Sigma J Eng & Nat Sci 35 (2), 2017, 347-358

Sigma Journal of Engineering and Natural Sciences
Sigma Mühendislik ve Fen Bilimleri Dergisi

Research Article

PRACTICAL METHODS FOR THE ESTIMATION OF HYDROELECTRIC POWER POTENTIAL OF POORLY GAUGED BASINS

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Received: 29.09.2016 Revised: 13.03.2017 Accepted: 29.03.2017

ABSTRACT

Determining the hydroelectric power potential of ungauged or poorly gauged basins gains importance parallel with the increasing electricity consumption. This study presents some simple methods to predict flow to determine the hydroelectric power potential of poorly gauged basins, such as the precipitation–elevation, average precipitation, and average basin elevation methods. Results of these methods are compared with the available flow measurements. The poorly gauged Solaklı Basin, which is located in Trabzon, in the Eastern Black Sea Region of Turkey, is selected as the pilot area. The hydroelectric power potential of the planned small hydroelectric power plants in this area is estimated using different flow prediction methods.
Keywords: Hydroelectric potential, monthly mean flow, monthly precipitation, poorly gauged basin, Solaklı Basin.

1. INTRODUCTION

Energy demand, especially electrical energy demand, increases every year. However, nonrenewable energy resources, such as oil and coal, decrease. Consequently, several countries have focused on renewable energy sources, such as hydropower, wind, and wave energy.

Hydroelectric power plants (HEPPs) can be classified into mini, micro, and small plants, which have 10–99-, 100–999-, and 1000–2500-kW capacities, respectively. These types of HEPPs are mostly established in mountainous regions with insufficient flow gauges.

Recently, studies related to HEPPs have increased because of the world energy crisis, and numerous HEPPs have been built in developing countries. In China, more than 43,000 unstored HEPPs with potentials of less than 500 kW have been established [1]. In Nepal, 1,000 HEPPs have been constructed, of which only 3% have more than 20-kW capacities. In Ghana, Burma, Guatemala, Philippines, Nicaragua, Equator, Indonesia, and New Guinea, several HEPPs have

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been constructed to address their own energy needs. These types of HEPPs can also be found in USA, Canada, Japan, Russia, and Europe. The estimated total capacities of micro HEPPs in Asia, Africa, South America, Middle America, Europe, and Australia are 32661, 228, 1280, 2096, 10723, and 198 MW, respectively [2].

In Turkey, hydroelectric energy is also important because it is a renewable, clean, cheap, and native source. However, the hydroelectric power potentials of many rivers and tributaries in the country have not been determined yet. In addition, the rivers in the mountainous regions of East Anatolia, Southeast Anatolia, and Black Sea have considerable hydroelectric power potentials. However, the present potential could not be evaluated because of insufficient flow data.

The hydroelectric power potential of a plant is linearly proportional with the flow rate and height of the water body. First, the water runoff at a specific location is determined to estimate the hydroelectric power potential of a plant. Several methods have been developed for ungauged or poorly gauged basins to determine their flows, while others depend on meteorological parameters, such as rainfall, temperature, relative humidity; several others depend on geographical parameters, such as elevation, distance to sea, and altitude. Different methods are used to estimate flow, including regression or multiregression analysis [3] and conceptual models [4]. Kriging methods are also applied to determine basin parameters [5]. Annual flow estimation is studied using regional relationships [6]. Several studies focused on flow–duration curve methods for hydropower assessment [7]. Geographic Information System (GIS) methods and remote sensing are used to estimate stream flows [8]. Artificial neural networks and fuzzy logic algorithms have been used for river estimation [9]. These methods require data, time, and money. Engineers prefer simple and practical methods over complex methods, particularly for preliminary feasibility studies.

Several practical methods to estimate flows for poorly gauged sub-basins are used in this study, and their results are compared. The estimated flows are used to determine the hydroelectric power potential. Solaklı Basin is selected as the pilot basin. This basin has considerable precipitation values and high elevations.

2. STUDY AREA AND PRELIMINARY DATA ANALYSIS

Solaklı Basin is a good representative basin for the Eastern Black Sea Region. The Eastern Black Sea Region is situated in the northeastern part of Turkey, with Ordu Province as the western boundary and Georgia in the east. It is surrounded by the southern Eastern Black Sea Mountains and Northern Black Sea. The region includes the Aksu, Kalanima, Fol, Değirmendere, Karadere, Sürmene, Solaklı, and Fırtına Streams. The annual average precipitation in the Eastern Black Sea Region varies from 600 to 2500 mm for different basins.

The Solaklı Basin covers lands in different districts, namely, Of, Dernekpazarı, and Çaykara districts from North to South. Solaklı Stream is the main basin that collects river water. The stream takes from the glacier lakes of the Soğanlı and Haldizen mountains. Solaklı Stream is 80 km long and is one of the longest rivers in Trabzon. The basin area of the Solaklı Basin is approximately 767 km^2. The basin has four rain and three flow gauges. Fig. 1 shows the rain gauges of Of, Çaykara, Köknar and Uzungöl and the flow gauges of Ulucami, Ögene, and Haldizen. The basic statistics for the available rain and flow series are presented in Table 1.

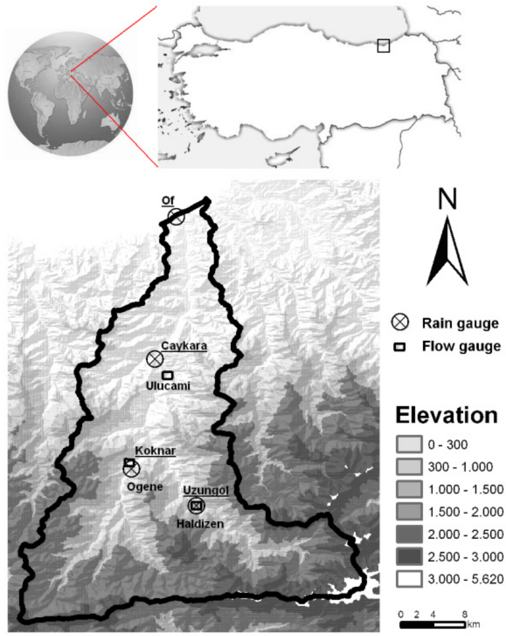

Figure 1. Location of Solaklı Basin and gauges

Table 1. Basic statistics of the monthly precipitation and flow data

Statistics	Çaykara–Ulucami		Köknar–Ögene		Uzungöl–Haldizen	
	Precip. (mm/month)	Flow (m^3/s)	Precip. (mm/month)	Flow (m^3/s)	Precip. (mm/month)	Flow (m^3/s)
Mean	84.5	14.26	69.1	5.28	69.1	4.27
Standard deviation	41.787	12.066	36.449	5.318	36.449	3.973
Skewness coefficient	0.288	1.599	0.696	1.850	0.696	1.603
Auto correlation	0.003	0.643	0.155	0.596	0.155	0.664

The sub-basin areas that correspond to the Haldizen, Ögene, and Ulucami flow gauges are 152, 242, and 579 km^2, respectively. The sub-basin areas were determined using a hydrological modeling system assisted by GIS. In addition, the digital elevation model (DEM) of Solaklı Basin was derived from 1:25000 scaled digital topographic maps with a 10-m spatial resolution. DEM was used to determine the flow accumulation and the direction data. A synthetic stream network was then obtained from this model and area. Elevation values were calculated for the sub-basins of Solaklı Basin [10].

The mean monthly total precipitation and flow measurements at any location were evaluated graphically. For example, the mean monthly total precipitations in Çaykara and the runoff depths in Ulucami are plotted in Fig. 2. In the basin, the runoff depths are higher than the precipitation depths in the spring and summer months (April–July), and the opposite is observed for the remaining part of the year (August–March).

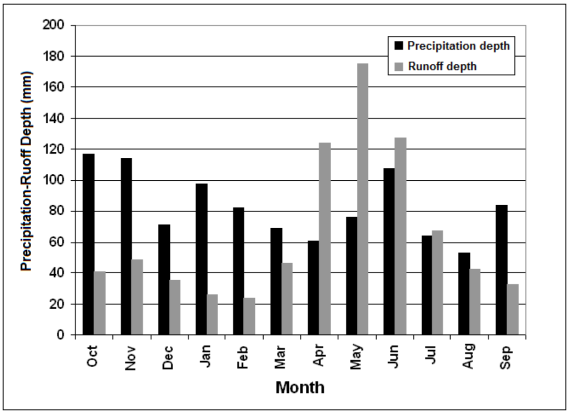

Figure 2. Mean monthly total precipitation depth in Çaykara and mean monthly runoff depth in Ulucami

The mean monthly flows in the Haldizen, Ögene, and Ulucami gauges are also plotted in Fig. 3, and the corresponding runoff yield per unit area are compared in Fig. 4. Fig. 3 shows that spring and summer runoffs are higher than those of the other seasons in all three gauges. Fig. 4 shows that Haldizen has higher runoff yield per unit area than the other sub-basin runoffs from August to December. This is because the Haldizen sub-basin has higher altitudes than the others and snow starts to melt later in the summer season. Conversely, for the entire year, the monthly runoff yields per unit area in Haldizen are generally greater than those in the other sub-basins [11, 12].

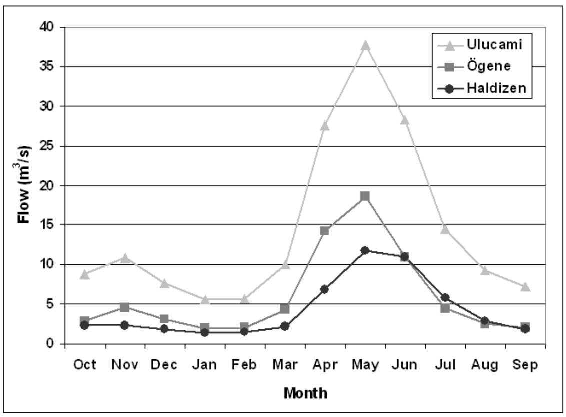

Figure 3. Mean monthly flows in Haldizen, Ögene, and Ulucami

The monthly runoff coefficients were computed as shown in Table 2. These coefficients vary from 0.25 to 2.31. Most of the runoff coefficients for the March–July period are higher than 1 because of the melted snow that flow to the river. The runoff yield per unit area–duration curves for the Haldizen, Ögene, and Ulucami stations are shown in Fig. 5. Three flow gauges have runoff yield per unit area values that are greater than 0.01 m3/s at 90% of the time. This implies that the region is suitable for hydroelectric development.

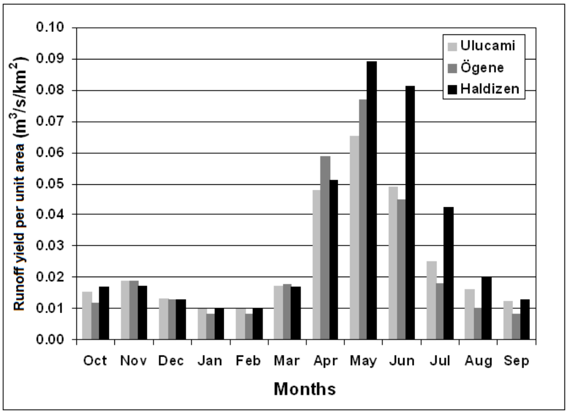

Figure 4. Runoff yield per unit area in Haldizen, Ögene, and Ulucami

Table 2. Runoff coefficients of Solakli Basin

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
Uzungöl–Haldizen	0.34	0.36	0.40	0.29	0.25	0.42	1.11	1.85	1.65	1.52	0.66	0.45	0.77
Ögene–Köknar	0.30	0.62	0.70	0.54	0.44	1.05	2.03	2.13	1.15	0.79	0.45	0,30	0.88
Ulucami–Çaykara	0.35	0.43	0.50	0.27	0.29	0.67	2.03	2.31	1.19	1.05	0.80	0.39	0.86

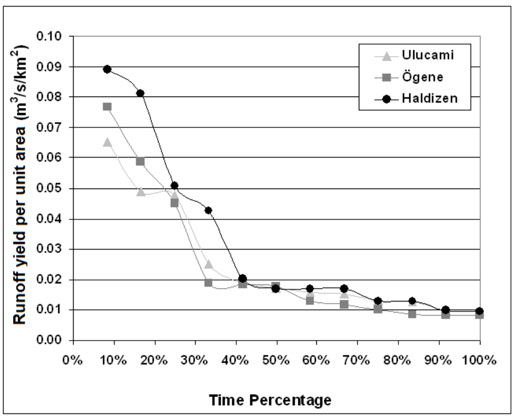

Figure 5. Runoff yield per unit area–duration curves of Haldizen, Ögene, and Ulucami

3. METHODS AND RESULTS

The density flow gauge network is low in the related basin. Thus, the rain gauges near the Solaklı Basin in the Eastern Black Sea Region should be considered to generate the relationship between precipitation and flow. In the region, the effect of elevation on precipitation distribution was analyzed and is shown in Fig. 6. In this figure, the depths of precipitation of the gauges that represent the same sub-basin are connected and presented as a line. In addition, the annual total precipitation generally decreases in several sub-basins with the increasing elevation. The precipitation in several sub-basins, such as Solaklı, tends to decrease in lower elevations and slightly increases in higher elevations.

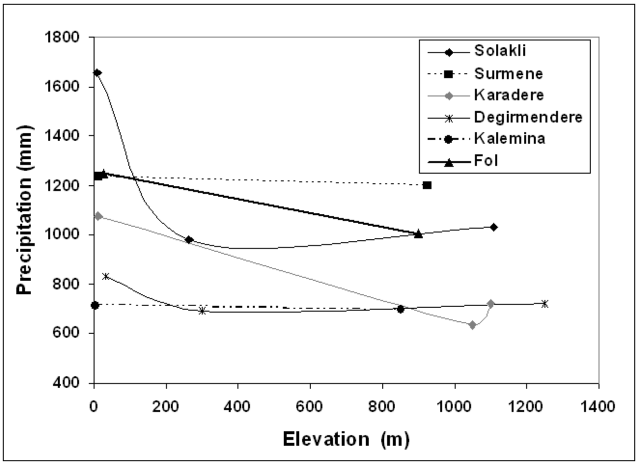

Figure 6. Variation of the annual total precipitation with the elevation in several sub-basins in the Eastern Black Sea Region

To estimate the hydroelectric power potential, several locations in the upper part of the Uzungöl gauge were selected as examples for the Solaklı Basin. For this purpose, precipitations and flows of these locations were determined. The highest and farthest point of Uzungöl Basin is the Demirkapı Hill, which has an altitude of 3370 m. No precipitation data exists for Demirkapı Hill, however Uzungöl has a rain gauge. The depths of precipitation between Demirkapı and Uzungöl were estimated using several simple methods.

Table 3. Monthly mean total precipitation depths (mm) in four stations

Station Name	Elevation (m)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Of	10	246	229	168	148	141	94	74	87	101	131	161	195	1773
Çaykara	280	117	114	71	97	82	69	61	76	107	64	53	84	996
Uzungöl	1090	116	110	77	84	89	92	103	110	112	67	76	71	1105
Monthly ave.	-	159	151	106	110	104	85	79	91	106	87	97	116	1291
Monthly ratio*		0.12	0.12	0.08	0.08	0.08	0.07	0.06	0.07	0.08	0.07	0.07	0.09	1
Demirkapı	3370	86	82	57	59	56	46	43	49	58	47	52	63	700

** Monthly ratio: monthly average/annual total*

The annual total precipitation depth in Demirkapı Hill was estimated from the isopluvials using 1:500000 scaled maps, which were obtained from the State Hydraulic Works (DSI). At an elevation of 3370 m, the annual total precipitation was estimated as 700 mm using this map. The monthly precipitation for Demirkapı Hill was calculated using both the value of 700 mm and the precipitation data in the Of, Çaykara, and Uzungöl gauges. The average values were calculated from the monthly total precipitation data in the Of, Çaykara, and Uzungöl gauges, as shown in Table 3. Then, the monthly ratios between these averages and the annual average precipitation (1291 mm) were determined. The monthly ratios were multiplied with the annual precipitation in Demirköprü Hill (700 mm) to obtain the monthly precipitation depths, as shown in the same table. The precipitations for the interval elevations between Uzungöl and Demirkapı Hill were interpolated using the values in Table 3.

3.1. Precipitation–elevation method

Different locations were selected as water intake places for possible HEPP stations in the upper part of the Uzungöl sub-basin. These locations are mostly situated on the confluence of tributaries. These locations are Yayla Köprüsü, Aşağı Mahalle, İpsil, and, Multat, as shown in Fig. 7. The precipitation depths at these locations were evaluated using linear interpolation between Uzungöl and Demirkapı Hill. The estimated precipitations were multiplied with the runoff coefficients between Uzungöl and Haldizen that were previously obtained to find the runoff depths of these locations (second row in Table 2). The monthly precipitations and runoffs in the possible plant locations are summarized in Table 4.

Table 4. Runoff depths based on precipitation–elevation relation

Depths of Precipitation (mm)													
Location	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Yayla Köprüsü	103	98	69	73	75	72	77	84	88	58	66	67	931
Aşağı Mahalle	106	101	71	76	79	78	84	91	95	61	69	68	979
İpsil	108	102	72	77	81	80	87	94	97	61	70	69	997
Multat	112	106	75	81	85	86	95	102	104	64	73	70	1050
Uzungöl	116	110	77	84	89	92	103	110	112	67	76	71	1105
Depths of Runoff (mm)													
Yayla Köprüsü	36	35	28	21	19	30	86	155	146	89	43	30	716
Aşağı Mahalle	37	36	28	22	20	32	93	168	156	92	45	30	761
İpsil	37	36	29	22	20	33	96	173	160	93	46	31	778
Multat	38	38	30	23	21	36	105	188	172	97	48	31	827
Uzungöl	40	39	31	24	23	38	114	203	184	101	50	31	879

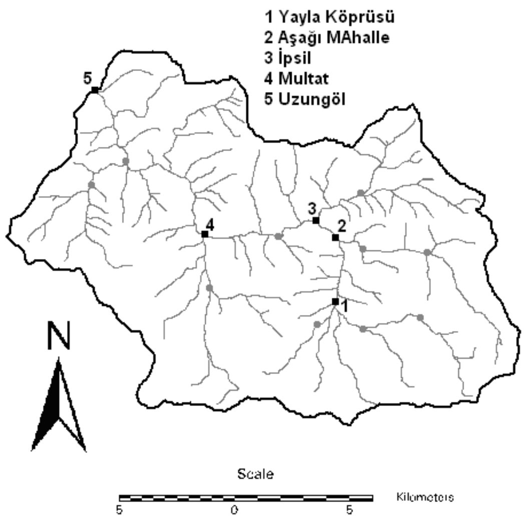

Figure 7. Selected locations for the possible intake structures

3.2. Basin average precipitation method

Basis average precipitation method can determine precipitation at different locations and depends on the average precipitation of the catchment area. In this method, the average precipitation of a catchment can be calculated as an arithmetic mean using the precipitation depth of the outlet and that of the highest point of the related catchment. For instance, the average precipitation of Yayla Köprüsü is (103+86)/2 = 95 mm for October, as shown in Table 5.

Table 5. Runoff depths obtained considering average precipitation of the sub-basin

Depths of Precipitation (mm)													
Location	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Yayla Köprüsü	95	90	63	66	66	59	60	67	73	53	59	65	816
Aşağı Mahalle	96	91	64	68	68	62	64	70	76	54	60	66	840
İpsil	97	92	65	68	68	63	65	71	77	54	61	66	848
Multat	99	94	66	70	71	66	69	75	81	56	62	66	875
Uzungöl	101	96	67	72	73	69	73	80	85	57	64	67	903
Depths of Runoff (mm)													
Yayla Köprüsü	33	32	25	19	17	25	67	123	120	80	39	29	608
Aşağı Mahalle	33	33	26	20	17	26	71	130	126	82	40	29	631
İpsil	33	33	26	20	17	26	72	132	128	83	40	29	639
Multat	34	33	26	20	18	27	76	140	133	85	41	30	664
Uzungöl	35	34	27	21	18	29	81	147	140	87	42	30	690

Following the same procedure, the runoff depths in the possible locations were calculated by multiplying the precipitation depths and the runoff coefficients.

3.3 Average basin elevation method

In this method, the elevation of each catchment is obtained using the following formula:

$$H_m = \frac{H_o - H_p}{\log H_o - \log H_p} \tag{1}$$

where H_m is the average catchment elevation, H_o is highest elevation of the catchment, and H_p is the elevation at the end of the catchment. The monthly precipitations were obtained for the estimated elevation value using the linear relation of Uzungöl–Demirkapı (Table 3). These precipitations were multiplied by the runoff coefficients, and the flows were calculated. The results are presented in Table 6.

Table 6. Mean runoff depths obtained using average basin elevation method

Depths of Precipitation (mm)														
Location	Ave. Elev. (m)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
Yayla Köprüsü	2665	95	90	63	67	67	60	62	68	74	53	60	65	825
Aşagi Mahalle	2501	98	92	65	69	69	64	66	72	78	55	61	66	854
İpsil	2438	98	93	65	69	70	65	68	74	80	55	62	66	866
Multat	2241	101	96	67	72	73	69	73	79	84	57	64	67	901
Uzungöl	2018	104	98	69	74	76	73	79	85	90	59	66	67	940
Depths of Runoff (mm)														
Yayla Köprüsü	2665	33	32	25	19	17	25	68	126	123	81	39	29	617
Aşagi Mahalle	2501	34	33	26	20	17	26	73	134	129	83	40	29	645
İpsil	2438	34	33	26	20	18	27	75	137	131	84	41	30	655
Multat	2241	35	34	27	21	18	29	81	147	139	87	42	30	688
Uzungöl	2018	36	35	28	21	19	30	87	158	148	89	44	30	725

Assuming that the depth of precipitation of Demirkapı Hill is 700 mm, the results of the three methods are summarized in Table 7 and Fig. 8. Accordingly, the runoff depths determined by the precipitation–elevation method are the highest and those of the basin average precipitation method are the lowest.

Table 7. Comparison of the mean annual runoff depths and flow rates for Demirkapı Hill (700 mm)

Location	Elevation (m)	Precipitation–elevation method		Basin average precipitation method		Average basin elevation method	
		Runoff depth (mm)	Flow rate (m^3/s)	Runoff depth (mm)	Flow rate (m^3/s)	Runoff depth (mm)	Flow rate (m^3/s)
Yayla Köprüsü	2070	716	0.56	608	0.47	617	0.48
Aşağı Mahalle	1800	761	1.17	631	0.97	645	0.99
İpsil	1700	778	1.55	639	1.27	655	1.3
Multat	1400	827	2.58	664	2.07	688	2.14
Uzungöl	1090	879	4.28	690	3.36	725	3.53

The flow results were compared with the observations at the Uzungöl gauge. The observed annual flow in Uzungöl was 4.28 m^3/s. The flows were 3.36 m^3/s and 3.53 m^3/s using the basin average precipitation and average basin elevation methods, respectively. The basin average precipitation and average basin elevation methods provided smaller estimations. The estimations using these methods were 21.5% and 17.5%, respectively, which are smaller than the observed value.

In Fig. 8, the estimated values are smaller than the observed ones. The value for Demirkapı Hill (700 mm) from the isopluvials may not be accurate in this study. The isopluvial map was generated based on the precipitation depths of gauges, which are located both inside and outside the basin. However, the gauges outside the basin, such as Sarımeşe, have different climatic characteristics than the gauges inside. For example, Solaklı Basin has a coastal zone climate, while Sarımeşe Basin has an inland climate. Therefore, the isopluvial map of the region, which was developed based on the characteristics of different climatic zones, yields considerable errors.

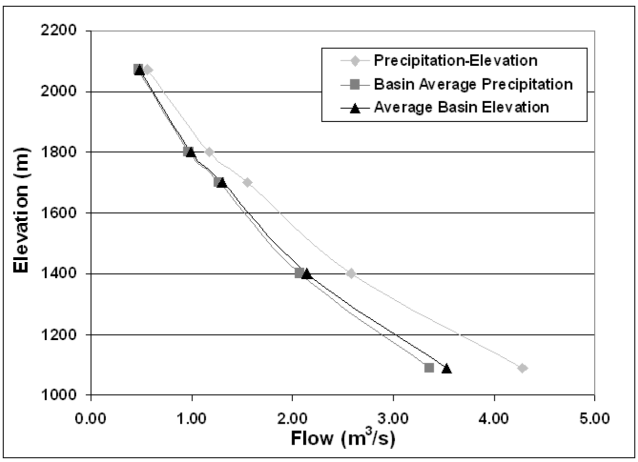

Figure 8. Variation of the mean flows obtained using the three methods

Depending on the results, the precipitation in Demirkapı Hill was estimated using the observed precipitation depths in Çaykara and Uzungöl rather than using the DSI map. A linear increase was assumed between Çaykara and Uzungöl, which extended up to Demirkapı Hill. Then, the precipitation of Demirkapı Hill should be 1396 mm (Fig. 9).

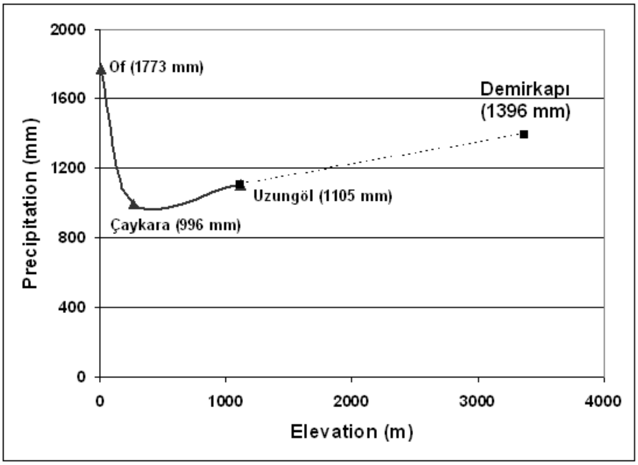

Figure 9. Variation of the precipitation with elevation

The flows were 4.57 and 4.52 m^3/s using the basin average precipitation and average basin elevation methods, respectively, (Table 8) based on the new precipitation depth of Demirkapı Hill, which is 1396 mm precipitation depth. The basin average precipitation and average basin elevation methods provided higher estimations. Their estimations were 6.8% and 5.6% greater than the observed value, respectively.

Table 8. Comparison of the mean annual runoff depths and flow rates for Demirkapı Hill (1396 mm)

Location	Elevation (m)	Precipitation–elevation method		Basin average precipitation method		Average basin elevation method	
		Runoff depth (mm)	Flow rate (m^3/s)	Runoff depth (mm)	Flow rate (m^3/s)	Runoff depth (mm)	Flow rate (m^3/s)
Yayla Köprüsü	2070	930	0.72	932	0.72	961	0.75
Aşağı Mahalle	1800	916	1.41	934	1.43	953	1.46
Ipsil	1700	911	1.81	935	1.86	949	1.89
Multat	1400	895	2.79	937	2.92	939	2.92
Uzungöl	1090	879	4.28	939	4.57	927	4.52

4. DETERMINATION OF THE HYDROELECTRIC POWER POTENTIAL

In hydro-electric power plants, power is calculated as follows [13]:

$$N = \gamma Q H_n e, \quad (2)$$

where N is the power (kW), γ is the unit weight of water (9.806 kN/m^3), Q is the flow (m^3/s), H_n is the net elevation (m), and e is the total efficiency. Total efficiency is the product of turbine, generator, and transformator efficiencies. These efficiency values are 0.90, 0.95, and 0.82, respectively. In this study, this formula was used to determine the hydroelectric power potential.

For the sustainability of ecosystem, 0.1 m^3/s of discharge is assumed to release. Then, the estimated flow rates were used to calculate the hydroelectric power potentials. In Table 9, the hydroelectric power potentials of the selected locations were determined using three methods for two different precipitation depths in Demirkapı Hill, and the results were compared. Table 9 shows that this study was divided into two stages to determine the hydroelectric power potentials for the selected locations. First, the depth of precipitation in Demirkapı Hill was estimated based on the 1:500000 scaled isopluvial map. In this case, the depths of precipitation decreased with the increasing elevation (700 mm in Demirkapı Hill). Second, the depths of precipitation were estimated given the variations in precipitation with the elevation. The estimated values were greater than the observed ones. Therefore, the hydroelectric power potentials were greater in the second stage. The flow, which is the main variable of the hydroelectric potential, was higher in the second than in the first stage.

Table 9. Characteristics of the locations and calculated hydroelectric powers (kW)

Water intake elevation (m)	Hydropower plant/height (m)	Tail water elevation (Hp) (m)	Mean basin elevation (m)	Basin area (km²)	Head (m)	Precipitation–elevation method		Basin average precipitation method		Average basin elevation method	
					(3-2)	700 mm	1396 mm	700 mm	1396 mm	700 mm	1396 mm
1	2	3	4	5	6	7	8	9	10	11	12
Yayla Köprüsü (2070 m)	Aşagı Mahalle (1800 m)	2070	2665.6	24.49	270	993.6	1339.2	799.2	1339.2	820.8	1404
Aşağı Mahalle (1800 m)	İpsil (1700 m)	1800	2501.8	48.39	100	856	1048	696	1064	712	1088
İpsil (1700 m)	Multat (1400 m)	1700	2438.9	62.66	300	3480	4104	2808	4224	2880	4296
Multat (1400 m)	Baca (1200 m)	1400	2241.1	98.2	200	3968	4304	3152	4512	3264	4512

5. CONCLUSION

In this study, several simple methods to estimate the hydroelectric power potentials of ungauged or poorly gauged basins were used, and their results were compared.

The monthly average flows in a sub-basin were calculated using three methods. These methods are the precipitation–elevation, average precipitation, and average basin elevation methods.

The precipitations were evaluated based on the isopluvial map, which was generated based on the precipitation depths of the gauges located both inside and outside the basin. However, the gauges outside the basin have different climatic characteristics than the gauges inside. Therefore, the isopluvial map of the region, which was developed based on the characteristics of the different climatic zones, yields considerable errors. Precipitation can be also estimated using the relation between the observed values and the elevations rather than using the isopluvials. The estimated precipitations were multiplied by the monthly runoff coefficients, and the corresponding monthly flows were computed subsequently.

The three methods in the second stage provided more acceptable results than the first stage. The values obtained using the average precipitation and average basin elevation methods were 6.8% and 5.6% greater than the observed values in the sub- basin, respectively.

The hydroelectric power potential of the selected locations can be determined using the estimated flows using the three methods presented.

In conclusion, this study presented several simple methods to determine hydroelectric power potential, and these methods can be used for the preliminary planning studies of poorly gauged basins, particularly for water resource assessment.

Acknowledgements

This study is a part of a research Project of The Scientific and Technological Research Council of Turkey (TUBITAK) with Project number106M043.

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