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CFD-2D COMPUTATIONAL MODELING OF DRAINAGE SYSTEMS FOR SOLAR FARM

Joel B. Kazadi[1], Gilberto Figueiredo[1] Gabriel C. Nascimento[1] Elson Nascimento[1]

1 Federal Fluminense University, Niteroi (Brazil)

Summary

Drainage design is a key component in photovoltaic plant infrastructure with environmental and economic challenges related to the understanding of the areas to be properly drained. Traditional methods applied to drainage projects related to roads, and urban and agricultural areas, have also been applied for solar farms in Brazil. It can lead to either oversized or insufficient drainage structures, which may add risks to the project's goals. The present study applies the Two-dimensional Computational Fluid Dynamics Modeling - CFD-2D to design a drainage system for a solar farm where the results were compared to the traditional Rational Method runoff calculation. The computational modeling method resulted in a 22.54% reduction in the length of gutters compared to the traditional calculation procedure. A significant reduction in the final hydrological volume allocated to the delay reservoirs was also achieved. This means cost reduction, better compliance with the construction schedule, and less environmental impact in the project surrounding areas.

Keywords: photovoltaic plant, drainage system, CFD-2D modeling, HEC-RAS,

1. Introduction

The energy transition, driven by the need to replace or complement the fossil fuel foundations of the energy matrix with sustainable sources, has become a major challenge for engineers and entrepreneurs worldwide. In this context, photovoltaic power plants, also known as solar farms, have attracted growing investment interest in Brazil, particularly in arid regions with gentle topography, which are well suited for this type of construction project(Fig.1).

Figure 1 – Solar Farm

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However, the expansion of these large-scale power plants poses significant hydrological and environmental challenges, mainly due to the increased surface runoff over extensive impervious areas and the lack of specific drainage standards tailored to this type of project. Both in Brazil and in other countries, such as Australia and the United States, drainage infrastructure has proven to be one of the main points of concern, given the high costs and the risk of environmental impacts that may compromise the viability and safety of the facilities, as well as affect surrounding areas. In light of this regulatory gap, professionals in the sector have relied on methodologies traditionally applied in urban, highway, and agricultural drainage such as the references established by the National Department of Transport Infrastructure (DNIT, 2005) and by the Municipality of Rio de Janeiro (RIO-ÁGUAS, 2019).

On the other hand,, these practices are largely based on conventional hydraulic and hydrological calculation methods, which do not always adequately represent the behavior of surface runoff in large-scale developments, potentially resulting in oversized or undersized drainage structures (MAIA, 2021).

Aiming to contribute to the technical improvement of such projects, the actual study presents the analysis of a drainage system for a photovoltaic power plant using two-dimensional hydrodynamic modeling ,CFD-2D, by appluying the HEC-RAS software. Complemtary it was developed a comparison between de Modeling results and those derived from the traditional Rational Method application.

Initially, a functional characterization of the drainage systems of photovoltaic plants was performed, with an emphasis on stormwater management in areas with extensive impervious surfaces, such as solar modules, and soils susceptible to erosion. This phase identified the main problems associated with inadequate drainage, such as soil instability, erosion, siltation, and reduced bearing capacity of the panel foundations (Fig.2).

Fig. 2 – Soil instability and erosion (LANCASTER, 2023)

Specifically, the study aims to: (i) collect topographic, hydrological, and permeability data to generate a Digital Terrain Model - DTM and delineate sub-basins using QGIS; (ii) simulate surface runoff considering hydrological scenarios with return periods of 50 years for channels and 100 years for detention basins; and (iii) evaluate the potential for optimizing the drainage system by reducing channel lengths and basin volumes, while ensuring hydraulic efficiency and environmental sustainability.

Subsequently, an assessment was conducted of the components of the drainage system, including surface and subsurface drains, flow channels, infiltration basins, and sediment control dams. Complementary erosion control practices were also analyzed, such as the use of stabilizing vegetation and energy dissipation structures. This analysis aimed to determine the hydraulic and environmental efficiency of each component and their interrelationships within the integrated drainage system.

For the planning and design of drainage solutions, site-specific conditioning factors were considered, such as topography, soil permeability, rainfall regime, and the arrangement of photovoltaic modules. These parameters supported the formulation of hydrological and hydraulic model representative of the actual operating conditions.

The hydrological and hydraulic analyses were complemented by a geotechnical assessment of foundation materials, taking into account the infiltration rates and the soil response to saturation. This data integration enabled the development of an optimized drainage model focused on minimizing environmental impacts and maximizing the plant's hydraulic efficiency.

Finally, the simulation results were analyzed from the perspective of operational efficiency and system sustainability, allowing for the identification of critical points and the proposal of corrective or preventive measures. The adopted methodology enabled not only the appropriate technical sizing of the drainage systems but also the formulation of guidelines for the planning of more resilient, durable, and environmentally integrated solar power plants (BUFFON, 2010; SANTOS et al., 2021).

2. Metodology

2.1. Rational Method Calculation

The calculation of surface runoff discharge using the Rational Method was developed based on data obtained from the Digital Terrain Model - DTM, which provides a three-dimensional representation of the topographic variations within the study area. The DTM was generated from topographic data acquired through conventional surveys and aerial photogrammetry, processed using specialized software such as Autodesk Civil 3D and QGIS, which enable detailed geomorphological analysis and the automatic delineation of contributing basins.

Based on the DTM, the boundaries of the sub-watersheds and their respective drainage areas were defined, allowing the application of the Rational Method to estimate surface runoff. This method is widely used in drainage design due to its simplicity and effectiveness in determining the peak discharge associated with rainfall events of a given intensity and duration.

In this study, the total area of approximately 100 hectares was subdivided into 72 sub-basins to enable runoff calculation and verification of the results obtained through numerical modeling. While the two-dimensional hydrological model considered the mass movement within a mesh of about 50,000 points, the Rational Method was used as a comparative reference, reinforcing the consistency of the simulated results.

2.2. Fundamental Equations and Their CFD-2D Formulation

The equations governing these phenomena are derived from the fundamental conservation principles of physics. With the advent of high-performance computing, the numerical solution of these equations has become feasible, giving rise to the field of Computational Fluid Dynamics - CFD. The CFD-2D Modeling approach, in particular, is extremely valuable in river and floodplain hydraulics, where geometric complexity and spatial extent make analytical solutions impractical.

The core of any CFD simulation lies in the solution of the governing equations. For a Newtonian and incompressible fluid, a common approximation for water in free-surface flows the main equations are as follows:

2.2.1. Mass Conservation - Continuity Equation

This equation states that mass cannot be created or destroyed. For a control volume, the rate of mass accumulation is equal to the net mass flux entering and leaving the volume. Its differential form for a 2D incompressible fluid is:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \text{(eq. 1)}$$

Where (u) and (v) are the velocity components in the (x) and (y) directions, respectively. In the context of open-channel and floodplain flows, HEC-RAS uses an integrated form of this equation that accounts for the flow depth (h), commonly referred to as the Shallow Water Continuity Equation.

2.2.2. Navier-Stokes Equation and Saint-Venant Equation

Derived from Newton's Second Law, this equation states that the rate of change of a fluid's momentum is equal to the sum of the forces acting on it, both surface and gravitational forces. For an incompressible fluid, the Navier–Stokes equations in the (x) and (y) directions are:

$$\rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = \rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) \quad \text{(eq. 2)}$$
$$\rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) = \rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) \quad \text{(eq. 3)}$$
$$\rho g_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = \rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) \quad \text{(eq. 4)}$$

Where:

(t) is time,
(p, u, v, w) are the unknown variables,
(g_x, g_y), and (g_z) are the components of gravitational acceleration.

In shallow water models, such as the one used in HEC-RAS 2D, these equations are vertically integrated, resulting in the SWE – Shallow Water Equation, also known as the full Saint-Venant Equation (BALZANO, 1998).

This mathematical representation allows for the calculation of velocity and water depth over space (2D) and time (transient). The two-dimensional approach is suitable for problems in which the water depth (along the (z)-axis) is small compared to the domain's horizontal extent (along the (x) and (y) axes). These equations describe the flow of fluids with a free surface (such as rivers, channels, and floodplains) in two horizontal dimensions, representing the conservation of mass and momentum for free-surface flows.

2.3. CFD-2D Modeling

The CFD-2D modeling stage aimed to simulate the hydrodynamic behavior of water flow over the terrain, in order to understand surface runoff dynamics and evaluate the efficiency of the proposed drainage solutions. To achieve this, digital terrain modeling and flow simulation were performed using integrated computational tools such as HEC-RAS 6.4.1 and QGIS.

Initially, Digital Elevation Models (DEMs) were used to identify preferential flow paths, accumulation zones, and potential areas susceptible to erosion or flooding. The Digital Terrain Model (DTM) was generated from a raster base with a 7-meter spacing, resulting in an interpolated mesh with approximately 3.5-meter spatial resolution, composed of about 50,000 points. This mesh was processed in QGIS and imported into HEC-RAS for the definition of boundary conditions and hydraulic parameterization of the domain.

The hydrodynamic simulation was conducted based on the Shallow Water Equations (SWE), also known as the full Saint-Venant Equations, within the CFD-2D (Computational Fluid Dynamics) framework, as described by Balzano (1998). This numerical model allows a detailed representation of two-dimensional flow over complex surfaces, capturing spatial variations in velocity, depth, and energy across the terrain.

A total of 72 contributing sub-basins were automatically delineated and used to validate the results against the Rational Method, ensuring consistency between simplified hydrological estimates and the numerical modeling results. The mass balance was analyzed considering the total area of 100 hectares, which enabled the evaluation of the efficiency of the pre-sized drainage structures under different rainfall scenarios, providing technical support for the improvement of the proposed system.

2.4. Rational Method

The Rational Method is one of the most traditional and widely used approaches for estimating the peak surface runoff in watersheds during intense precipitation events. Its principle is based on the direct relationship between the maximum rainfall intensity, the runoff coefficient, and the watershed's contributing area, allowing the calculation of peak discharge at the outlet point.

The rainfall intensity used in the method is a function of the time of concentration, which represents the time required for rainwater to travel across the entire watershed to the outlet. This time depends on factors such as topography, soil roughness, vegetation cover, land use, and occupation, as well as climatic variables, including return period and regional rainfall history. The contributing area, expressed in hectares, corresponds to the surface over which surface runoff occurs and is one of the fundamental parameters in the formula (Equation 5).

$$Q = 0{,}0028 \times C \times I \times A \quad \text{(eq. 5)}$$

Q – Runoff flow (m^3/s)

C – Runoff coficient

I – Precipitation intensity (mm/h)

A – Contribuition area (ha)

Although widely adopted, the Rational Method has some conceptual and practical limitations. Garcez (1969) points out that the method can be considered "not very rational," since the definition of certain parameters particularly the runoff coefficient, C, involves subjectivity on the part of the designer. This coefficient is intended to indirectly represent the rate of water infiltration into the soil, functioning as a global index that does not account for local variations in velocity and infiltration within the watershed. As a result, the method provides the total runoff, that is, the discharge at the watershed outlet, without detailing the internal distribution of flows. In this context, some authors suggest that the term "runoff coefficient" would be more appropriate for the parameter "C" in the equation.

Due to these simplifications, the Rational Method is more suitable for small to medium-sized watersheds with short times of concentration, and it is less effective in large areas or during long-duration events. Nevertheless, it remains a practical and efficient tool, widely used in urban and highway drainage projects, as well as in preliminary stormwater management analyses. Its operational simplicity and immediate applicability make it a valuable starting point for initial discharge estimates, which can later be complemented by more complex methods, such as the Unit Hydrograph, capable of more accurately representing flood wave attenuation and the hydrological dynamics of the system.

3. Results

3.1. Hydrological and hydrogeological parameters

The study focused on projects located in the northern region of Minas Gerais, adopting the IDF - Intensity-Duration-Frequency equation from the Colônia do Jaíba/MG Meteorological Station, developed by the Research Group on Hydrology and Hydrological Modeling of Watersheds at UFPel. For the design of the channels, a return period (Tr) of 50 years was adopted in accordance with DNIT standards (2005), and the temporal rainfall distribution was applied using the Alternating Block Method with a 10-minute interval, which presented the highest precipitation intensities.

Soil permeability, an essential factor in drainage calculations, was determined using the Double Ring Infiltrometer Test, yielding infiltration rates ranging from 50 mm/h to 78.3 mm/h, with an average value of 56.9 mm/h. To spatially represent these variations, the Voronoi Diagram or Thiessen Polygons was used, defining the areas of influence of each sampled point. Although indirect methods based on geomorphological characteristics and vegetation cover exist, their application is more suitable for preliminary studies due to lower precision.

The analysis of the temporal and spatial distribution of rainfall proved essential for the efficient design of drainage systems in photovoltaic power plants, as it allows the prediction of surface runoff behavior and the identification of critical water accumulation points. In the present study, a return period (Tr) of 50 years, an average infiltration rate of 56.9 mm/h, and a total rainfall duration of 140 minutes divided into 10 blocks of 10 minutes each were adopted. The resulting effective rainfall had a total depth of 20.2 mm, composed of excess portions of 3.38 mm and 16.83 mm, which were used to calculate the runoff volumes allocated to the drainage structures.

3.2. CFD-2D Model

3.2.1. Flood water depth - Without a drainage system

Water depths in the most critical flooding areas exceeded 75 cm, highlighted in red in the color code used for visualization (Fig. 3). Areas shown in yellow represent locations where water depths exceed 30 cm, the maximum limit established for the project. These markings allow the identification of both regions with water depths above 75 cm, considered highly critical, and areas close to the 30 cm limit, which is the maximum tolerable height between the ground and the photovoltaic modules (Fig. 3). It should be noted that all areas with water depths above the acceptable limit will require interventions through the installation of appropriate drainage structures. Surface runoff velocities were also analyzed, showing, predominantly, values below 0.4 m/s. However, some points were identified with velocities exceeding the maximum permissible limit of 0.7 m/s, as defined by the regional environmental regulatory agencies. This assessment allows for the precise determination of optimal locations for installing velocity-reducing devices, thereby preventing soil erosion processes.

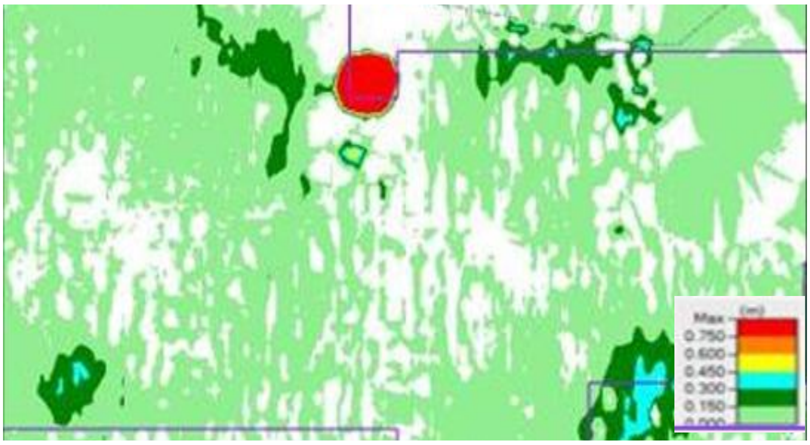

Figure 3 – Scenario 1: Without drainage system

3.2.2. Flood water depth – Based on traditional drainage system calculation

The drainage network was designed based on the runoff estimated by applying the Rational Method, which represented a total channel length of 4,161 m (Fig. 4). Based on that, a two-dimensional hydrodynamic simulation, CFD-2D, was performed in order to evaluate the drainage system. The results showed that water depths mostly remained below 20 cm throughout the analyzed domain, with no flood areas grater then 30 cm (Fig. 4). This indicated that the designed drainage system meets the project criteria. On the other hand, the developed simulation also highlighted some areas where water depth remained below the admissible limit even without projected channels (Fig. 4). It means that some traditional calculated channels are not required or can be removed when a more accurate calculation procedure is applied. It is worth noting that the topographic base used had an average spacing between points of 7 m, while the interpolation mesh adopted for the simulation had an approximate resolution of 3.5 m. This level of detail allowed for the accounting of small water accumulations on the surface, which cannot be achieved by traditional methods. It means an accurate identification of surface runoff toward lower elevations or drainage structures. Although not showed in the present study, the 2D simulation enable the determination of flow lines, allowing the identification of regions where velocities exceeded the limit established for the soil erosion risk.

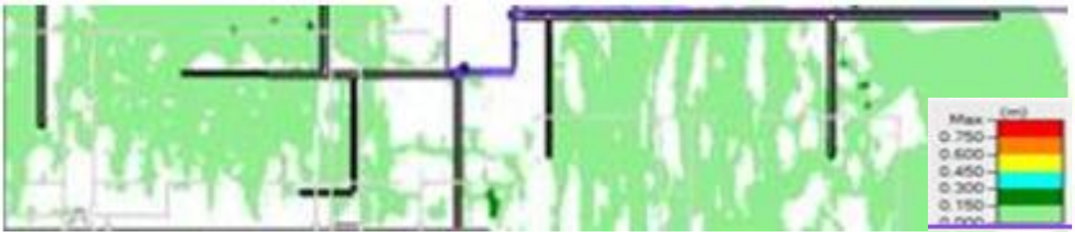

Figure 4: Channels sized under traditional calculated method

3.2.3. Flood water depth – Based on CFD-2D drainage system calculation

Based on the previous discussed analysis, a project optimization was performed by reducing or increasing channel length where required. In other words, it was adopted the criterion of mainly reducing or eliminating channels in areas where the water depths resulting from the simulation were less than 10 cm. As a result, all flood in the solar panel area were lesser than 30 cm height (Fig. 5). From the total channel length, the net reduction of 938 m was achieved, which means of 22.54% decrease, when compared to the traditional design procedure. Beside the direct cost reduction, the results indicate favorable to the project schedule performance, too.

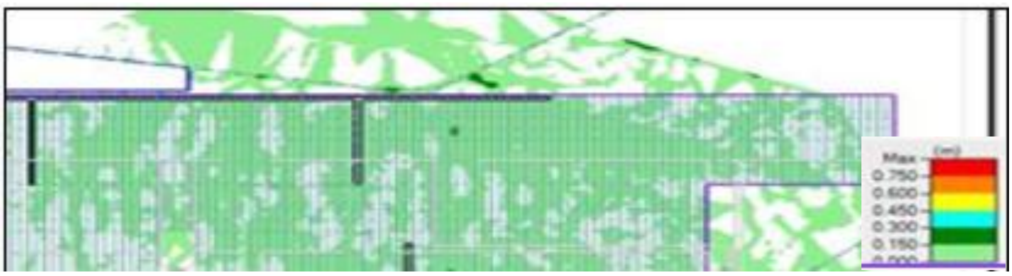

Figure 5 – Channel sized under CD-2D calculation with reduced drainage gutters

4. Conclusion

The application of CFD-2D modeling resulted in a 22.54% reduction in the length of the drainage gutters, representing a significant cost saving, especially in large-scale projects. The higher precision of the simulation allowed for a detailed analysis of velocities and water depths, enabling the identification of critical points.

Additionally, post-processing tools facilitated the strategic placement of detention basins and energy dissipators. This integrated approach contributes to the project's sustainability, aligning with the Sustainable Development Goals - SDGs by minimizing environmental impacts.

5. Acknowledgments

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6. References

BALZANO, A. *Evaluation of methods for numerical simulation of wetting and drying in shallow water flow models*. Coastal Engineering, v. 34, p. 83-107, 1998.

BUFFON, Franco Turco. *Aproveitamento de águas Pluviais: Efeito Sobre o sistema de Drenagem Urbana. 2010.* Disponível em: https://www.lume.ufrgs.br/bitstream/handle/10183/26044/000755504.pdf?sequence= 1. Acesso em: 19 jan. 2025.

DNIT, Departamento Nacional de Infraestrutura de Transportes. *Manual de Hidrologia Básica para Estruturas de Drenagem*. 2ª Edição. Publicação IPR-715. Ministério dos Transportes. Diretoria de Planejamento e Pesquisa. Coordenação Geral de Estudos e Pesquisas. Instituto de Pesquisas Rodoviárias. Rio de Janeiro, 2005.

HEC-RAS. *User's Manual*. Version 6.5. U. S. Army Corps of Engineers. Hydrologic Engineering – River Analysis System. USA. 2024.Disponível em: https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest

LANCASTER, Tim. *Solar farm erosion protection is not one-size-fits-all*. North American Clean Energy. 2023. Available at: https://www.nacleanenergy.com/solar/solar-farm-erosion-protection-is-not-one-size-fits-all (accessed 22 October 2025).

MAIA, M. de B. M.; ARBELOA, J. A. S.; Andriani, C. D.; PAGOTTO, F. O. S.; ROTUNNO FILHO, O. C. *Resposta hidrológica em parques solares: soluções de ecodesign como parte integrante do sistema de drenagem*. In: XXIV Simpósio Brasileiro de Recursos Hídricos, 2021.

RIO-ÁGUAS. *Instruções técnicas para elaboração de estudos hidrológicos dimensionamento hidráulico de sistemas de drenagem urbana*. 2ª Versão. Prefeitura da Cidade do Rio de Janeiro. Secretaria Municipal de Obras. Subsecretaria de Gestão de Bacias Hidrográficas - Rio Águas. Rio de Janeiro. 2019.

Santos, J.M.S., Silva, S.R., Silva Junior, M.A.B., Fonseca Neto, G.C., Cabral, J.J.S.P., Moura Júnior, J.M., 2022. Modelagem de drenagem pluvial em ambiente CAD utilizando a ferramenta Pipe Network. *Revista Brasileira de Cartografia*, 74(3), 743–760.