 211–221. [CrossRef]
7. Manik, S.M.N.; Pengilley, G.; Dean, G.; Field, B.; Shabala, S.; Zhou, M. Soil and Crop Management Practices to Minimize the Impact of Waterlogging on Crop Productivity. *Front. Plant Sci.* **2019**, *10*, 140. [CrossRef]

8.   Estimating Long-Term Regional Groundwater Recharge for the Evaluation of Potential Solution Alternatives to Waterlogging and Salinisation-ScienceDirect. Available online: https://www.sciencedirect.com/science/article/pii/S0022169411004434?casa_token=LQtlR1vdwh0AAAAA:bZwfRpx1CZgPAxG-b4RC3iAX4cNEuAPcVrZ7QNZoEnVTfOAwlGBrHa_uxFLVnBRWS-2D13b4Wg (accessed on 9 March 2021).

9.   Chandio, A.S.; Lee, T.S.; Mirjat, M.S. Simulation of horizontal and vertical drainage systems to combat waterlogging problems along the Rohri Canal in Khairpur District, Pakistan. *J. Irrig. Drain. Eng.* **2013**, *139*, 710–717. [CrossRef]

10.   Ritzema, H.P.; Satyanarayana, T.V.; Raman, S.; Boonstra, J. Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. *Agric. Water Manag.* **2008**, *95*, 179–189. [CrossRef]

11.   Gupta, S.K. Sub-surface drainage for waterlogged saline soils. *Water Energy Int.* **1985**, *42*, 335–344.

12.   Velmurugan, A.; Swarnam, T.P.; Ambast, S.K.; Kumar, N. Managing waterlogging and soil salinity with a permanent raised bed and furrow system in coastal lowlands of humid tropics. *Agric. Water Manag.* **2016**, *168*, 56–67. [CrossRef]

13.   Bakker, D.M.; Hamilton, G.J.; Houlbrooke, D.J.; Spann, C. The effect of raised beds on soil structure, waterlogging, and productivity on duplex soils in Western Australia. *Soil Res.* **2005**, *43*, 575–585. [CrossRef]

14.   Sayre, K.D.; Moreno Ramos, O.H. *Applications of Raised-Bed Planting Systems to Wheat*; CIMMYT: El Batan, Mexico, 1997; ISBN 9706480005.

15.   Johnson, S. Large scale irrigation and drainage schemes in Pakistan: A study of rigidities in public decision making. *Food Res. Inst. Stud.* **1982**, *18*, 149–180.

16.   Tariq, A.-R. *Drainage System Engineering*; Center of Excellence in Water Resources Engineering, University of Engineering and Technology: Lahore, Pakistan, 2008.

17.   Smedema, L.K.; Abdel-Dayem, S.; Ochs, W.J. Drainage and agricultural development. *Irrig. Drain. Syst.* **2000**, *14*, 223–235. [CrossRef]

18.   Qureshi, A.S.; McCornick, P.G.; Sarwar, A.; Sharma, B.R. Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. *Water Resour. Manag.* **2010**, *24*, 1551–1569. [CrossRef]

19.   Kelleners, T.J.; Chaudhry, M.R. Drainage water salinity of tubewells and pipe drains: A case study from Pakistan. *Agric. Water Manag.* **1998**, *37*, 41–53. [CrossRef]

20.   Waller, P.; Yitayew, M. *Subsurface Drainage Design and Installation BT-Irrigation and Drainage Engineering*; Waller, P., Yitayew, M., Eds.; Springer International Publishing: Cham, Germany, 2016; pp. 531–544, ISBN 978-3-319-05699-9.

21.   Hamid, Y. *Experience Gained from Interceptor Drains Installed in LBOD Stage-1 Project*; Water and Agriculture Division NESPAK: Lahore, Pakistan, 1998. Available online: https://pecongress.org.pk/images/upload/books/578.pdf (accessed on 9 March 2021).

22.   Llor, M.; Bel, A.; Ortuño, J.F.; Meseguer, F. Oxygen Consumption in Two Subsurface Wastewater Infiltration Systems under Continuous Operation Mode. *Water* **2020**, *12*, 3007.

23.   Huang, P.; Han, S. Assessment by multivariate analysis of groundwater-surface water interactions in the Coal-mining Exploring District, China. *Earth Sci. Res. J.* **2016**, *20*, G1–G8. [CrossRef]

24.   Sohag, S. Groundwater Investigation in Awlad Salameh. *Earth Sci. Res. J.* **2010**, *14*, 63–75.

25.   Fortier, S.; Scobey, F.C. Permissible Canal Velocities. *Trans. Am. Soc. Civ. Eng.* **1926**, *89*, 940–949. [CrossRef]

26.   Ritzema, H.P.; Nijland, H.J.; Croon, F.W. Subsurface drainage practices: From manual installation to large-scale implementation. *Agric. Water Manag.* **2006**, *86*, 60–71. [CrossRef]

27.   Government of Pakistan. *Surface Drainage Manual for Pakistan: Irrigation System Management Project: II, USAID Project Number 391-0467*; Government of Pakistan: Islamabad, Pakistan, 1993.

28.   Rilinger, G. Toward a Sociology of Economic Engineering: The Creation and Collapse of California's Electricity Markets between 1993 and 2001. Ph.D. Thesis, The University of Chicago, Chicago, IL, USA, 2020.

29.   Deshmukh, S.; Pansare, K.; Balsane, V.; Borse, K.; Samtani, B.K. Analytical study of quantitatvie chracheterists of watershed between Tapi and Wansuki distry River of Kakarapar and Ukai Command Area. *Ecol. Environ. Conserv.* **2015**, *21*, 345–354.

30.   Fisher, L. Minnesota Water Management Law and Section 404 Permits: A Practitioner's Perspective. *Hamline L. Rev.* **1984**, *7*, 249.

31.   Simons, D.B.; Richardson, E.V. A study of variables affecting flow characteristics and sediment transport in alluvial channels. In *Proceedings of the Federal Interagency Sedimentation Conference, Agricultural Research Service*; U.S. Department of Agriculture: Jackson, MI, USA, 1963; pp. 193–206.

32.   Witaschek, F.V. International Control of River Water Pollution. *Denver J. Int. Law Policy* **2020**, *2*, 6.

33.   Simons, D.B.; Rlchardson, E.V.; Nordin, C.F., Jr. Sedimentary structures generated by flow in alluvial channels. *AAPG Bull.* **1964**, *48*, 547.

34.   Lackey, K.A. Innovation in large capacity wastewater pumping station design. In Proceedings of the NC AWWA-WEA, WInston-Salem, NC, USA, 14–17 November 2010.

35.   Okwany, R.O.; Prathapar, S.; Bastakoti, R.C.; Mondal, M.K. Shallow Subsurface Drainage for Managing Seasonal Flooding in Ganges Floodplain, Bangladesh. *Irrig. Drain.* **2016**, *65*, 712–723. [CrossRef]