Solar Irrigation Pump (SIP) Sizing Tool

User Manual

Beta Version

Santosh S. Mali
Paresh B. Shirsath
Shilp Verma
A.K. Sikka

March 2022

IWMI International Water Management Institute | CGIAR Research Program on Water, Land and Ecosystems | BISA Borlaug Institute for South Asia | ICAR | CGIAR | german cooperation DEUTSCHE ZUSAMMENARBEIT | Implemented by giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Solar Irrigation Pump (SIP) Sizing Tool: User Manual [Beta Version]

S.S. Mali, P.B. Shirsath, S. Verma and A.K. Sikka

Year of Publication: March, 2022

Citation:

Mali, S.S., Shirsath, P.B., Verma, S. and Sikka, A.K. (2022) Solar Irrigation Pump (SIP) Sizing Tool. Beta Version User Manual.

ICAR, International Water Management Institute (IWMI), BISA and GIZ collaborative project.

Published by:

International Water Management Institute, Anand

Disclaimer

The Beta Version of the Solar Irrigation Pump (SIP) Sizing Tool and this User Manual were developed as part of the collaborative work by IWMI, GIZ, ICAR and BISA.The designations employed and the presentation of the material on the maps do not imply the expression of any opinion whatsoever on the part of authors concerning the legal status of any territory, area or city or of its authorities, or concerning the delimitation of its frontiers or boundaries. While all carehas been taken in creation of the maps, the spatial or temporal accuracy of the map or its features or fitness for a particular use is not warranted. The developers reserve all rights to the programming codes and routines used in this tool. No part of codes may be reproduced or transmitted in any form, without the prior consent of the developers. The Solar Irrigation Pump (SIP) sizzing tool does not constitute any form of legal, accounting, tax or actuarial advice. The inbuilt databases used in the tool were adapted from sources that have posted data in the public domain. The sizing of pump is based on data provided by these sources. The developers accept no responsibility for the accuracy or completeness of the underlying information included in these data sources. The developers will not be liable, in any way, for any indirect or consequential loss or damage of any kind resulting from use of the information contained in this document. The authors also declare no competing financial or commercial interests. Under no circumstances and under no legal theory shall the developers or any affiliates, officers, employees, or other representatives be liable to any person for direct, indirect, special, incidental, or consequential damages of any character specifically resulting from the application of the tool.

Acknowledgements

The Beta Version of the Solar Irrigation Pump (SIP) Sizing Tool and this User Manual have been developed jointly by IWMI, ICAR and BISA specifically for the Ministry of New and Renewable Energy (MNRE), Government of India's PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan) initiative with support from Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ). The work is part of the partnership between GIZ and IWMI on "Solar irrigation expansion in India: Opportunities and challenges in co-management of energy, water, agriculture and climate". The work is also mapped to the IWMI-led CGIAR research program on Water, Land and Ecosystems (WLE) and the CIMMYT-led CGIAR research program on Climate Change, Agriculture and Food Security (CCAFS). The work has also benefitted immensely from the contributions and leadership of the Indian Council for Agricultural Research (ICAR), specifically its Regional Center for Eastern Region (RCER), Ranchi.

Besides the developers, several individuals have contributed to the development of the tool through important contributions to coding and inputs and suggestions during stakeholder consultations. We would like to specifically thank key officials from MNRE and GIZ for their active support and encouragement: J.K. Jethani, Shobhit Srivastava, Aditya Gangwar, Himani Mehta and V.S.S. Chaitanya (MNRE); Nilanjan Ghose, Florian Postel and Prasun K. Das (GIZ). We would also like to thank industry participants from Jain Irrigation,Ecozen, CEEW, Khethworks, Rotomag, Shakti Pumps, UL, Yoda and several others who provided useful feedback and suggestions during (virtual) stakeholder consultations and MNRE training workshop for PM-KUSUM state nodal agencies. The developers would like to acknowledge the support of Neha Durga, Punjan Patel and Sudharshan Maliappan (IWMI); and Neha Nair (former student, IRMA) for their inputs to the tool and the manual.

Contents

List of Tables

List of Figures

List of Abbreviations

Abbreviation	Definition
AC	Alternating Current
BISA	Borlaug Institute for South Asia
CCAFS	CGIAR Research Program on Climate Change, Agriculture and Food Security
CEEW	Council on Energy, Environment and Water
CIMMYT	International Maize and Wheat Improvement Center
DC	Direct Current
ETIR	Evapotranspiration based Irrigation Requirement
FAO	Food and Agriculture Organization of the United Nations
FC	Field Capacity
GDP	Gross Domestic Product
HWSD	Harmonized World Soil Database
ICAR	Indian Council for Agricultural Research
IRMA	Institute of Rural Management, Anand
IWMI	International Water Management Institute
MNRE	Ministry of New and Renewable Energy, Government of India
MS	Microsoft
PMET	Penman-Monteith Evapotranspiration
PM-KUSUM	Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan
RCER	Regional Complex for Eastern Region
RZWB	Root Zone Water Balance
SCS	Soil Conservation Service
SIP	Solar Irrigation Pump
SP	Saturation Percentage
SPV	Solar Photovoltaic
USDA	United States Department of Agriculture
WLE	CGIAR Research Program on Water, Land and Ecosystems
WP	Wilting Point

List of Symbols used

Symbol	Meaning
IR	Infiltration rate
DP	Deep percolation
DP_m	Maximum deep percolation rate of a soil
ET_o	Reference evapotranspiration
ET_c	Crop evapotranspiration
P_e	Effective rainfall
P_{em}	Monthly effective rainfall
I_r	Irrigation depth
ET	Evapotranspiration
R_u	Net radiation at the crop surface
G	Soil heat flux density
T	Air temperature at 2 m height
U_2	Wind speed at 2 m height
E_s	Saturation vapour pressure
E_a	Actual vapour pressure
Δ	Slope vapour pressure curve
K_c	Psychrometric constant
P_m	Monthly amount of rainfall
I_{rm}	Monthly amount of irrigation applied
IE	Irrigation efficiency
A	Area of the plot
V_{mg}	Monthly gross irrigation volume
K	Number of plots to be irrigated
TW	Total water
MC_i	Initial soil moisture content
RSW	Residual soil water
RO	Runoff

AP	Allowable percentage
Iru	User specified irrigation depth
CL	Critical limits of soil moisture for irrigation
I_{rmg}	Monthly gross amount of irrigation
Q_s	System discharge
N	Number of days allocated for irrigation within a month
L_s	Length of pipe on suction side
L_d	Length of pipe on delivery side
D_s	Diameter of the pipe on suction side of pump
D_d	Diameter of the pipe on delivery side of pump
$Q_{s'}$	System discharge requirement in drought scenario
Ht'	System head requirement in drought scenario
H'_{geo}	Geodetic head in increased water table depth scenario
H_t	Total dynamic head
H_{geo}	Geodetic head
H_f	Friction loss
H_o	Operational head requirement
H_e	Elevation head
WL_{min}	Minimum water level in ponds/streams/wells
dp	Depth of pond
d_{ow}	Depth of open well
h_s	Friction loss on suction side
h_d	Friction loss on delivery side
h_{fit}	Friction loss in fittings and accessories
h_{syst}	Friction loss in irrigation system
G	Percent decrease drawdown in water table decrease scenario
T_{max}	Maximum Temperature
T_{min}	Minimum Temperature

Executive Summary

In most regions in the 'Global South', solar photovoltaic pumps can offer 1,400 – 2,200 peak-hours of reliable and affordable green energy for irrigation. With unit costs declining by the day, and significant promotion by state and union government, it is not surprising that solar pumps are rapidly expanding in India. Over the next few years, PM-KUSUM, the Government of India's ambitious campaign is expected to invest ₹34,035 crores (approx. US$ 4.6 billion) to support the installation of 3.5 million solar irrigation pumps. This can help significantly expand irrigated area; make irrigation more affordable and accessible for smallholders; reduce pressure on electricity utilities to supply subsidised electricity to farmers; eliminate pump irrigation's carbon footprint; and improve the overall returns from agriculture.

Selection of optimally sized solar pumping systems is a challenging task, not least because farmers' demand for energy for irrigation is a complex, derived demand. Keeping in view the huge investments by the governments in solarization of agriculture, design of pump sets based on scientific protocols therefore has a key role in large scale adoption of solar pumping systems.

The sizing of solar irrigation pumping systems involves a set of complex algorithms, each addressing a specific module in the design procedure. Several technical, biophysical and social factors govern the pump set size, which needs to be properly accounted while designing a matching solar pumping system.

The Beta version of the Solar Irrigation Pump (SIP) sizing tool is aimed at assisting farmers, researchers and technical persons involved in adoption and promotion of solar pumping systems across India. The tool has universal applicability in the sense that it uses nationwide datasets on climate, soils and crops, wherein users can fetch the required data for the location of interest.

The tool presented in this manual is comprised of four modules viz. crop water requirement module, discharge estimation module, head loss estimation module and the pump selection module which works on the principles laid down by the Ministry of New and Renewable Energy (MNRE), Government of India.The manual is designed to offer basic information about solar pump sizing and to provide the step-by-step procedure to work with SIP Sizing tool to solve real-world problems. This technical manual is divided in two parts. The first part explains the basic concepts and procedures in solar pump designing while the second part deals with the step-by-step procedure to use the MS Excel based Beta version of the SIP sizing tool.

This 'Beta version' of the tool has been shared with solar pump manufacturers and industry experts during two (virtual) consultations co-organized with GIZ and MNRE. During both of these, the tool received positive feedback and useful suggestions for improvement. The tool was also shared with state nodal agencies for PM-KUSUM during a training workshop organized by MNRE. Going forward, MNRE has suggested that a mobile version of the tool should be developed by HKRP Innovations LLP. IWMI and ICAR have reiterated their commitment to support GIZ, MNRE and HKRP in mobile version development as well as development of future versions of the tool based on user inputs and feedback.

Introduction

A recent report by the International Renewable Energy Agency[1] notes that as of 2018, out of 547 MW capacity of 'off-grid solar-powered pumping capacity for agriculture' installed around the world, India is home to nearly 512 MW or 93.6 per cent. This is not surprising given the rapid pace with which solar irrigation pumps have grown in the country – from a couple of thousand in 2010-11 to nearly 272,000 by 31st December 2020[2]. The Government of India's ambitious PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan) initiative aims to build on this early expansion and promote more than 2 million off-grid and 1.5 million grid-connected solar irrigation pumps (SIP) through a combination of national and state subsidies, bank loans and farmer contributions. With an expected outlay of ₹34,035 crores (approx. US$ 4.6 billion) and solar generation capacity target of 30.8 GWp (Giga-watt-peak), PM-KUSUM is indisputably the world's largest and perhaps the most ambitious agri-solarisation program. Yet, even with such impressive growth, it would leave plenty of room for further expansion given that India's massive minor irrigation economy includes more than 15.5 million grid-connected and nearly 6 million off-grid irrigation pumps [3,4].

According to one estimate[5], solarisation of India's 20 million agricultural pumps can add about 150 GWp of additional solar generation capacity. Doing this would involve significant public investment from the government, civil society and electricity utilities as well as private investments from farmers. To ensure that the assets created through these investments are optimally utilized, 'right sizing' of these SIPs is critical. Negligent 'under-sizing' or unnecessary 'over-sizing' of SIP might lead to poor user experience and this can - in the long run - limit the overall size of the SIP economy.

Farmers' demand for irrigation and the derived demand for pumping capacity is complex and depends on a large number of variables. It is important, therefore, for solar developers, bankers and policy makers to have access to a robust decision support tool that can help them understand farmers' demand and work out the matching optimal SIP size. This tool is designed to estimate the irrigation demand, calculate the peak discharge and head requirements to arrive at optimal size of SIP. The tool also considers prevalent irrigation pump sizes (using data from the Fifth Minor Irrigation Census) and different hydrological and management scenarios. In designing a solar pumping system, the tool takes into consideration the agro-ecology of the area, effective precipitation, type and seasonality of crops, number of crops grown, area potential for different corps and the pumping technology used (AC or DC; Submersible or Surface). This user manual describes the procedures and protocols used in the tool and would be useful to Financial institutions, farmers, developers and agencies involved in promotion of solar pumping systems in India. The first part of the manual describes the theoretical background and governing equations of each module within the SIPS. The second part outlines the step-by-step procedure for application of tool in selection of appropriate pump size.

[1] IRENA 2020. Off-grid Renewable Energy Statistics 2020. International Renewable Energy Agency (IRENA), Abu Dhabi. Available online: https://www.irena.org/publications/2020/Dec/Off-grid-renewable-energy-statistics-2020

[2] MNRE 2021. Annual Report 2020-21. Ministry of New and Renewable Energy (MNRE), Government of India. Available online: https://mnre.gov.in/img/documents/uploads/file_f-1618564141288.pdf

[3] GoI 2017. Report of 5th census of minor irrigation schemes. November 2017, Minor Irrigation (Statistics) Wing, Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India. Available online: http://www.mowr.gov.in/report-5th-minor-irrigation-census-has-been-released

[4] Rajan, A. and Verma, S. 2017. Evolving nature of India's irrigation economy: Insights from the Fifth Minor Irrigation Census. Water Policy Research Highlight #07, Anand: IWMI-Tata Water Policy Program. Available online: https://cgspace.cgiar.org/handle/10568/96928

[5] ITP, Greenpeace and GERMI. 2018. From rooftops to farmtops: Augmenting India's distributed solar goals through net-metered solar pumps. White paper by IWMI-Tata Water Policy Program (ITP), Anand; Greenpeace India and Gujarat Energy Research and Management Institute (GERMI), Gandhinagar. Available online: https://storage.googleapis.com/planet4-india-stateless/2018/07/White-Paper-Farm-Top-Potential-in-India.pdf

PART-I
Solar pump sizing protocols

The Part-I of this manual describes the overall architecture of the of the SIP Sizing tool. The section describes the data requirements and methodologies for estimation various parameters required in the solar pump sizing procedure.

General architecture of SIP Sizing tool

The MS Excel based tool was developed keeping in view the limited or slow internet connectivity in some regions. The excel based version is programmed using the Visual Basic Applications for MS excel. This is very portable and handy tool which can be used on any computer system without sophisticated software or installation requirements. The excel version has three different modules: Crop water requirement module, System head calculation module and Scenario Module. The 'Evapotranspiration based Irrigation Requirement (ETIR)' module uses both the Penman-Monteith Evapotranspiration (PMET) and a Root Zone Water Balance (RZWB) subroutines to estimate the irrigation water requirements. The RZWB subroutine simulates the inflow and outflow processes in the root zone at daily time step. The second module estimates the system head requirement considering frictional loss in pipes and fittings, elevation heads and the operational head requirements of irrigation methods selected for each plot. Third module works on estimating the head and discharges for different futuristic scenarios of kind of 'What if' analysis. The basic architecture of the excel version is presented in Fig. 1.

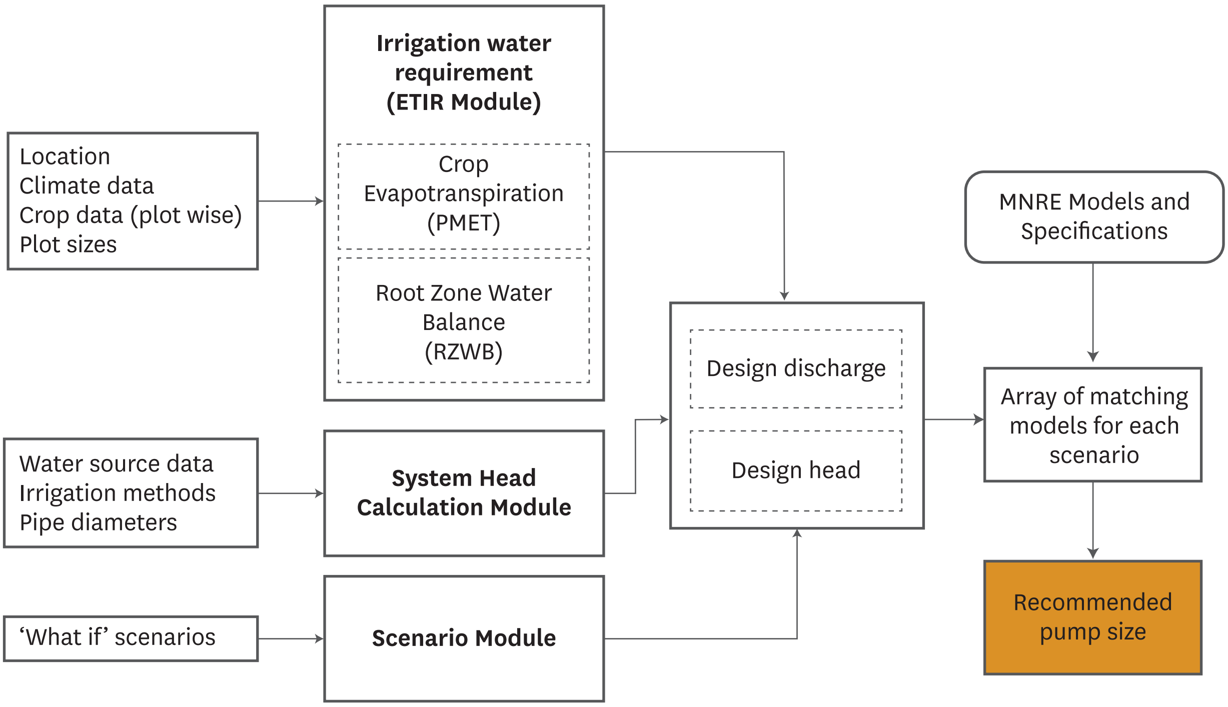


Figure 1 General architecture of the MS Excel based version of SIP sizing tool

Design considerations in solar pumps

Solar pumping system comprises of a pump (AC or DC), a solar panel to meet the power requirements of the pump and set array of regulatory and storage instruments connected in a sequential manner for the operation of the system. Although, the tool has limited links to the design of solar pumps *per se*, it only assists in selection of appropriate pump sizes in relation to climate, soil, groundwater levels, source of irrigation water and water demands.

Data inputs

The SIP sizing tool requires data pertaining to climate, soil, water source and plot wise details on crops and cropping systems of the area to be irrigated. Various data requirements and data sources are presented in Table 1 and Table 2. The gridded spatial data on soils and climate at the resolution of 0.5° latitude x 0.5° longitude is embedded in the tool. Upon selection of a particular location, the soil and climate data of that location is automatically loaded in the tool and is used in the further calculations. The gridded spatial data on soil properties is taken from Harmonized World Soil Dataset (HWSD), Version 1.2 of the Food and Agriculture Organization (FAO)[6]. Soil type for each grid within the boundary of India is taken from FAO dataset. The general values of related soil water properties like field capacity (FC), wilting point (WP), saturation percentage (SP), infiltration rate (IR) and maximum deep percolation rate (DP_m) of soil type under consideration are retrieved from Table 3. High- resolution (1° latitude × 1° longitude) daily gridded temperature data[7] and 0.25° latitude × 0.25° latitude gridded daily rainfall data[8] for the period 2009–2018 over Indian region was obtained from India Meteorological Department (IMD) Pune, India. Since the spatial resolution of the gridded data for rainfall and temperature are different, the climatic data for the grid point under consideration (user's location) is fetched from the girds of rainfall and temperature data using a nearest grid point approach.

Table 1. Data requirements in SIP Sizing tool

Data embedded in tool	
Soil	Soil texture, field capacity, wilting point, saturation percentage and infiltration rate, percolation rate
Spatial reference	Latitude, longitude, elevation
Climate	Maximum temperature, Minimum temperature, Rainfall
Irrigation system	Operating heads for different irrigation methods
User inputs	
Location	Selected directly on the map of India
Crop data	Type of crop, cropped area, planting date, planting month
Irrigation system	Type of water source (Well, pond, stream, river etc.), Depth to water table (in case of groundwater sources), Depth of the water level (in case of surface sources), Number of days allocated for irrigation in a month

[6]FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

[7]Srivastava, A., Rejeevan, M. and Kshirsagar, S. (2009). Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. Atmospheric Science Letters, 10: 249-254.

[8]Pai, D. S., L. Sridhar, M. Rajeevan, O. P. Sreejith, N. S. Satbhai, and B. Mukhopadhyay (2014), Development of a new high spatial resolution (0.25° × 0.25°) long period (1901-2010) daily gridded rainfall data set over the region, Mausam, 65, 1–18.

Table 2 Data sources

Variable	Data Source
Location (Latitude, Longitude, Altitude)	Gridded interactive map of India in provided in 'Location' sheet of the tool
Plot wise crop, area, sowing date and water application system	User entered
Water source (type of water source, Depth to Water level or depth of tube well)	User entered
Irrigation system data (distance of the plot from water source, conveyance pipe diameter, number of days allowed for irrigation in a month)	User entered
Rainfall (daily), Temperature (daily T_{max}, T_{min})	India Meteorological Department [2009 to 2018][9,10] https://www.imdpune.gov.in
Crop Details (Kc, rooting depth)	Indian literature and FAO-56[11] http://www.fao.org/3/x0490e/x0490e0b.htm
Soil (Texture, FC, WP, DP)	NBSSLUP, HWSD[12] http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
Database: Model type, head and discharge	Indicative Technical Specifications of Pumps by MNRE[13] https://mnre.gov.in/img/documents/uploads/file_s-1584510667387.pdf

Table 3 Soil properties of different textured soils as used in the SIP Sizing tool

Texture	Field capacity v/v %	Wilting point v/v %	Saturation percentage v/v %	Infiltration rate cm/h	Percolation rate cm/h
Sand	100	30	395	170.0	5.51
Loamy Sand	120	50	410	90.0	4.47
Sandy Loam	180	90	435	59.0	3.89
Loam	280	110	451	7.0	1.94
Sandy Clay Loam	350	200	420	20.0	2.73
Clay	410	250	482	7.0	1.94

[9] Pai D.S., Latha Sridhar, Rajeevan M., Sreejith O.P., Satbhai N.S. and Mukhopadhyay B., (2014). Development of a new high spatial resolution (0.25° X 0.25°) long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region., Mausam, 65, 1–18.

[10] Rajeevan, M., Jyoti Bhate, A.K. Jaswal, (2008) Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data., Geophysical Research Letters, Vol.35, L18707, doi:10.1029/2008GL035143.

[11] Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper-56, Food and Agriculture Organization of the United Nations, Rome, Italy.

[12] FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

[13] MNRE (2019). Specification for solar photovoltaic water pumping systems. Division, Ministry of New and Renewable Energy, Annexure-I of Circular No. F. No. 41/3/2018-SPV.

Monthly irrigation water requirement

Assessment of crop water requirement can be based on either climatological or root zone water balance approach. The tool has Evapotranspiration based Irrigation Requirement (ETIR) subroutine which uses the climatological approach to estimate the reference evapotranspiration (ET_o), crop evapotranspiration (ET_c), effective rainfall (P_e) and irrigation water requirement (I_r) of each crop within the selected cropping sequences. The ETIR subroutine estimates these parameters for the period of 10 years (2009-2018) at daily time step.

The 10-year average irrigation water requirement of each month then converted to monthly water requirements in volumetric units. The tool estimates irrigation water requirements based on root zone water balance using the subroutine called as Root Zone Water Balance (RZWB). In RZWB subroutine, all the input and output parameters of the water balance model are simulated at daily time step. The details of ETIR and RZWB subroutines are explained in following sections.

The PMET subroutine

Crop evapotranspiration is the indirect measure of crop's water demand. The term evapotranspiration (ET) is commonly used to describe two processes of water loss from land surface to atmosphere, evaporation and transpiration. In climatological approach, the crop evapotranspiration for different crop growth stages is estimated as certain percentage of reference evapotranspiration (ET_o) of the respective period. ET_o is the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation[14]. ET needs to be estimated for each crop and stage of growth and is referred to as crop ET (ET_c). The Penman- Monteith Evapotranspiration (PMET) module estimates the ET_o using the FAO-56 Penman-Monteith (PM) method[15]. Daily maximum and minimum temperature, latitude and altitude of the grid point (or location) are inputs to the PMET module. Other input parameters to PM method *viz.* humidity, radiation, wind speed were estimated using the inbuilt functions as specified in FAO-56[16].

FAO-56 equation was selected as it closely approximates grass ET_o at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters. The ET_o is estimated as;

$$ET_o = \frac{0.408\Delta\,(R_n - G) \; + \; \gamma \dfrac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\, u_2)}$$

Where,
ET_o= reference evapotranspiration (mm day^{-1}),
R_n= net radiation at the crop surface (MJ m^{-2} day^{-1}),
G= soil heat flux density (MJ m^{-2} day^{-1}),
T= air temperature at 2 m height (ºC),
u_2= wind speed at 2 m height (m s^{-1}),
e_s= saturation vapour pressure (kPa),
e_a= actual vapour pressure (kPa),
(e_s – e_a)= saturation vapour pressure deficit (kPa),
Δ= slope vapour pressure curve (kPa ºC^{-1}),
G= psychrometric constant (kPa ºC^{-1}).

ET_c is determined by the crop coefficient (K_c) approach wherein the effect of the various weather conditions is incorporated into ET_o and the crop characteristics into the Kc coefficient. The ET_c at daily time step is obtained by multiplying the ET_o with K_c.

$$ET_c = ET_o * K_c$$

The calculation procedure for crop evapotranspiration, ET_c, consists of:

1. Identifying the crop growth stages, determining their lengths, and selecting the corresponding Kc coefficients;
2. Adjusting the selected Kc coefficients for frequency of wetting or climatic conditions during the stage;
3. Constructing the crop coefficient curve (allowing one to determine Kc values for any period during the growing period); and
4. Calculating ET_c as the product of ET_o and Kc.

Daily values of ET_c are then aggregated to get the monthly ET_{cm} values of a crop for each calendar month as;

$$ET_{cm} = \sum_{j=1}^{n} ETo_j \times Kc_j$$

Where,
ET_{cm} is the monthly ET_c of month m, and ET_{oj} is the reference evapotranspiration on jth day of the month and n is total number of days in a month K_{cj} is the crop coefficient on jth day of the month.

The length of the crop growth stage is counted from the date of sowing. Crop growing period is mainly divided in to four stages viz. initial, development, middle and late. FAO Irrigation and Drainage Paper No. 24 provides general lengths for the four distinct growth stages and the total growing period for various types of climates and locations. In tool, a database of the length of growth stages and K_c values of crops is developed from several published researches within India[17] (Table 4).

[14]Allen, R. G., Walter, I. A., Elliot, R. L., Howell, T.A., Itenfisu, D., Jensen, M. E. and Snyder, R. (2005). The ASCE standardized reference evapotranspiration equation. ASCE and American Society of Civil Engineers.

[15]Zotarelli, L., Dukes, M. D., Romero, C. C., Migliaccio, K. W., and Morgan, K. T. (2010) Step by Step Calculation of the Penman–Monteith Evapotranspiration (FAO-56 Method), IFAS Extension, University of Florida, Florida, available at: http://edis.ifas.ufl.edu.

[16]Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper-56, Food and Agriculture Organization of the United Nations, Rome, Italy.

[17]Doorenbos, J. and Pruitt, W.O., 1977. Guidelines for Predicting Crop Water Requirements. Food and Agriculture Organisation of the United Nations, FAO Irrigation and Drainage Paper 24, Rome, 143 pp.

Table 4 Length of growth stages and crop coefficient of selected crops in PMET module

Crop	Length of the growth stage				Crop coefficient (K_c)			
	Initial	Dev	Mid	Late	Initial	Dev	Mid	Late
Barley/Oats	15	27.5	57.5	35	0.35	0.75	1.15	0.45
Bean/green	17.5	27.5	27.5	10	0.4	0.7	1.1	0.9
Bean/dry	17.5	27.5	37.5	20	0.4	0.7	1.1	0.3
Bajra	17.5	27.5	47.5	30	0.35	0.7	1.1	0.65
Cabbage	22.5	27.5	62.5	17.5	0.45	0.75	1.05	0.9
Carrot	22.5	32.5	50	20	0.45	0.75	1.05	0.90
Cotton/Flax	30	50	60	47.5	0.45	0.75	1.15	0.75
Cucumber	22.5	32.5	45	17.5	0.45	0.7	0.9	0.75
Eggplant	30	40	42.5	22.5	0.45	0.75	1.15	0.8
Fruit Tree - High water demand	0	0	365	0	0	0	1.1	0
Fruit Tree - Middle water demand	0	0	365	0	0	0	0.85	0
Fruit Tree - Low water demand	0	0	365	0	0	0	0.6	0
Grain/small	22.5	32.5	62.5	40	0.35	0.75	1.1	0.65
Groundnut	27.5	37.5	45	25	0.45	0.75	1.05	0.7
Gram	22.5	32.5	65	40	0.45	0.75	1.1	0.5
Jowar	20	32.5	42.5	30	0.35	0.75	1.1	0.65
Lentil	22.5	32.5	65	40	0.45	0.75	1.1	0.5
Lettuce	27.5	40	30	10	0	1	1	0.9
Maize, sweet	20	27.5	37.5	10	0.4	0.8	1.15	1
Maize, grain	25	42.5	50	35	0.4	0.8	1.15	0.7
Melon	27.5	40	52.5	20	0.45	0.75	1	0.75

Millet	17.5	27.5	47.5	30	0.35	0.7	1.1	0.65
Onion/green	25	35	15	7.5	0.5	0.7	1	1
Onion/dry	17.5	30	90	42.5	0.5	0.75	1.05	0.85
Paddy	30	30	70	35	0.35	0.75	1.1	0.65
Peanut/Groundnut	27.5	37.5	45	25	0.45	0.75	1.05	0.7
Pea	17.5	27.5	35	15	0.45	0.8	1.15	1.05
Pepper	27.5	37.5	75	25	0.35	0.7	1.05	0.9
Potato	27.5	32.5	40	25	0.45	0.75	1.15	0.85
Radish	7.5	10	15	5	0.45	0.6	0.9	0.9
Sorghum	20	32.5	42.5	30	0.35	0.75	1.1	0.65
Soybean	20	30	65	27.5	0.35	0.75	1.1	0.6
Spinach	20	25	27.5	7.5	0.45	0.6	1	0.9
Squash	22.5	32.5	32.5	20	0.45	0.7	0.9	0.75
Sugarbeet	35	50	70	40	0.45	0.8	1.15	0.8
Sugarcane	35	50	70	40	0.45	0.8	1.15	0.8
Sunflower	22.5	35	45	25	0.35	0.75	1.15	0.55
Tomato	32.5	42.5	55	27.5	0.45	0.75	1.15	0.8
Wheat	15	27.5	57.5	35	0.35	0.75	1.15	0.45

Irrigation water requirement of the crops is obtained after adjusting the estimated ET_c for effective rainfall. Effective rainfall (P_e) is the portion of the seasonal or monthly rainfall that is effectively been used by the crop in the process of evapotranspiration. It refers to the portion of a rainfall that infiltrates into the soil, is stored in the crop root zone and is useful for the growth of the crop. The Soil Conservation Service effective rainfall estimation method followed by the United States Department of Agriculture (USDA-SCS method) is being widely used. In this method, the upper limit of mean monthly effective rainfall is the mean monthly ET. In tool, the month implies the calendar month of the year. Based on sowing and harvesting dates, the tool makes necessary adjustments in P_e to consider only those days of the starting and end months which are part of the crop growing period, so that the P_e of the start and end months is not overestimated. The effective rainfall is calculated as:

$P_{em} = P_m \times (125 - 0.2 \times P_m)/125$ for P<250mm

$P_{em} = 125 + 0.1 \times P_m$ for P>250 mm

Where, P_{em} is the effective rainfall (mm) of m^{th} month (mm) and P_m is the Total rainfall (mm) of m^{th} month (mm).

Irrigation water requirement of a month (I_{rm}) is the portion of the monthly crop evapotranspiration (ET_{cm}) that is in excess of monthly (P_{em}). The monthly irrigation water requirement of the crop is then estimated as;

$$I_{rm} = ET_{cm} - P_{em} \qquad \text{if } P_{em} < ET_{cm}$$
$$I_{rm} = 0 \qquad \text{if } P_{em} > ET_{cm}$$

Irrigation requirement obtained using above equations is the net irrigation water requirement of the crops. The gross irrigation water requirement (I_{rg}) is estimated considering the irrigation efficiencies of the respective irrigation methods in each plot. In tool, the irrigation efficiencies (IE) of surface, sprinkler and drip systems are considered as 45, 75 and 90%, respectively.

$$I_{rmg} = \frac{I_{rm}}{IE}$$

The gross irrigation water requirement is converted into volumetric units by multiplying the I_{rmg} of each plot with the area of the respective plots. Volumetric irrigation water requirement of each calendar month is calculated as;

$$V_{mg} = \sum_{j=1}^{j=K} \frac{I_{rmgj} \times A_j}{4000}$$

Where, K is the number of plots considered in the command area of the solar pumping system, I_{rmgj} is the monthly gross irrigation water requirement of j^{th} plot (mm), A_j is the area of the j^{th} plot (acre). In tool the number of plots that user can enter are limited to 8. Factor 4000 is added in the denominator of above equation to convert the crop water requirement in the units of litre per month.

The RZWB subroutine

RZWB subroutine simulates the root zone water balance at daily time step considering the inflow and outflow process within the root zone. In solving this water balance equation for particular crop and soil type combo, daily values of ET_c are obtained from the PMET subroutine as discussed in the previous section. The soil properties like saturation percentage (SP), field capacity (FC), wilting point (WP) and maximum deep percolation rate (DP_m) at a particular grid point are fetched from the gridded soil database. Initial soil water content before the start of the simulation is also one of the important inputs in the model. The RZWB subroutine has an option to use the 'field capacity' of soil or user specified value of soil moisture as the initial soil moisture content before the start of growing period.

The simulation starts with computation of 'total water' (TW) which is the total inflow of water in the modelling domain. Mathematically, it is the sum of 'residual soil water' carried forward from previous day and 'rainfall + irrigation' of the present day. This is the total inflow in to the system which will be distributed among different outflow components as the simulation period progresses. Conceptually, TW represents the soil water storage, ponded water, potential runoff and deep percolation on a particular day (Fig. 2). Note that the model assumes that lateral inflows are balanced by outflows and there is no upward flux from a shallow water table.

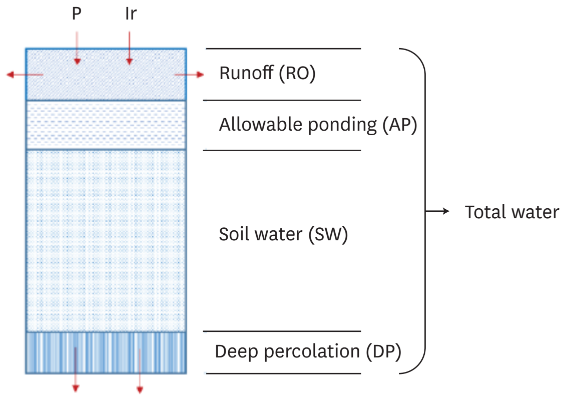


Figure 2 Conceptual representation of total water on i[th] day within the crop growing period

On first day of crop growing period, simulation starts with the total water as sum of initial moisture content (MC_i), rainfall (P_i) and irrigation (I_{ri}) on day-1 (i[th] day). Using the water balance approach, the residual soil water (RSW) on i[th] day is estimated considering the ET, RO and DP on i[th] day as follows:

$$TW_i = MC_i + (P_i + I_{ri})$$
$$RSW_i = TW_i - (ET_{ci} + RO_i + DP_i)$$

The residual moisture content on i[th] day is carried forward to next day (i+1), and the total water on (i+1)[th] day is estimated considering the P and I_r on (i+1)[th] day. The residual soil water on (i+1)[th] day is then obtained after accounting for the ET_c, RO and DP estimates of (i+1)[th] day.

$$TW(_{i+1}) = RSW_i + (P_{(i+1)} + Ir_{(i+1)})$$
$$RSW(_{i+1}) = TW(_{i+1}) - (ET_{c(i+1)} + RO_{(i+1)} + DP_{(i+1)})$$

Deep percolation

If the RSW is more than FC, the system is programmed to deduct excess soil moisture towards DP as per the following conditions. The logic here is, if the residual soil moisture on a particular day is not enough for deep percolation to occur at maximum deep percolation rate (DP_m), then the excess moisture above FC should be accounted towards deep percolation loss. If the RSW is in excess of FC + DP_m, then the deep percolation on that day should occur at maximum deep percolation rate of the soil.

$DP = DP_m$	if $(RSW - FC) > (FC + DP_m)$
$DP = RSW - FC$	if $RSW > FC$ and $RSW < FC + DP_m$
$DP = 0$	if $RSW < FC$

Runoff

If the RSW is more than SP, the system is programmed to deduct excess soil moisture towards RO as per the following conditions. In case of crops like paddy where fields are generally bunded and the height of bunds may vary from 5-15 cm. If the selected crop is paddy, then the default value of AP is set to 10cm however, the RZWB subroutine has an option to input the user specified depth of bund (allowable ponding, AP).

Paddy crop

$RO = RSW - (SP + AP)$	if $RSW > (SP + AP)$
$RO = 0$	if $RSW < (SP + AP)$

Paddy crop

$RO = RSW_{(i+1)} - SP$	if $RSW_{(i+1)} > SP$
$RO = 0$	if $RSW_{(i+1)} < SP$

Irrigation water requirement

The RZWB subroutine has two irrigation scheduling approaches viz. 'Refill to field capacity' and 'Application of specified depth'. In first option, if the moisture content carried forward from previous day (RSM_i) is below the critical limit (CL), an equivalent amount of irrigation is added to bring back the soil moisture level to field capacity. In second option, if the moisture content carried forward from previous day (RSM_i) is below the critical moisture limit, a user specified irrigation depth (I_{ru}) is added to the total soil water in the root zone. In both the options total depth of irrigation added over a growing period is summed up for each month to estimate the monthly irrigation water requirement of a crop. The default value of critical moisture limit is set at 50% of the available water. Available water is the amount of water present between FC and WP of the soil.

$$CL = 0.5 \times (FC - WP)$$

Option – 1: User specified depth

$$I_{r(i+1)} = I_{ru} \qquad \text{if } RSM_i < (WP + CL)$$
$$I_{r(i+1)} = 0 \qquad \text{if } RSM_i \geq (WP + CL)$$

Option – 2: Refill to field capacity

$$I_{r(i+1)} = FC - RSM_i \qquad \text{if } RSM_i < (WP + CL)$$
$$I_{r(i+1)} = 0 \qquad \text{if } RSM_i \geq (WP + CL)$$

Irrigation requirement obtained using above equations is the 'net irrigation requirement' of the crops. The gross irrigation water requirement is estimated considering the irrigation efficiency (IE) of the respective irrigation methods in each plot. In tool, the irrigation efficiencies of surface, sprinkler and drip systems are considered as 45, 75 and 90%, respectively. Monthly gross irrigation water requirement of a crop is estimated as the sum of daily irrigation water requirements within a calendar month. Total amount of water applied during each irrigation event of the calendar month is summed to get the monthly irrigation water requirement. In tool, the month implies the calendar month of the year.

$$I_{rmg} = \sum_{i=1}^{n} \frac{I_{ri}}{IE}$$

Where, I_{rmg} is the gross irrigation water requirement of m^{th} month (mm) and n is the number of irrigation events in the calendar month under consideration, I_{ri} is the net irrigation water requirement of the i^{th} irrigation event in m^{th} month (mm).

The gross irrigation water requirement is converted into volumetric units by multiplying the I_{rmg} of each plot with the area of the respective plots. Volumetric irrigation water requirement for each calendar month m is calculated as;

$$V_{mg} = \sum_{j=1}^{j=K} \frac{I_{rmgj} \times A_j}{4000}$$

Where, K is the number of plots considered in the command area of the solar pumping system, I_{rmg} is the monthly gross irrigation water requirement of j^{th} plot (mm), A_j is the area of the j^{th} plot (acre). Factor 4000 is added in the denominator of above equation to convert the crop water requirement in the units of litre per month.

Net system discharge

Precise estimation of irrigation water requirement is important task in designing of the solar pumping systems for irrigation purpose. Previous sections detailed the procedure to estimate the monthly gross irrigation requirements. Many a times, because of cloudy weather it is not possible to operate the solar pumping system for all the days of month. The management also has to keep some days reserved for repair and maintenance of the systems and to account for unforeseen breakdowns.

Further, it is not possible for the farmer to devote all the days of a month for irrigation. Therefore, the number of days the pump can be operated within a month are reduced to some practical limits. If the pump is scheduled to operate on limited days in a month, the discharge of the pump needs to be increased so that the monthly irrigation requirement is fulfilled within the number of days available for irrigation in that month. Decision on number of days available for irrigation in a month is the most critical factor in selecting a matching pump size. Larger number of operational days in a month will lead to lower discharge requirements and the selected pump will be of smaller size. The converse is also true.

To ensure that selected pump meets the water requirement of all the months of the year, the month having the maximum irrigation requirement is selected in determining the discharge capacity of the system. From the array of monthly vales, the maximum irrigation water requirement (V_{max}) for use in determining the system discharge is selected as;

V_{max} = Max(V_{mg})......m=1(January) to m=12 (December)

The design discharge of the solar pumping system is estimated as;

$$Q_s = \frac{V_{max}}{N \times 6 \times 3600}$$

Where, Q_s is the design discharge of the solar pumping system (l/sec), V_{max} is the maximum monthly gross irrigation requirement (l) and N is the user specified value of number of days available for irrigation in a month. Note that the number of days available for irrigation in a month is same for all months. The tool does not allow users to enter different number of days of operation for different months. The factor (6x3600) is added in the denominator to convert the discharge in the unit of l/day to l/s. An extensive review of the literature indicated that the duration of pumping in a day generally varies between 4.5 to 7.0 hrs with 6.0 hrs as median value. Therefore, in tool the duration of pump operation is fixed at 6 hrs per day.

Total dynamic head of the system

System operation head is another important criterion in selection of solar pump. Total head requirement is combination of geodetic head, friction head, operational head and the elevation head. Total dynamic head is calculated based on user inputs about the pumping water level, distance of the field from water source and the diameter of the conveyance pipe being used to carry water from water source to the field. Geodetic head refers to the actual physical difference in height between the pumping water level of at the water source and the highest point of the discharge. In estimating the geodetic head, the tool considers the elevation of tube well head at the ground surface as the discharge point while in case of other water sources elevation of the delivery side of the pump is considered as the point of discharge (Fig. 3). Friction head is the loss of head on account of friction in the pipes and fittings. Elevation head is the elevation difference between the delivery point at water source and the highest point in the command area of the system. The head required for operation of an irrigation system (say, drip or sprinkler) is termed as operational head requirement. Total dynamic head is calculated as;

$$H_t = H_{geo} + H_f + H_o + H_e$$

Where, H_t is total dynamic head requirement of the pumping system (m), H_{geo} is the geodetic head, H_f is the friction head loss in pipes and fittings, H_o is the operational head requirements for irrigation system and H_e is the elevation head.

Geodetic head

Geodetic head depends on the type of water source and the placement of the pump with respect to pumping water level. In case of streams, the geodetic head is the difference in elevation of the pump and the maximum possible lowest water level in the stream. If the water source is an open well, the depth of the open well is considered as the total geodetic head. If the water source is a tube well, 95% of the depth of the tube well is considered as the geodetic head. Geodetic head is limited to the maximum practical suction lift of the centrifugal pump (7.0 m) in the installations where pumps are placed at the ground surface (Table 5).

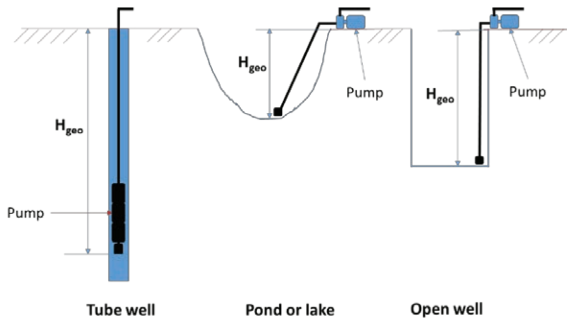


Figure 3 Computation of geodetic head for different water sources

Table 5 Computation of geodetic head for different water sources

Water source	Condition	Geodetic head, m
Stream	WL_{min} <7 m WL_{min} >7 m	$H_{geo} = WL_{min}$ $H_{geo} = 7.0$
Open well	d_{ow} <7 m d_{ow} >7 m	$H_{geo} = d_{ow}$ $H_{geo} = 7.0$
Pond/lake	d_p < 7 m d_p > 7 m	$H_{geo} = d_p$ $H_{geo} = 7.0$
Tube well	Submersible pump	$H_{geo} = 0.95 \times d_{tw}$

Where, WL_{min} is the minimum possible water level in the stream with respect to pump (m), d_{tw}, d_p and d_{ow} are the depths of tube well, pond and open well, respectively.

Friction head in pipes and fittings

Friction loss through the pipes is function of system discharge (Q_s) and the dimeter (D) of the pipeline. tool account for the friction loss on suction and delivery sides separately. User input is the diameters of the suction and delivery pipes and the distance of the field from the water source. The length of suction side is assumed to be the same as that of geodetic head.

$$H_f = h_s + h_d + h_{fit} + h_{syst}$$

Where, h_s is the friction loss on suction side of the pump (m), h_d is the friction loss on the delivery side of the pump (m), h_{fit} is the friction loss in fittings and accessories and h_{syst} is the friction loss in irrigation system (applicable to pressurised irrigation systems only).

The friction loss in the suction (h_s) and delivery (h_d) sides of the pump is calculated using Darcy Weisbach equation.

$$h_s = \frac{789000 \times L_s \times Q_s^{1.75}}{D_s^{4.75}}$$

$$h_d = \frac{789000 \times L_d \times Q_s^{1.75}}{D_d^{4.75}}$$

Where, L_s and L_d are the lengths of the pipes on suction and delivery sides (m), Q_s is the system discharge (l/s) and D_s and D_d are the diameters of the suction and delivery pipes (mm).

The friction loss in fittings and accessories is reasonably assumed as 10% of the total friction loss in pipes.

$$h_{fit} = 0.1 \text{ X } (h_s + h_d)$$

At the stage of pump selection, if the actual friction loss within the selected system (drip or sprinkler) is known, user can directly input this value in the tool for calculation of the system head. If the water application systems are yet to be designed, but the choice of systems for each plot have been finalised then the friction loss within the water application system is based on some thumb rule and the friction loss in these systems is assumed as 10% of the operational heads of these systems.

$$h_{syst} = 0.1 \text{ X } H_o$$

Where, h_{syst} is the frictional loss in the selected system of irrigation (m), H_o is the operational head of the selected water application system (m).

Operational head

Each irrigation system has its specific requirements for its operation to achieve higher application efficiencies. These head ranges often vary from 2 m in case of gravity fed systems to about 80m in case of rain guns. Variety of water application devises are available in the market with wide range of operational head requirements. It is bit difficult to generalise these ranges for its implementation in the tool. As in case of frictional losses within the water application systems, here also user gets the option to input actual operational requirement of the system or use the default value of the operational head for the selected water application method. The default system operational heads considered in the SIPS are presented in Table 6.

Table 6 Default values of the operational head of different systems

Irrigation Method	Operational head (m)
Surface/flood	0
Drip or trickle	10
Micro-sprinklers	15
Sprinklers	25

Elevation head

Elevation head is the difference in the elevation of the highest point in the command and the elevation of the pump discharge point. The tool assumes that the land is flat and the default value of elevation is set equal to zero. However, users get an option to override the elevation head where they can input the actual elevation head obtained from field surveys or visual observations of biophysical conditions within the command area.

Pump selection

The estimated parameters system discharge (Q_s) and the total dynamic head (H_t) are the two parameters used in the final selection of the optimal pump size. The Ministry of New and Renewable Energy (MNRE) of Government of India has issued the benchmarking criterion for solar water pumping systems. These guidelines provided technical specifications for six models (Model-I to Model-VI) for shallow well pumping systems (surface pumps) and fourteen models (Model-I to Model-XIV) for deep well pumping systems (submersible pumps) for AC induction motor (Table 7) as well as for brush less DC motor (Table 8) operated pump sets. In these models, the head ranges for shallow well pumping models varies between 10 to 30 m while that for deep well pumping models it is in the range of 30 to 100m

Table 7 Indicative technical specifications of solar pumping systems with A.C. induction motor

Model	Photovoltaic array Wp	Motor HP	Recommended Head, m	Shutoff Head m	Water output lpd
Deep well (Submersible)					
Model-I	1200	1	30	45	42000
Model-II	1800	2	30	45	63000
Model-III	3000	3	30	45	105000
Model-IV	3000	3	50	70	63000
Model-V	3000	3	70	100	42000
Model-VI	4800	5	50	70	100800
Model-VII	4800	5	70	100	67200
Model-VIII	4800	5	100	150	43200
Model-IX	6750	7.5	50	70	141750
Model-X	6750	7.5	70	100	94500
Model-XI	6750	7.5	100	150	60750
Model-XII	9000	10	50	70	189000
Model-XIII	9000	10	70	100	126000
Model-XIV	9000	10	100	150	81000
Shallow well (Surface)					
Model-I	900	1	10	12	89100
Model-II	1800	2	10	12	178200
Model-III	2700	3	10	12	267300
Model-IV	2700	3	20	25	132300

Model-V	4800	5	10	12	475200
Model-VI	4800	5	20	25	235200
Model-VII	4800	5	30	45	168000
Model-VIII	6750	7.5	10	12	641025
Model-IX	6750	7.5	20	25	330750
Model-X	6750	7.5	30	45	236250
Model-XI	9000	10	10	12	890000
Model-XII	9000	10	20	25	441000
Model-XIII	9000	10	30	45	324000

Table 8 Indicative technical specifications of solar pumping systems with brush less D.C. motor

Model	Photovoltaic array Wp	Motor HP	Recommended Head, m	Shutoff Head m	Water output lpd
Model-I	1200	1	30	45	45600
Model-II	1800	2	30	45	68400
Model-III	3000	3	30	45	114000
Model-IV	3000	3	50	70	69000
Model-V	3000	3	70	100	45000
Model-VI	4800	5	50	70	110400
Model-VII	4800	5	70	100	72000
Model-VIII	4800	5	100	150	50400
Model-IX	6750	7.5	50	70	155250
Model-X	6750	7.5	70	100	101250
Model-XI	6750	7.5	100	150	70875
Model-XII	9000	10	50	70	207000
Model-XIII	9000	10	70	100	135000
Model-XIV	9000	10	100	150	94500
Shallow well (Surface)					
Model-I	900	1	10	12	99000
Model-II	1800	2	10	12	198000

Model-III	2700	3	10	12	297000
Model-IV	2700	3	20	25	148500
Model-V	4800	5	10	12	528000
Model-VI	4800	5	20	25	264000
Model-VII	4800	5	30	45	182400
Model-VIII	6750	7.5	10	12	42500
Model-IX	6750	7.5	20	25	371250
Model-X	6750	7.5	30	45	256500
Model-XI	9000	10	10	12	990000
Model-XII	9000	10	20	25	495000
Model-XIII	9000	10	30	45	342000

The tool makes use of these model specification to work out the matching pump size for the system under consideration. The pump selection module is programmed to select the smallest capacity model that meets the requirements of estimated Q_s and H_t of the command area. In first stage, the tool selects the type (submersible or surface) of pump from the wide array of the models specified in MNRE guidelines. If the water source is tube well, a 'submersible' type of model is selected and in all other cases a 'surface' type of model is selected. In second stage, the selection module identifies a subset (Hp_i) of all the possible models that meet the estimated Q_s and H_t requirements. In third stage, the model with lowest capacity (Hp or lowest panel capacity) is selected from the subset (Hp_i). The flowchart in Fig. 4 explains the logic used in tool for selection of matching pump size as per MNRE guidelines.

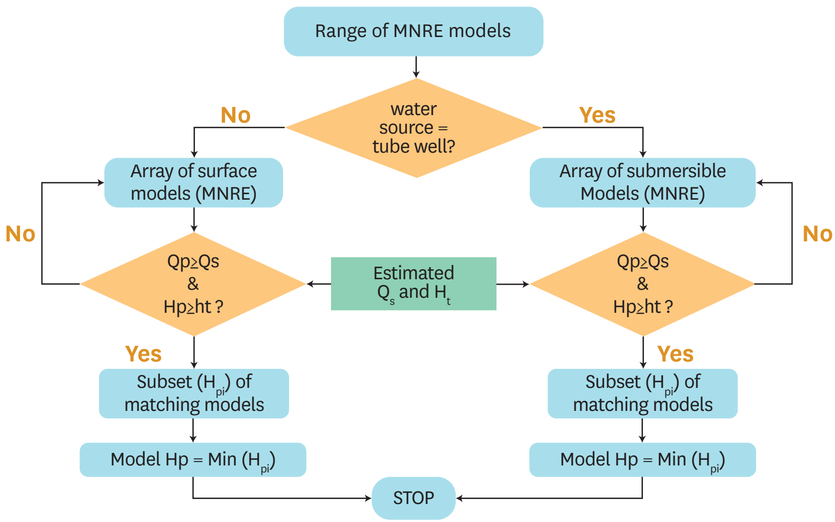


Figure 4 Flowchart of pump selection procedure in the tool

Scenarios

The design discharge and total dynamic head obtained in previous sections is under prevailing set of bio-physical conditions. However, the selection of pump should also consider the futuristic scenarios likely to occur due to adverse weather, changed agricultural scenario and changing water table levels within the region. An under designed pump may not be able to meet the increased water demands under such scenarios. The tool incorporates such scenarios to select a pump which will have enough capacity to cater to the water demands under unforeseen conditions likely to occur in near future.

Scenario I: Baseline scenario

This is the baseline scenario under prevailing climatic and bio-physical conditions of the region. The system discharge and the total dynamic head selected under this scenario is the same as that estimated using the methodology described in the previous sections. In this scenario the estimated values of Q_s and H_t are used in selecting the matching pump size.

Scenario II: Increased irrigation

The increased irrigation requirements can be result of increased temperature or change in other bioclimatic conditions. Instead of calculating effects of those parameters on irrigation requirements, we adopted simplified approach. We used user specified coefficients to account for increased irrigation requirements. Irrigation requirement increase must be specified carefully considering all the factors on farm. All calculation to estimate coefficient must be done by user externally. Increased irrigation requirements would need higher daily discharge and hydraulic parameters like friction losses are recalculated again for this scenario.

Scenario III: Change in water table depth

With increased competition from non-agricultural sectors, there has been increasing pressure on the groundwater resources. In many parts of the country increased aquifer draft has led to decline in water tables at an accelerated rate. The increased drawdown will increase the geodetic head requirements and the pump discharges will be much lower than the design capacity. Under such conditions, pump selected on the basis of prevailing water table conditions many not be sufficient to meet the discharge requirements under deeper water table conditions. This scenario is accounted in the tool in such way that user gets an option to increase the drawdowns by certain percentage (G). New geodetic head requirements are then recalculated using the user entered value. In this scenario the discharge requirement is same as that of baseline scenario, while the head requirement changes as per the user specified percentage value (G). The new geodetic head requirement is calculated as;

$$H'_{geo} = H_{geo} \times \frac{G}{100}$$

This revised value of H'_{geo} is used to compute the new total dynamic head H_t'.

$$H_t' = H'_{geo} + H_f + H_o + H_e$$

Using the Q_s for baseline scenario and H_t' calculated above, the final pump size is selected as per the procedure specified in 'Pump selection' section.

Scenario IV: Target discharge

This scenario gives the freedom to user to define the target discharge for the system under consideration. Here, the tool bypasses all the discharge calculation protocols and uses the user specified value of discharge (Q_u) in selecting the pump size. In this scenario head requirement is assumed to be the same as that of baseline scenario.

Final model selection

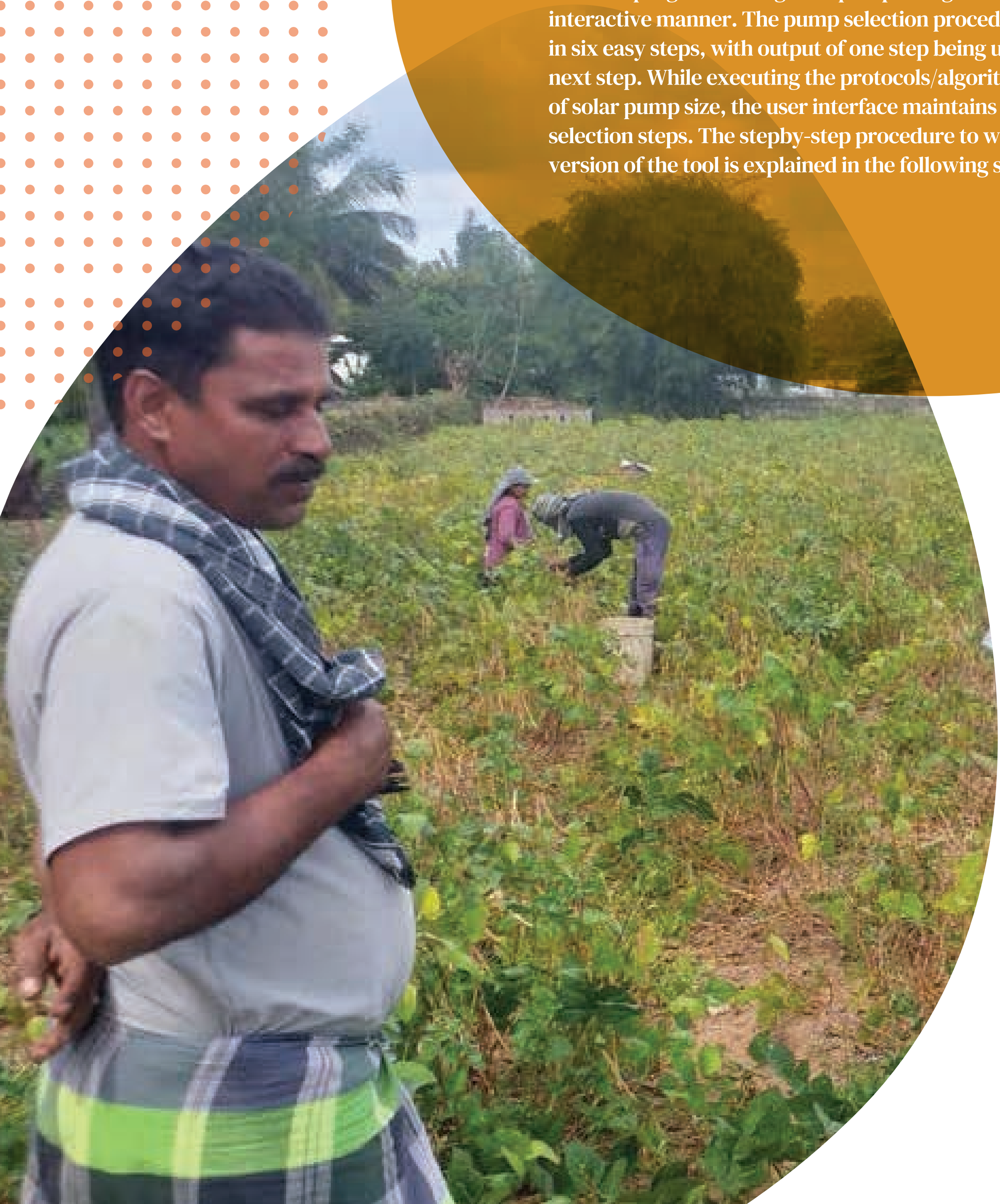
The tool has four operational scenarios (I, II,III, and IV). The tool identifies the array of best suiting models (M_i) for each scenario. Here, user has the choice to select any of the model from this array based on understating of the present and future likely changes in biophysical conditions of the region. The developers of the tool recommend to select the final model (M_f) that meets the head and discharge requirements across all the futuristic scenarios. In doing so, the user can be sure that the selected the pumping system will be flexible enough to accommodate the changes in irrigation requirements and deepening ground water levels. The final model from the array of scenario models will be selected as;

$$M_f = Max(M_i)$$

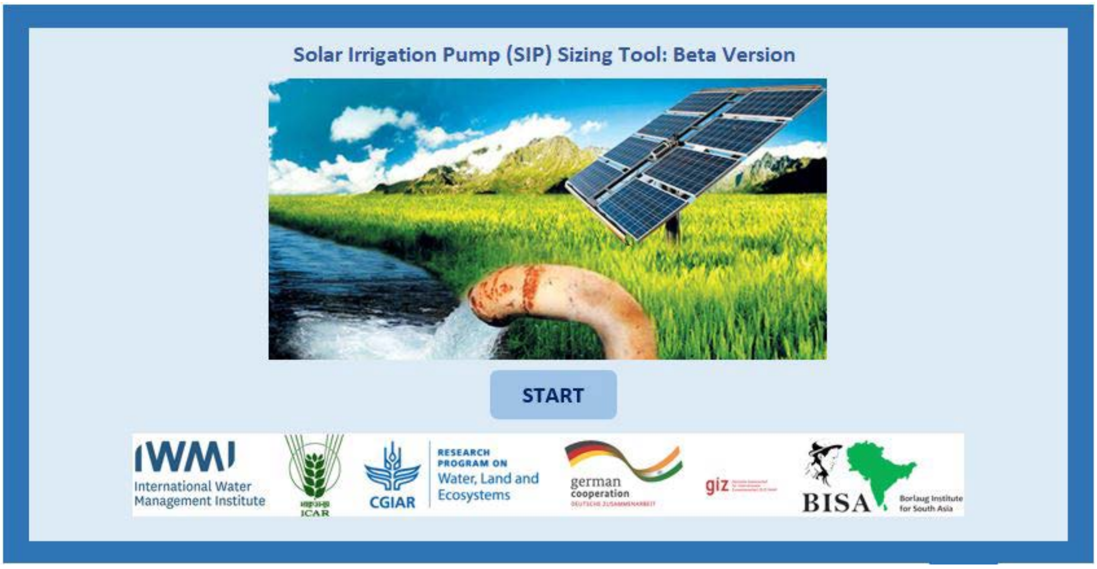
Where M_i is the array motor capacities of the scenario models and M_f is the motor capacity of the final selected model. The tool provides output in the form of MNRE model number, motor capacity (Hp), operational head (m), shutoff head (m), discharge (lpd) and required panel capacity of model for each scenario and the final selected model.

PART-II Working with SIP Sizing Tool Beta version

Excel based SIP sizing tool is a user-friendly Beta version wherein user can progress through the pump sizing exercise in an interactive manner. The pump selection procedure is completed in six easy steps, with output of one step being used as input to the next step. While executing the protocols/algorithms for selection of solar pump size, the user interface maintains the sequences of selection steps. The stepby-step procedure to work with the Beta version of the tool is explained in the following section.

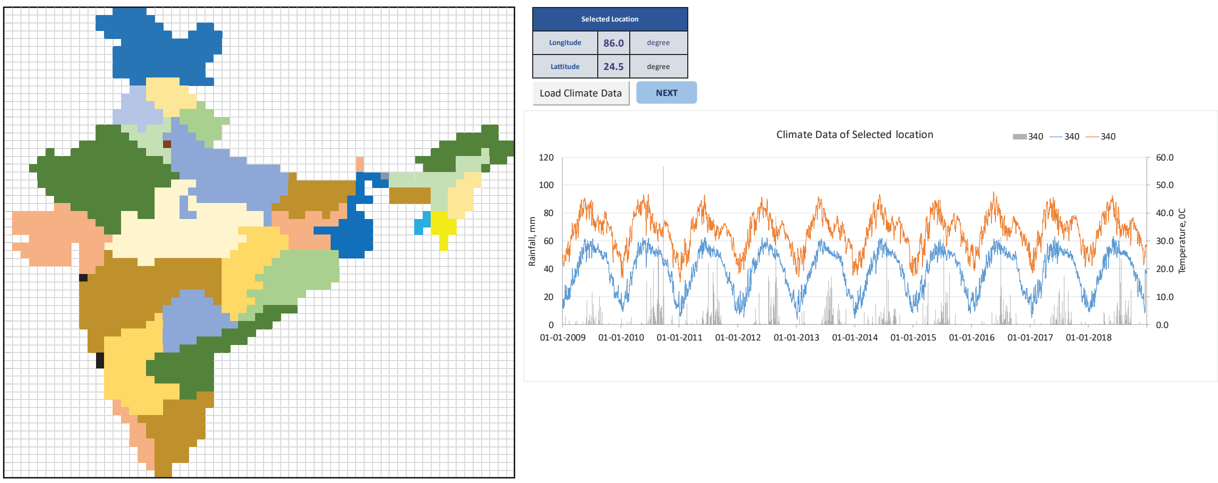


Step 1: Open the excel file SIP Sizing Tool and it will display the 'Start screen'.



a. Click on 'Start'. This will open the 'Location' sheet.

Step 2: "Location" sheet



a. Select the location of by clicking within the coloured grid. Here the boundaries of states are marked in different colours. The latitude and longitude of the 'selected location' will update automatically.

b. Click on 'Load Climate Data'. The graph will be updated with climate data of selected grid point.

c. Click on 'Next'. This will open the 'Input' sheet.

Step 3: “Input” sheet

Cropping System Details						
Sl. No.	Crop	Area, acre	Planting date	Planting Month	Irrigation system	Operating Head,m
Crop 1	Paddy	1	20	Jul	Surface/flood	3
Crop 2	Pea	1	10	Oct	Micro-sprinklers	14
Crop 3	Potato	1	20	Oct	Surface/flood	3
Crop 4	none	0	0	Aug	Surface/flood	3
Crop 5	none	0	0	Jan	Surface/flood	3
Crop 6	none	0	0	jan	Surface/flood	3
Crop 7	none	0	0	jan	Surface/flood	3
Crop 8	none	0	0	jan	Surface/flood	3
Crop 9	Pea	0	25	Feb	Surface/flood	3
Crop 10	none	0	26	Sep	Surface/flood	3

BACK NEXT

a. Select the crops from the dropdown menus. You can select ten crops at the maximum. Not necessary that all the crops are from same cropping season.

b. Enter the area of each plot in the ‘Area’ column. Area is in the units of ‘acre’.

c. Enter the planting date of each crop in ‘Planting date’.

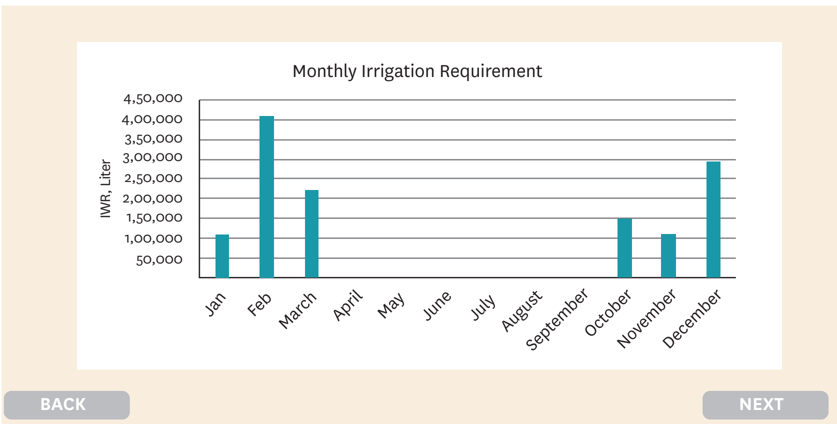
d. Against each planting date, select the month of planting from dropdown menu.

e. Select the present or proposed irrigation systems for each plot from the dropdown menu in column ‘Irrigation system’.

f. The operational head of the selected system will be updated automatically in the last column ‘Operating head’. Here user can change the default head values based the actual head requirements provided by the designer of irrigation system.

g. Click ‘NEXT’. This will open the irrigation water requirement ‘IWR’ page.

Step 4: ‘IWR’ sheet



a. This sheet is just a visual presentation of monthly irrigation water requirement of all the crops in a cropping sequence

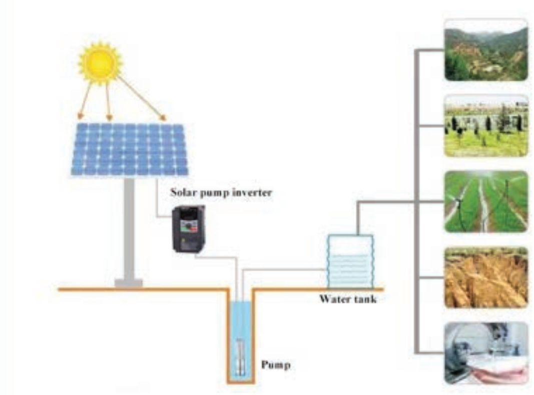
b. Click ‘NEXT’. This will open the system head calculation module ‘SYSTEM-HEAD’

Step 5: ‘SYSTEM-HEAD’ sheet

System head requirement		
INPUTS		
Parameter	Value	Unit
Depth to pumping water level/tube well	10	m
Distance from source to field	50	m
Elevation of the highest point in field	3	
Pipe diameter from source to field	50	mm
Water Source	Open well	
Number of days allocated for irrigation in a month	10	days

OUTPUT	
Estimated total head requirement	
Head component	**Head, m**
Operatonal head of irrigation system	12.0
Friction loss in the irrigation system	1.2
Frictional head loss in suction and delivery sides	1.2
Friction loss in fittings and accessories	0.1
Total System head, m	**27.4**

NEXT



a. Enter all the required data in the ‘INPUTS’ section of the sheet
b. Pipe diameter from source to field is the diameter of the pipe used to convey water from water source to the field.
c. Select the water source from dropdown menu
d. Enter ‘Number of days allocated for irrigation in a month’. This field denotes the actual number of days on which irrigation is to be done. This is same for all months.
e. Last row of the ‘OUTPUT’ section is the total system head. It includes all the elevation head, friction head and geodetic head.
f. Click ‘NEXT’. It will open the sheet ‘RESULTS’

Step 6: The ‘Results’ sheet

Input for Futuristic Scenarios		
Scenario		**Enter data here**
I	Farmers choice of pump type	AC
II	Increased irrigation requirement, %	500%
III	Increased Depth to Water Level, %	20%
IV	Target Discharge Scenario, lpd	80,000

SIP Sizing Tool Results

	Scenario	Design Discharge liter per day	Design Head, meter	Motor HP	Category	Model	Pvarray_Wp	Head, m	Shutoff head, m	Discharge, LPD
Scenario- I	Base Scenario	50,969	26.5	2	Submersible	Model-II	1800	30	45	63,000
Scenario- II	Increased irrigation requirement	76,454	26.7	5	Submersible	Model-VI	4800	50	70	1,00,800
Scenario-III	Increased Depth to Water Level	50,969	29.3	2	Submersible	Model-II	1800	30	45	63,000
Scenario-IV	Target Discharge Scenario	80,000	26.7	5	Submersible	Model-VI	4800	50	70	1,00,800
BACK	Recommended model			5	Submersible	Model-XII	4800	50	70	1,00,800

a. Enter the choice of pump type as 'AC' or 'DC'.

b. Enter the values of possible changes in irrigation requirement or depth to water table in Scenario – II and III.

c. Enter the value of target discharge for the Scenario-IV.

d. As you enter the inputs the 'SIP sizing tool Results' will be updated automatically.

e. The section 'SIP sizing tool Results' provides the best selected model for each scenario

f. Last row of the 'SIP sizing tool Results' is the final selected model that can meet the head and discharge requirements across all the scenarios.

"Redesign" message on results sheet

Input for Futuristic Scenarios		
Scenario		Enter data here
I	Farmers choice of Pump type	AC
II	Increased irrigation requirement scenario %	50%
III	Increased Depth to Water Level, %	20%
IV	Target Discharge Scenario, lpd	2,00,000

SIP Sizing Tool Results										
	Scenario	Design Discharge	Design Head	Motor HP	Category	Model	Pvarray_WP	Head, m	Shutoff head, m	Discharge, LPD
		litre per day	Meter							
Scenario - I	Base Scenario	2,54,847	29.9	Redesign	Submersible	Redesign	Redesign	Redesign	Redesign	Redesign
Scenario - II	Increased irrigation requirement	3,82,270	33.7	Redesign	Submersible	Redesign	Redesign	Redesign	Redesign	Redesign
Scenario - III	Increased Depth to Water Level	2,54,847	32.8	Redesign	Submersible	Redesign	Redesign	Redesign	Redesign	Redesign
Scenario - IV	Target Discharge Scenario	2,00,000	28.7	Redesign	Submersible	Redesign	Redesign	Redesign	Redesign	Redesign
Back	Recommended model			0	Redesign	Redesign	Redesign	Redesign	Redesign	Redesign

Sometimes the tool may return a "Redesign" message in the result cells of a particular scenario as shown above. This situation arises when the calculated pump size is too large and that the matching model is not available under the PM-KUSUM scheme. In such cases users are advised to reduce the number of plots so that the effective area to be irrigated is reduced. After reducing the number of plots or area of plots, follow the entire design procedure described in above sections.

Limitations of the Tool

In practice, there may be a greater number of plots in the command area of the solar pump, but at present, the tool has the capability to include data from eight plots. Climate data acquired from nearby meteorological station should be preferred in estimation of crop water requirements used in computation of pump discharge. Instead of local meteorological observatory data, the tool uses a gridded climatic data, which may lead to slight deviation in the discharge calculated using the tool and final model selection may also vary. The selection of pumps matching to estimated head and discharge is based on the MNRE guidelines. The actual duration of pumping of water on a particular day and the quantity of water pumped could vary depending on the solar intensity, location, season, etc.

A Note on Using the Tool

While the tool has made every attempt to incorporate all influencing variables and scenarios, the developers would suggest that the tool be used for better understanding needs, rather than prescribing solar pump sizes for farmers. Our consultations with partners and solar developers also confirmed that the ideal users of this tool would be state nodal agencies, financing partners, agricultural extension officials, civil society organizations, pump manufacturers and electricity utilities (for grid-connected solar pumps). All of these can benefit from an improved understanding of factors that drive farmers' irrigation demand, pumping behavior, and decisions about 'pump size'.

Developers of the tool

Santosh S. Mali
Senior Scientist (Soil and Water Conservation Engineering)
ICAR – Research Complex for Eastern Region (RCER), Patna
santosh.mali@icar.gov.in

Paresh B. Shirsath
Climate Change Adaptation Specialist
Borlaug Institute for South Asia (BISA), New Delhi
p.bhaskar@cgiar.org

Shilp Verma
Senior Researcher (Water-Energy-Food Policies)
International Water Management Institute (IWMI), Anand
shilp.verma@cgiar.org

Alok K. Sikka
Country Representative and Principal Researcher
International Water Management Institute (IWMI), New Delhi
a.sikka@cgiar.org

Note

International Water Management Institute (IWMI)

The International Water Management Institute (IWMI) is an international, research-for development organization that works with governments, civil society and the private sector to solve water problems in developing countries and scale up solutions. Through partnership, IWMI combines research on the sustainable use of water and land resources, knowledge services and products with capacity strengthening, dialogue and policy analysis to support implementation of water management solutions for agriculture, ecosystems, climate change and inclusive economic growth. Headquartered in Colombo, Sri Lanka, IWMI is a CGIAR Research Center with offices in 13 countries and a global network of scientists operating in more than 30 countries.

International Water Management Institute
Anand:
IWMI-Tata Water Policy Research Program,
"Jal Tarang", Near Smruti Apartment, Behind IRMA Gate,
Mangalpura, Anand- 388001, Gujarat, India
Tel/ Fax: +91 2692 263816/817
E-mail: iwmi-anand@cgiar.org
New Delhi:
2nd Floor, CG Block C, NASC Complex, DPS Marg, Pusa,
Opp Todapur, New Delhi 110 012, India
Tel: +91 11 25840811, 25840812 and 25843536
Fax: +91 11 25840811 E-mail: iwmi-delhi@cgiar.org
W: www.iwmi.org

IWMI International Water Management Institute
CGIAR
RESEARCH PROGRAM ON Water, Land and Ecosystems

Copyright © 2022, IWMI. All rights reserved. IWMI encourages the use of its material provided that the organization is acknowledged and kept informed in all such instances.