Uncertainty Analysis in Geospatial Merit Matrix–Based Hydropower Resource Assessment

M. Fayzul K. Pasha, M.ASCE[1]; Dilruba Yeasmin[2]; Sen Saetern[3]; Majntxov Yang[4]; Shih-Chieh Kao[5]; and Brennan Smith[6]

Downloaded from ascelibrary.org by Oak Ridge National Laboratory on 06/08/16. Copyright ASCE. For personal use only; all rights reserved.

Abstract: Hydraulic head and mean annual streamflow, two main input parameters in hydropower resource assessment, are not measured at every point along the stream. Translation and interpolation are used to derive these parameters, resulting in uncertainties. This study estimates the uncertainties and their effects on model output parameters: the total potential power and the number of potential locations (stream-reach). These parameters are quantified through Monte Carlo simulation (MCS) linking with a geospatial merit matrix–based hydropower resource assessment (GMM-HRA) model. The methodology is applied to flat, mild, and steep terrains. Results show that the uncertainty associated with the hydraulic head is within 20% for mild and steep terrains, and the uncertainty associated with streamflow is around 16% for all three terrains. Output uncertainty increases as input uncertainty increases. However, output uncertainty is around 10–20% of the input uncertainty, demonstrating the robustness of the GMM-HRA model. Hydraulic head is more sensitive to output parameters in steep terrain than in flat and mild terrains. Mean annual streamflow is more sensitive to output parameters in flat terrain. **DOI: 10.1061/(ASCE)WR.1943-5452.0000654.**
© 2016 American Society of Civil Engineers.

Introduction

Hydropower is a valuable source of renewable energy because of its low greenhouse gas emission, low operational cost, and quick response to peak demands (Madani and Lund 2009). Although the development of U.S. hydropower plants has slowed down in the past few decades (Uría Martínez et al. 2015), hydropower is still expected to increase globally at approximately 2.3–3.6% each year through 2020 (Lehner et al. 2005).

Hydropower resource assessment (HRA) is the first step when developing hydropower in a region. It provides an initial estimate of total hydropower potential in a specific region and can be used to identify potentially-suitable stream-reaches for further engineering feasibility assessment. One of the earliest HRA studies in the United States was the national hydroelectric power resources study (NHS), conducted by the U.S. Army Corps of Engineers (USACE) and published in 1983 (USACE 1983). The study, spanning all 50 states and Puerto Rico, assessed about 60,000 sites, including run-of-river, storage, and diversion projects, to identify potential sites for further feasibility evaluation. The NHS considered both river basin topography and stream yield for the calculation of long-term and short-term power potentials (USACE 1983). Conner et al. (1998) conducted another state-by-state HRA focusing on existing dams or undeveloped sites previously studied by various federal or state agencies. Later, Hall et al. (2004, 2006) conducted a comprehensive HRA to cover all the streams across the United States. The focus of these studies was to estimate the total hydropower potential only. Potential locations were not the focus.

In light of the rapid development of multiple national geospatial datasets for topography, hydrology, and environmental characteristics, Pasha et al. (2014) proposed a geospatial merit matrix–based hydropower resource assessment (GMM-HRA) model to estimate the total hydropower potential within a region. The GMM-HRA model was tested on two basins in the southeastern United States by Hadjerioua et al. (2013), and later applied to the entire continental United States by Kao et al. (2014). With the advancement of computational technology and geospatial data sets, GMM-HRA can utilize various high-resolution geospatial inputs (e.g., digital elevation) to identify potential sites, their potential power and energy, and their relative ranking based on hydrologic and hydraulic conditions. A merit matrix, defined as the product of hydraulic head, annual mean flow, and average channel slope, was used to help identify stream-reaches with high power density and small surface inundation. Storage, an important parameter in HRA, can provide buffer and affect power generation by changing potential energy in the system. However, the GMM-HRA model assumes that the maximum flooding level is up to 100-year water surface elevation to minimize the inundation impacts. Full description of GMM-HRA can be found in Pasha et al. (2014, 2016).

Hydropower resource assessment is growing in terms of providing more useful information for the engineering feasibility study. However, the HRA data level of precision remains to be determined. All HRAs, including the GMM-HRA method, use several input parameters to calculate outputs. The level of uncertainty in the input parameters and their joint and separate impacts on the outputs are unknown. Input parameters include data on stream hydrology, hydraulics, elevation (and hence slope), river geometry, flood limits, etc. Inherently, all of these parameters may include

[1]Assistant Professor, Dept. of Civil and Geomatics Engineering, California State Univ., Fresno, 2320 E. San Ramon Ave., M/S EE94, Fresno, CA 93740 (corresponding author). E-mail: mpasha@csufresno.edu

[2]Research Scientist, California Water Institute and Center for Irrigation Technology, California State Univ., Fresno, CA 93740.

[3]Research Assistant, Dept. of Civil and Geomatics Engineering, California State Univ., Fresno, CA 93740.

[4]Research Assistant, Dept. of Civil and Geomatics Engineering, California State Univ., Fresno, CA 93740.

[5]Research Scientist, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831.

[6]Program Manager and Group Leader, Energy-Water-Ecosystem Engineering Group, Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831.

Note. This manuscript was submitted on July 6, 2015; approved on January 7, 2016; published online on March 30, 2016. Discussion period open until August 30, 2016; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496.

a level of uncertainty, and these uncertainties may contribute to uncertainty in output parameters, which can ultimately bias the decision and cause additional—and in some cases unnecessary—studies costing more resources.

Hence, it is important to quantify the level of uncertainty associated with the input parameters and the effect of these input uncertainties on the output parameters. One of the two main input parameters, mean annual streamflow (Q), is calculated from historical observations which may be collected at daily intervals or more frequently. Historical observations are not available at every point along the streams, so interpolation or translation of data is required over the area to which the HRA model is applied. This information transformation in time and space can add uncertainty to mean annual streamflow (Q).

The other parameter, hydraulic head (H) in GMM-HRA, is obtained from channel elevation, the flood limit to constrain inundation, and the river geometry such as the center line, banks, overbanks, etc. The elevation data are typically obtained from an elevation data set such as from the digital elevation model (DEM) in the National Elevation Dataset (NED). Both the horizontal and vertical information is required to determine the hydraulic head and hence the slope of the stream. The resolution and scale disagreement between different data sources can be the source of uncertainty in the hydraulic head. The other parameters used in hydropower calculation, including unit weight of water and power generation efficiency, are typically assumed to be constant. Capacity factor, which is used to convert power (watt) into energy (watt-hour), can be a source of uncertainty, as it depends on streamflow variability, seasonality, and the region's pattern of hydropower generation. In general this parameter is not used in hydropower resource assessment.

If it is assumed that there are no horizontal or vertical uncertainties (uncertainties associated with hydraulic head, residence time, inundation, etc.) and that there are no minimum criteria for site selection (e.g., minimum hydraulic head and power), then the output uncertainty will be directly proportional to the input uncertainty. However, most of the HRA models include constraints in the calculation of total hydropower potential and the location of potential sites as presented in the GMM-HRA model. If streamflow is constant and the hydraulic head is considered to be uncertain, and if there are some minimum constraints (i.e., minimum power and head) and some inundation and residence time criteria, then the output uncertainties in total power potential and locations (stream-reaches) are not directly proportional to the input uncertainty in the hydraulic head. If both streamflow and hydraulic head are uncertain, then their influence on the output uncertainties can be nonlinear. Thus, it is critical to understand the levels of uncertainties associated with each input parameter, along with their separate and joint impacts on the output parameters.

This study identifies the level of uncertainties associated with the input parameters: (1) hydraulic head (H) at different DEM resolutions and (2) mean annual streamflow (Q) obtained from United States Geological Survey (USGS) National Hydrography Dataset Plus (NHDPlus) data set. This study also uses the GMM-HRA model to investigate the effects of the input uncertainties on the output parameters: (1) total hydropower potential and (2) total number of stream-reaches. Methodology has been applied to three USGS 8-digit hydrologic units' (HUC8) subbasins.

Methodology

Fig. 1 shows the general steps used in this study. Once the study area is selected in the first step, the level of uncertainty in the input parameters of the GMM-HRA model is estimated in the second step. The third step links MCS with the GMM-HRA model, and the fourth step calculates the output uncertainties through the Monte Carlo sampling (MCS) method.

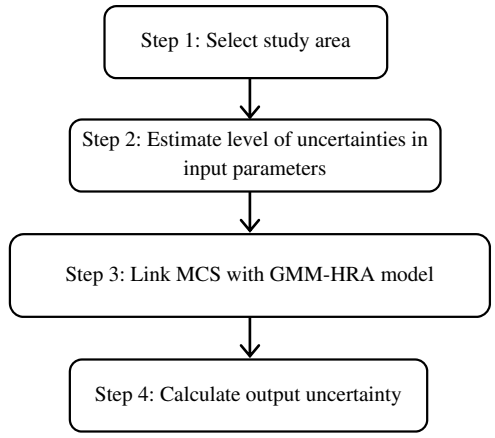

Fig. 1. Methodology steps

Estimation of Input Uncertainty

If mean annual streamflow (Q) and hydraulic head (H) of a stream are known with certainty, the potential hydropower can be calculated

$$P_i = \eta \times \gamma \times H_i \times Q_i / 10^6 \tag{1}$$

in which hydropower = P, calculated in megawatt (MW) for stream-reach i. Efficiency, η, is assumed to be a typical value of 0.85. The unit weight of water, γ, is 9,810 $\mathrm{N/m^3}$. The hydraulic head = H (meters); and the mean annual streamflow = Q (cubic meters per second). If the stream system is discretized at a predetermined resolution, the total hydropower potential of a stream system is the sum of the hydropower at the stream-reaches (discretized), as shown in the following:

$$P = \sum_{i=1}^{n} P_i \tag{2}$$

in which n = total number of stream-reaches (discretized) identified for potential development. The GMM-HRA model identifies the stream-reaches suitable for hydropower development through a ranking matrix based on the product of hydraulic head (H), mean annual streamflow (Q), and slope of the stream (S), or the HQS criterion. Based on Eq. (1), it is clear that the primary input parameters are mean annual streamflow (Q) and hydraulic head (H). These two parameters are often the sources of uncertainties, as they are derived from other sources, or they require measurements.

Uncertainty in Mean Annual Streamflow (Q)

In the GMM-HRA model, the mean annual streamflow (Q) is taken from the National Hydrography Dataset Plus (NHDPlus). In NHDPlus, the unit area runoff method (USGS 2010) was used to determine Q across the stream-reaches because all the streams may not have streamgauges. Streamflow data may not be collected at similar time intervals at all the streamgauges either. Therefore, the interpolations in time and space contribute to the uncertainty in mean annual streamflow (Q). The following steps have been used to quantify the uncertainty in Q in this study:

Downloaded from ascelibrary.org by Oak Ridge National Laboratory on 06/08/16. Copyright ASCE. For personal use only; all rights reserved.

1. Collect the historical daily average flow from streamgauges across the study area.
2. Calculate the mean annual streamflow for the streamgauges.
3. Identify the stream-reaches that belong to the streamgauges.
4. Calculate the difference in the mean annual stream flows obtained from streamgauge data and NHDPlus data.
5. Perform statistical analysis on the difference in the mean annual streamflow.

The mean annual streamflow calculated from collected streamgauge data is assumed to be the basis to determine the uncertainty associated with the NHDPlus mean annual streamflow.

Uncertainty in Hydraulic Head (*H*)

In the GMM-HRA model, H is calculated as the difference in elevations between channel elevation and 100-year flood level (i.e., water surface elevation for the event of a 100-year flood) at the locations of the discretization. Given the higher insurance rate and other regulatory considerations, there are usually fewer existing residences or civil structures in the current FEMA 100-year floodplains (FEMA 2012). Therefore, the current 100-year flood line can be regarded as an invisible boundary of existing civil development to guide this hydropower resource assessment [see Pasha et al. (2014) for further discussion]. With this main assumption, the stream-reaches identified by GMM-HRA will be mostly run-of-river and have a relatively smaller head and storage when compared to the conventional storage-type peaking hydropower projects. The channel elevation at the centerline of the stream is obtained by laying the stream system on top of a topographic model such as on the Digital Elevation Model (DEM) and extracting the elevation data at the discretization points. The flood elevation is obtained by laying the flood limit polylines, which can be obtained from any flood regulatory agency on the DEM, and extracting the elevation values from the DEM. As seen, different sources of data (system layout, DEM, flood limits, etc.) and their different resolutions can contribute uncertainty to the hydraulic head.

To measure the level of uncertainty associated with the hydraulic head, four sources of data have been used: stream system layout from NHDPlus, flood limits from FEMA, elevation data from the National Elevation Dataset (NED), and elevation data from Google Earth (Google 2013). Stream's centerline elevation, which refers to channel elevation, is extracted by laying out the centerline polyline on (1) Google Earth, (2) 10-m resolution DEM, and (3) 30-m resolution. Similarly, 100-year flood elevations have been obtained from these three sources. Google Earth processes raw data and validates the final elevation before publishing it, thus offering better data (Hoffmann and Winde 2010). Google Earth data are considered as the basis to calculate the uncertainties associated with hydraulic head when 10- and 30-m DEMs are concerned. The following steps are used to calculate the uncertainty:

1. Calculate hydraulic head (i.e., the difference between the 100-year flood elevation and the channel elevation at each discretized point on the stream system). These points are located at 150-m intervals throughout the stream system.
2. Calculate the difference in hydraulic heads between two sources (such as difference in hydraulic heads calculated from Google Earth and 10-m DEM) for all discretized points throughout the stream network.
3. Perform statistical analysis on the difference in hydraulic heads between the two sources.

Estimation of Output Uncertainty

The MCS method has been used to calculate the uncertainties associated with the GMM-HRA output parameters. The GMM-HRA model finds total hydropower potential and the potential locations in the stream network by using a merit matrix which can be written in the following form:

$$\text{Maximize}\, M_j(H, Q, S) = H_j \times Q_j \times S_j \times b \tag{3}$$

subject to

$$H_{\min} \leq H_j \leq H_{\max} \tag{4}$$

$$Q_j \geq Q_{\min} \tag{5}$$

A merit matrix is a one-dimensional vector with n number of elements corresponding to the total number of stream-reaches identified for potential hydropower development. j is any discrete stream-reach in the stream network. H_j, Q_j, and S_j are respectively hydraulic head, mean annual stream flow, and slope for the stream-reach j. For a given stream reach length, the higher slope will lead to greater hydraulic head and hence the higher power potential.

The objective is to maximize the *HQS* function in Eq. (3) such that the mean annual flow and hydraulic head are constrained within the given ranges. The minimum ($H_{\min}$) and maximum hydraulic ($H_{\max}$) in GMM-HRA are assumed to be 1.52 m (5 ft) and 100-year flood depth, respectively. The minimum mean annual flow ($Q_{\min}$) in GMM-HRA is assumed to be 1 m^3/s (35 cfs). The binary variable b denotes whether there is an existing lake. If there is an existing lake, the binary variable takes the value of 0; otherwise the value of b is 1. For a given level of input uncertainty associated with Q and H, the output uncertainties in total hydropower potential and the number of stream-reaches are calculated. In this study, the two input parameters, Q and H, are assumed to follow normal distribution. Using this assumption, new input parameters are calculated with the following equation:

$$P_{\text{new}} = \mu + \sigma \times Z \tag{6}$$

in which P_{new} = generated input parameter. The standard deviation = σ, calculated for a certain coefficient of variation (CV). Z = standard normal deviation that can be calculated by using numerical approximation methods (Abramowitz and Stegun 1972) based on some random numbers. Fig. 2 shows the MCS steps used in this study. The new input parameters are generated in Step 1. In Step 2, the GMM-HRA model is run to calculate the outputs.

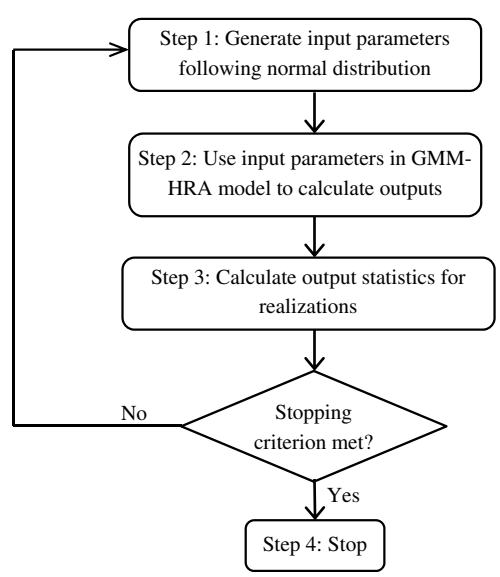

Fig. 2. Monte Carlo sampling (MCS) method used in the study

Downloaded from ascelibrary.org by Oak Ridge National Laboratory on 06/08/16. Copyright ASCE. For personal use only; all rights reserved.

Statistical analysis is performed in Step 3. The MCS is stopped when a stop criterion is met, such as the convergence of the mean, or the completion of a predefined number of realizations (iterations).

Applications

Three USGS subbasins at the HUC8 level were selected based on their general terrain and the slope of the streams. These three subbasins are located in California and were given names based on their average slopes (Table 1 and Fig. 3). Subbasin 18040003 is mostly flat (mean stream slope is less than 0.0009), Subbasin 18010110 is mildly steep (mean stream slope is between 0.0009 and 0.009), and Subbasin 18030010 is mostly steep (mean stream slope greater than 0.009). Therefore, the study areas are referred to as the flat, mild, and steep study areas. Physical and statistical descriptions of mean annual streamflow and the slope of each study area are shown in Table 1 and Fig. 3.

The mean, standard deviation, and other statistical information of the hydraulic head were calculated for the 10 and 30-m DEM resolutions for each study area, assuming the head calculated using the data obtained from Google Earth as the basis. Table 2 lists the statistical information. The first three columns of data contain the

Table 1. Statistics of Slope and Mean Annual Streamflow for Selected Study Areas

Statistics	Slope information (m/m)			Flow information (m^3/s)		
Subbasin identifier (HUC8)	18040003	18010110	18030010	18040003	18010110	18030010
Terrain	Flat	Mild	Steep	Flat	Mild	Steep
Minimum	0.00001	0.00001	0.00001	1	1	1
Maximum	0.04000	0.10638	0.71018	1,138	47	21
Mean	0.00034	0.00347	0.04820	225	13	10
SD	0.00324	0.00860	0.07589	298	14	6
25 (%)	0.00001	0.00011	0.01316	4	2	5
50 (%)	0.00001	0.00144	0.03122	12	6	8
75 (%)	0.00001	0.00351	0.05774	350	21	16

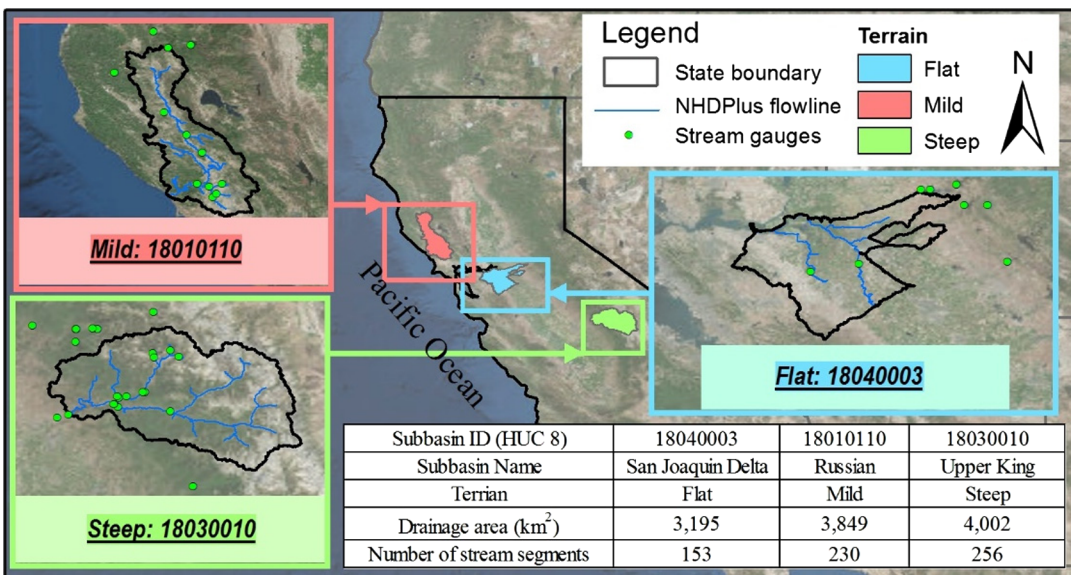

Fig. 3. Study areas

Table 2. Uncertainty Associated with Hydraulic Head

Statistics/terrain	Base hydraulic head (m)			Uncertainty [difference in head (m)]					
	Flat	Mild	Steep	Flat		Mild		Steep	
DEM	—	—	—	10-m	30-m	10-m	30-m	10-m	30-m
Mean	1.76	7.01	7.50	0.62	0.71	0.65	0.86	0.93	1.54
Minimum	0.30	0.30	0.30	0.00	0.00	0.00	0.00	0.01	0.02
Maximum	7.01	19.96	19.96	3.20	3.20	4.80	4.82	4.98	4.91
Median	1.52	6.40	6.71	0.39	0.49	0.42	0.54	0.62	1.27
25 (%)	0.76	3.81	3.81	0.15	0.18	0.19	0.24	0.29	0.53
75 (%)	2.29	9.44	10.67	0.86	1.00	0.86	1.20	1.17	2.34
SD	1.26	4.04	4.50	0.67	0.71	0.70	0.90	0.96	1.21

Downloaded from ascelibrary.org by Oak Ridge National Laboratory on 06/08/16. Copyright ASCE. For personal use only; all rights reserved.

base hydraulic heads, calculated from Google Earth. The remaining set of columns contains the difference in head between the data from Google Earth and the data from either the 10 or 30-m DEMs. A few quality controls have been made to remove some noises in the data. First, stream-reaches with hydraulic heads larger than 20 m or smaller than 0.3 m were discarded. Second, to avoid any horizontal disagreements between data layers, any head difference of more than 5 m is discarded from the study. This disagreement may result because of a horizontal scale issue.

The difference in hydraulic head is larger for the 30-m DEM than it is for the 10-m DEM across all the three subbasins (Table 2). This observation coincides with the knowledge that the 10-m DEM provides better data than the 30-m DEM. The uncertainty in hydraulic head increases as the terrain changes from flat to steep. For example, in the order of flat, mild, and steep, the median values for the 10-m DEM are 0.39, 0.42, and 0.62 m, respectively. The same pattern is observed for the 30-m DEM. An equivalent coefficient of variation can be computed by comparing the difference in hydraulic head to the average base hydraulic head. For example, in the steep terrain, for 10-m resolution, the equivalent coefficient of variation can be calculated as the ratio of 0.93–7.5. For the mild and steep terrains, the equivalent coefficient of variation is below 20%.

Historical daily streamflow data were collected from 48 streamgauges across the study area. These streamgauges are owned and operated by the USGS and California Department of Water Resources (DWR). These data were processed to compute the mean annual streamflow (Q). The computed Q was then compared with the NHDPlus Q, which was obtained by using the unit area runoff method (USGS 2010) to quantify the percentage error in the NHDPlus streamflow. The Q computed directly from the streamgauge data was considered as the basis of this calculation. Table 3 shows the uncertainty associated with Q for 48 locations. The uncertainty ranges from 0 to 33.2% with an average of 16.7%.

Coefficients of variation (CV) of 5 and 10% were considered in the input parameters, which were applied to the MCS, to observe the effect of uncertainty on total power potential and the locations. The outputs of uncertainties were calculated based on three conditions: input uncertainty in hydraulic head (H) only, in streamflow (Q) only, and jointly in H and Q. Table 4 lists the output uncertainties in total power potential for all three study areas, and they are also illustrated in Fig. 4. The middle line of each box of box and whisker plot represents the mean. The top and bottom of the box represent the mean plus or minus one standard deviation. The top and bottom whiskers represent the 95 and 5% values respectively.

Generally output uncertainty increases with the increase of input uncertainty. The output uncertainty due to input uncertainty in Q is the highest in flat terrains and lowest in steep terrains. As seen, input uncertainty in H contributes the least amount of output uncertainty in flat and mild terrains, but contributes the most in the steep terrain. This is because H provides a larger contribution to hydropower potential than Q in steep terrain, and vice versa for flat and mild terrains. Looking at CV (Table 4), the level of uncertainty in the output ranges from 0.3 to 1.2% for different levels of input uncertainty in H, 0.7–3.0% for different levels of input uncertainty in Q, and 0.7–3.6% for different levels of input uncertainty in H and Q jointly. These low output CVs show the robustness of the GMM-HRA model.

The uncertainty in the number of stream-reaches potential for hydropower development was also calculated (Table 5). All three terrains show a general pattern of a higher average number of

Table 3. Uncertainty Associated with Mean Annual Streamflow

Streamgauge identifier	Agency	River name	Error (%)
11241500	USGS	Stevenson Creek	19.5
TUL	DWR	Stanislaus River	4.5
11245000	USGS	South Fork Willow Creek	6.1
11229500	USGS	South Fork San Joaquin River	13.5
11325000	USGS	South Fork Calaveras River	9.0
11468070	USGS	South Fork Big River	23.4
11466320	USGS	Santa Rosa Creek	24.7
BDT	DWR	San Joaquin River	13.2
SSH	DWR	Salt Slough	31.0
11463500	USGS	Russian River	6.3
HAC	DWR	Russian River	31.3
11214400	USGS	Post Corral Creek	24.4
11237500	USGS	Pitman Creek	9.5
11238000	USGS	Pitman Creek	4.5
BBI	DWR	Old River	7.7
11214000	USGS	North Fork Kings River	32.4
11216000	USGS	North Fork Kings River	23.7
11216050	USGS	North Fork Kings River	10.7
11216300	USGS	North Fork Kings River	13.3
11323500	USGS	Mokelumne River	23.7
PAR	DWR	Mokelumne River	18.9
CMN	DWR	Mokelumne River	0.0
11465500	USGS	Mark West Creek	10.0
11466800	USGS	Mark West Creek	13.8
11208000	USGS	Marble Fork Kaweah River	27.7
11465750	USGS	Laguna De Santa Rosa	15.0
11213000	USGS	Kings River	4.4
11213500	USGS	Kings River	17.9
11218499	USGS	Kings River	11.1
11218500	USGS	Kings River	14.1
11218501	USGS	Kings River	26.1
11221500	USGS	Kings River	22.5
11222000	USGS	Kings River	19.2
11214500	USGS	Helms Creek	3.9
11214600	USGS	Helms Creek	22.4
11462700	USGS	Feliz Creek	25.3
11471500	USGS	Eel River	7.9
11472000	USGS	Eel River	16.3
EVA	DWR	Eel River	27.2
ELP	DWR	Eel River	13.8
11216500	USGS	Dinkey Creek	15.7
11218000	USGS	Dinkey Creek	12.1
MHB	DWR	Cosumnes River	33.2
NHG	DWR	Calaveras River	11.2
11463200	USGS	Big Sulphur Creek	24.4
11238380	USGS	—	31.1
11238400	USGS	—	22.7
11274538	USGS	—	0.3

Note: Maximum = 33.2; Mean = 16.7; Median = 15.3%; Minimum = 0.0.

Table 4. Output Uncertainty in Total Power Potential

		Flat		Mild		Steep	
		Input CV					
Statistics	Uncertain parameters	5%	10%	5%	10%	5%	10%
Mean (MW)	Base	17.9		33.5		219.9	
	H	17.6	17.6	33.5	33.6	230.6	234.2
	Q	19.2	20.9	34.8	37.1	208.4	214.2
	H and Q	18.6	20.1	34.7	36.8	221.6	232.0
SD (MW)	H	0.08	0.08	0.09	0.11	2.54	2.91
	Q	0.35	0.62	0.24	0.41	1.79	2.03
	H and Q	0.40	0.72	0.26	0.47	3.00	3.44
Coefficient of variation (CV)	H (%)	0.5	0.4	0.3	0.3	1.1	1.2
	Q (%)	1.8	3.0	0.7	1.1	0.9	0.9
	H and Q (%)	2.2	3.6	0.7	1.3	1.4	1.5

Downloaded from ascelibrary.org by Oak Ridge National Laboratory on 06/08/16. Copyright ASCE. For personal use only; all rights reserved.

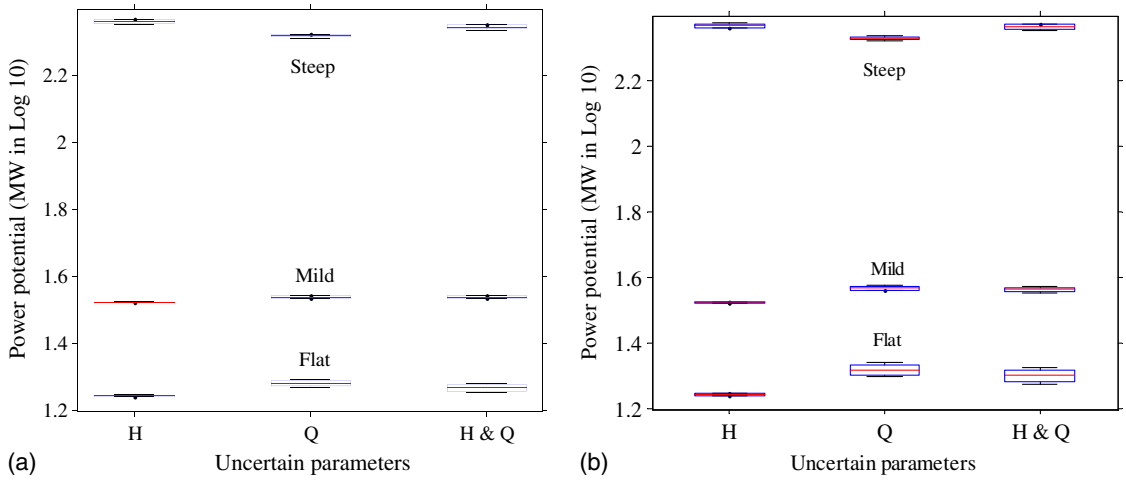

Fig. 4. Box and Whisker diagram for MCS results for hydropower resource assessment for (a) 5%; (b) 10% input coefficient of variation

Table 5. Output Uncertainty in Number of Potential Stream-Reaches

Statistics	Uncertain parameters	Flat		Mild		Steep	
		Input CV					
		5%	10%	5%	10%	5%	10%
Mean	Base	124		196		475	
	H	117	115	190	186	480	475
	Q	130	129	193	194	446	446
	H and Q	121	118	189	187	454	453
SD	H	3	3	5	6	10	17
	Q	3	4	13	11	26	31
	H and Q	4	5	6	8	19	17
Coefficient of variation	H (%)	2.6	2.6	2.6	3.2	2.1	3.6
	Q (%)	2.3	3.1	6.7	5.7	5.8	7.0
	H and Q (%)	3.3	4.2	3.2	4.3	4.2	3.8

streams for 5% input CV than that for the 10% input CV. Generally, for flat terrain, the output uncertainty was found to be the lowest for uncertainty in H, and the highest for joint input uncertainty in H and Q. For mild and steep terrains, the output uncertainty was found to be the lowest for H and the highest for Q.

Conclusions

In this study, uncertainties associated with the input parameters in the hydropower resource assessment were quantified. The uncertainties in the model (GMM-HRA) outputs were also quantified for a set of given input uncertainties. The methods were applied to three subbasins of flat, mild, and steep terrains from California. Historical streamflow and NHDPlus streamflow data were used to calculate the uncertainty in mean annual streamflow to be used in the hydropower resource assessment model, GMM-HRA. 10-m DEM, 30-m DEM, Google Earth, 100-year flood elevation from the FEMA dataset, and the NHDPlus dataset were used to calculate the uncertainty in the hydraulic head. The uncertainties in the model outputs, as well as the total power potential and the number of potential stream-reaches, were evaluated through MCS.

Several observations were made. The level of uncertainty associated with the input parameter, hydraulic head, was found to be about 20% for the mild and steep terrains. For the flat terrain, the level of uncertainty was found to be higher. MCS results show that output uncertainty increases with the increase of input uncertainty for all three terrains. The output uncertainty associated with the total hydropower potential varies with terrain. Although output uncertainty in total hydropower due to hydraulic head is found to be larger in steep terrain, this output uncertainty due to mean annual streamflow is found to be larger in the flat terrain. It is expected that the contribution of mean annual streamflow is smaller, but the contribution of hydraulic head is larger in the hydropower calculation in the steep terrain. Because output uncertainty due to hydraulic head is larger in the steep terrain, extra attention is required in data collection in this terrain. The ranges of output uncertainties in total power potential are found from 0.3 to 2.2% for 5% input CVs and from 0.3 to 3.6% for 10% input CVs. This demonstrates the robustness of the GMM-HRA model.

Generally, uncertainties in the input and output parameters of conventional hydropower resources assessment models were not fully quantified. The National Hydroelectric Power Resources Study made an attempt and found that the energy output from the plant could be increased up to 11% (USACE 1983). Model robustness can be evaluated by comparing the uncertainties in the input and output parameters. In that sense, the GMM-HRA model is found to be robust. Although the higher storage would provide greater power potential, the GMM-HRA model considered the maximum storage only up to the 100-year flood level to keep the inundation minimum. In the study, it was assumed that the NHDPlus polylines represent the stream centerline. The stream polylines and flood limit polylines were also assumed to represent the correct locations on the topographic map. Therefore, the uncertainties due to differences in the horizontal scale were not considered.

Acknowledgments

This research was sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Program. Support from California State University–Fresno is also acknowledged. This paper was coauthored by employees of Oak Ridge National Laboratory, managed by UT Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy. Accordingly, the publisher, by accepting the article for publication, acknowledges that the United States government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States government

Downloaded from ascelibrary.org by Oak Ridge National Laboratory on 06/08/16. Copyright ASCE. For personal use only; all rights reserved.

purposes. The U.S. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

References

Abramowitz, M., and Stegun, I. (1972). *Handbook of mathematical functions*, Dover Press, New York.

Conner, A. M., Francfort, J. E., and Rinehart, B. N. (1998). "U.S. hydropower resource assessment." *Final Rep. DOE/ID-10430.2*, Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID.

FEMA (Federal Emergency Management Agency) (2012). *Flood insurance manual*, National Flood Insurance Program, Washington, DC.

Google. (2013). "Google earth, version 7.0." ⟨https://www.google.com/earth/download/ge/⟩ (Apr. 1, 2013).

Hadjerioua, B., et al. (2013). "An assessment of energy potential from new stream-reach development in the United States: Initial report on methodology." *Technical Manual 2012/298*, Oak Ridge National Laboratory, Oak Ridge, TN.

Hall, D. G., et al. (2004). "Water energy resources of the United States with emphasis on low head/low power resources." Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID.

Hall, D. G., Reeves, K. S., Brizzee, J., Lee, R. D., Carroll, G. R., and Sommers, G. L. (2006). "Feasibility assessment of the water energy resources of the United States for new low power and small hydro classes of hydroelectric plants." Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID.

Hoffmann, E., and Winde, F. (2010). "Generating high-resolution digital elevation models for wetland research using Google Earth imagery—An example from South Africa." *Water SA*, 36(1), 53–68.

Kao, S.-C., et al. (2014). "New stream-reach development: A comprehensive assessment of hydropower energy potential in the United States." *GPO DOE/EE-1063*, Wind and Water Power Program, Dept. of Energy, Washington, DC.

Lehner, B., Czischb, G., and Vassolo, S. (2005). "The impact of global change on the hydropower potential of Europe: A model-based analysis." *Energy Policy*, 33(7), 839–855.

Madani, K., and Lund, J. (2009). "Modeling California's high-elevation hydropower systems in energy units." *Water Resour. Res.*, 45(9), in press.

Pasha, M., Yeasmin, D., Kao, S., Hadjerioua, B., Wei, Y., and Smith, B. (2014). "Stream-reach identification for new run-of-river hydropower development through a merit matrix-based geospatial algorithm." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000429, 04014016 .

Pasha, M. F. K., Yang, M., Yeasmin, D., Saetern, S., Kao, S., and Smith, B. T. (2016). "Identifying high energy–density stream reaches through refined geospatial resolution in hydropower resource assessment." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000599, 06016001.

Uría Martínez, R., O'Connor, P. W., and Johnson, M. M. (2015). "2014 hydropower market." *Rep. DOE/EE-1195*, U.S. Dept. of Energy Wind and Water Power Technologies Office, Washington, DC.

USACE. (1983). "National hydroelectric power resources study." *Rep. No. IWR-82-H-1*, U.S. Army Corps of Engineers, Government Printing Office, Washington, DC.

USGS. (2010). "NHDPlus user guide." U.S. EPA, Washington, DC.

Downloaded from ascelibrary.org by Oak Ridge National Laboratory on 06/08/16. Copyright ASCE. For personal use only; all rights reserved.