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Review

A Review of Gravitational Water Vortex Hydro Turbine Systems for Hydropower Generation

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Abstract: Hydropower is one of the most sustainable and desirable renewable energy sources. Gravitational water vortex hydro turbine (GWVHT) systems are one of the most suitable and sustainable renewable power generation devices for remote and rural areas, particularly in developing countries, owing to their small scales and low costs. There are various GWVHT systems with different configurations and various operating conditions. The main components of a GWVHT system include the inlet and outlet channels, a basin, and a turbine on which there are a number of blades attached. This paper presents a comprehensive review regarding the progress and development of various GWVHT systems, covering broad aspects of GWVHT systems, particularly various types of basins, inlet and outlet channels, turbines with blades which have different shapes, orientations, sizes, numbers, etc. The nature of the previous studies is summarised. The fundamentals of the vortex dynamics involved and the quantitative analysis of the performance of GWVHT systems are also described. The turbulence models and multiphase models used in some leading numerical simulation studies have been reviewed. As a case study, the implementation of a GWVHT system in PNG is presented. Based on the review of previous studies regarding GWVHT systems, the major issues and challenges are summarised, and some key topics are recommended for future research work on the performance of GWVHT systems.

Keywords: gravitational; water; vortex; vortex dynamics; hydropower; basin; turbine; blade; power output; efficiency

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1. Introduction

The use of electrical energy is an integral part of modern life. Extracting energy in a hydrodynamic environment has been widely carried out due to the sustainable nature of this energy source. In 2021, the total installed hydropower capacity was 1360 GW (gigawatts), and 4298 TWh (terawatt hours) of electricity was generated from hydropower, contributing to 16% of the world's total electricity [1]. This has attracted extensive research on numerous hydropower generation plants (systems) on a wide scale.

In the last 5 years, there has been an average annual increase of 22 GW from new hydropower plants, but it is still short of the 45 GW per year needed to keep the global temperature rise below 1.5 °C and to reach net zero emissions by 2050 [1]. The majority of the electricity generated by hydropower plants is from large-scale hydropower plants which have a power capacity of over 100 MW (Mega-Watts). However, such large-scale hydropower plants have serious impacts on the eco-system. Small-scale hydropower plants, which generally produce less than 10 MW, have much fewer impacts on the eco-system. More importantly, they are essential for some applications which have no access to or have difficulty in accessing the main grid. The global power capacity of small-scale hydropower plants is 78 GW, and increased efforts have been continually made to invest in small-scale hydropower plants.

Based on the power production capacity, small-scale hydropower plants can be divided into four categories in terms of size, as listed in Table 1 [2,3].

Table 1. Classification of small-scale hydropower plants [2,3].

Type of Hydropower Plant	Power Output	Applicability
Small hydropower plant	1–10 MW	Small communities, possibly to supply electricity to regional grid
Mini hydropower plant	100 kW to 1 MW	Small factory or isolated communities
Micro hydropower plant	5–100 kW	Small isolated communities
Pico hydropower plant	<5 kW	1–2 houses

A gravitational water vortex hydro turbine (abbreviated as GWVHT hereafter in this review) system is a specific micro hydropower plant (also called a system or a unit). Other terms such as 'gravitational water vortex power plant', 'gravitational water vortex hydraulic turbine system', 'gravitational vortex type water turbine system', 'gravitational water vortex hydropower system', etc., have also been used by different researchers.

As shown in Figure 1, a typical GWVHT system consists of a water inlet channel (inlet passage), a circular basin with an opening (usually an orifice) on its bottom for the discharge of water (the outlet, which is generally located at the center of the basin's bottom), a turbine with multiple blades and a vertical shaft connected to the electricity generator, and an exit channel (outlet passage) [4,5]. It utilises the natural flow of water from rivers, creeks, or mountains to create a free surface vortex caused by the Coriolis force. The vorticity increases towards the orifice at the basin bottom, which also increases the water circulation, and it causes the pressure to fall below atmospheric pressure, resulting in an air core. The radius of the air core decreases its trend towards the orifice [6]. The free flow of the vortex energy is converted into mechanical energy by the turbine blades and then into electric energy by the generator attached to the turbine through the shaft. The performance of a GWVHT system can be easily assessed by the power output produced and by its efficiency.

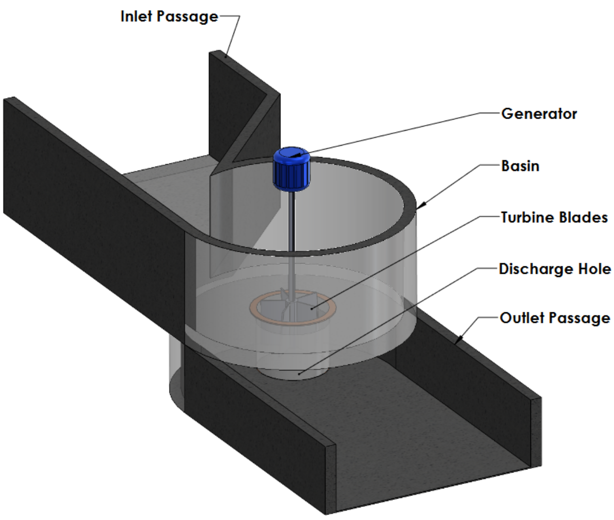

Figure 1. A sketch of a typical GWVHT system with a shallow cylindrical basin and flat channel, as well as its main components.

GWVHT systems are also often classified as low-head small hydropower systems, as they typically have a 1–2 m head and produce power outputs between 100 W and 20 kW at flow rates in the range of 0.1 to 2 m^3/s [5,7]. Many previous studies have been carried out to investigate the performance and the design of such micro-GWVHT systems, which will be reviewed here. Additionally, there have been some studies on GWVHT systems which are at a pico hydropower scale, with smaller heads and flow rates and thus significantly smaller power outputs. Such previous studies will also be reviewed in the present paper.

A GWVHT system is a powerful and eco-friendly technology that effectively harnesses natural water with low head. Its compact design and convenience make it an ideal micro hydropower system that holds great promise, particularly in remote, rural, and mountainous areas with low demand and no access to the main grid.

In addition to the gravitational water vortex hydro turbine systems considered in the present paper, there are some other types of small hydropower systems, such as hydrokinetic turbine systems. Nevertheless, it should be noted that although both hydrokinetic turbine systems and gravitational water vortex hydro turbine systems are similar in some aspects, such as that they both use water as the working medium; the power generated is in very small scales; they can similarly use water from rivers and canals; and they use similar turbines in some cases, etc., there are distinctive differences between them. The gravitational water vortex hydro turbine systems considered in our manuscript use low-head (potential) water flow from rivers, creeks, canals, etc., for hydropower generation, while hydrokinetic turbine systems use kinetic energy produced in water currents and waves in the ocean [8]. Another distinctive difference between them is that a gravitational water vortex hydro turbine system consists of a channel, a basin which is open to the air on the top and has a hole at its bottom to serve as the outlet to discharge the water after it passes and rotates the turbine, a turbine with multiple blades attached and an electric generator connected to the turbine, whereas in a hydrokinetic turbine, there is no basin like that in a gravitational water vortex hydro turbine system. More importantly, our review paper focuses on gravitational water vortex hydro turbine systems in terms of their three main components: the channel, the basin, and the turbine with multiple blades attached. Therefore, hydrokinetic turbine systems without a basin are out of the scope of our review. In addition, there are some excellent and comprehensive reviews (such as [8–11]) and some recent developments of hydrokinetic turbine systems (such as [12–17]) which the readers are referred to. Hence, in the present review, a review on hydrokinetic turbine systems is not included.

The GWVHT system technology was developed by Franz Zotlöterer in 2006 [18]. However, as noted by Timilsina et al. [5], it was also argued that this idea of harnessing water from a vortex flow was firstly conceived by Viktor Schauberger [19]. Nevertheless, it was Zotlöterer's 10 kW GWVHT system on a river in Obergrafendorf, Austria, in 2006 [18] that initiated international interest in this technology [5,20–22]. In their review on the developmental trends of water vortex hydropower technology, Timilsina et al. [5] presented an excellent and detailed description of the history of GWVHT systems and the development of some predominant GWVHT systems, which will not be repeated here. The readers are referred to this excellent review by Timilsina et al. [5].

Thirty-six installed GWVHT plants (systems) have been reported throughout the world, as summarised in Table 2, which is updated from [5,23,24]. These plants used heads in the range of 0.6 m to 3.2 m and operated at flow rates between 0.048 m^3/s and 2.2 m^3/s, which produced power outputs from 180 W to 20 kW at efficiencies in the range of 29% to 85%. Moreover, 67% of the plants operated under a 60% efficiency, and 42% of them produced a power output no more than 5 kW. In terms of regions, Europe has the majority, with 23 systems, followed by Australia with 4 systems, and the remaining are located in developing countries (India, Nepal, Peru, Chile). The majority of these systems utilise a cylindrical basin, mainly due to the ease of operation and construction concerns.

There are four major companies specialized in the design, manufacturing, and installation of GWVHT systems: Zotlöterer in Austria (Obergrafendorf) [18], Kourispower (KCT) and KapaLamda in Australia and Greece (Thessaloniki, also operating globally) [25,26], Turbulent in Belgium (also operating globally) [27], and AquaZoom (also operating in the UK and India) [28]. AquaZoom reported that they have 14 upcoming GWVHT systems in the UK and India, with heads, flow rates, and power outputs in the ranges of 1.5 m to 2.2 m, 0.9 m^3/s to 4 m^3/s, and 10 kW to 2 × 25 kW, respectively [29], while Turbulent reported that six installations were in progress in Taiwan, the Philippines, Thailand, Congo, Chile, and the UK with expected power outputs in the ranges of 7.5 kW to 140 kW [30].

Table 2. Information on the reported 36 installed GWVHT systems thorought the world (updated from [5,18,23,24]).

Site	Country	Company	Flow Rate (m^3/s)	Head (m)	Power (kW)	Efficiency (%)	Power Density ($kW{\cdot}s/m^3$)	Reference
1	Austria	Zotlöterer	0.70	0.90	3.30	53.00	4.71	[18]
2	Austria	Zotlöterer	0.50	1.50	4.40	60.00	8.80	[18]
3	Austria	Zotlöterer	0.50	1.40	4.00	58.00	8.00	[18]
4	Austria	Zotlöterer	0.90	1.00	4.60	52.00	5.11	[18]
5	Austria	Zotlöterer	0.60	1.40	5.00	61.00	8.33	[18]
6	Austria	Zotlöterer	1.20	1.20	7.50	53.00	6.25	[18]
7	Austria	Zotlöterer	1.00	1.80	10.00	57.00	10.00	[18]
8	Austria	Zotlöterer	2.00	1.60	18.00	57.00	9.00	[18]
9	Austria	Zotlöterer	0.90	1.00	4.60	52.00	5.11	[18]
10	Austria	Zotlöterer	1.00	1.50	9.00	61.00	9.00	[24]
11	Austria	Zotlöterer	1.00	1.50	8.50	58.00	8.50	[24]
12	Austria	Zotlöterer	0.80	1.80	9.00	64.00	11.25	[24]
13	Austria	Zotlöterer	0.90	1.50	8.30	63.00	9.22	[24]
14	Belgium	Turbulent	0.25	2.00	3.00	61.00	12.00	[5]
15	Chile	Turbulent	1.80	1.50	15.00	57.00	8.30	[5]
16	Indonesia	Turbulent	1.20	1.50	15.00	85.00	12.5	[5]
17	Indonesia	Turbulent	1.85	1.57	13.00	-	7.03	[30]
18	Chile	Turbulent	1.70	1.65	15.00	-	8.82	[30]
19	France	Turbulent	3.20	0.70	5.50	-	1.72	[30]
20	Estonia	Turbulent	1.60	0.75	5.50	-	3.44	[30]
21	Portugal	Turbulent	1.50	0.75	5.00	-	3.33	[30]
22	Germany	Aquazoom	1.50	1.20	6.00	51.00	6.00	[23]
23	Germany	Aquazoom	1.50	1.20	6.00	51.00	4.00	[5]
24	Nepal	Aquazoom	1.50	2.00	20.00	68.00	13.3	[5]
25	Germany	Aquazoom	0.50	1.20	3.00	52.00	6.00	[24]
26	India	Aquazoom	1.00	1.50	10.00	68.00	10.00	[24]
27	Australia	KCT	0.05	0.80	0.18	49.00	5.00	[24]
28	Australia	KCT	0.11	0.60	0.55	85.00	4.50	[24]
29	Australia	KCT	0.15	3.00	20.00	45.00	13.30	[25]
30	Australia	KCT	0.048	0.80	0.18	48.00	3.75	[25]
31	Papua New Guinea	PNG Unitech	0.093	1.73	0.48	49.00	5.16	[31]
32	Peru	-	1.20	1.20	3.50	29.00	3.43	[5]
33	Switzerland	-	1.00	1.50	10.00	68.00	6.70	[5]
34	Switzerland	-	2.20	1.50	15.00	46.00	10.00	[23]
35	Nepal	-	0.20	1.50	1.60	53.00	8.00	[5]
36	Switzerland	-	2.20	1.50	15.00	46.00	6.80	[5]

According to Rahman et al. [32], GWVHT systems had an overall efficiency of less than 50% before 2017. However, since then, there has been an improvement in the understanding of the mechanisms involved in GWVHT systems, and better designs have emerged, resulting in efficiencies as high as 85%, as shown in Table 2.

Most of the earlier studies were conducted to optimise and improve the parametric and operational features of GWVHT systems using analytical and experimental methods. More recently, the numerical method using computational fluid dynamics (CFD) packages (such as Ansys Fluent and CFX) has gradually became the main tool used to study GWVHT systems.

In the past, studies focused on improving and optimising GWVHT systems through analytical and experimental methods. Nowadays, computational fluid dynamics (CFD) packages like Ansys Fluent and CFX are increasingly being used as the primary tool to study GWVHT systems.

Based on previous research, the crucial factor for improving power generation is the strength of the vortex [33]. Several factors can affect the strength of the vortex, including inlet conditions, basin size and design, blade quantity, and shape of the turbine, as well as the size and design of the discharge.

Numerous studies have examined GWVHT systems, but their performance has generally been subpar. These systems have exhibited low efficiency and power outputs with significant variations. This can be attributed to a lack of understanding of the vortex dynamics created by the rotating turbine, which has multiple blades. Additionally, there has been insufficient comprehensive and detailed research on GWVHT systems, particularly their configuration and parametric studies on key components like the basin, turbine, and channels [23]. This calls for much more research to be carried out to improve their performance significantly.

We have come across a total of five reviews pertaining to previous research conducted on GWVHT [5,23,32,34,35]. Upon review, it was determined that the reviews conducted by Rahman et al. [32], Huwae et al. [34], and Sierra et al. [35] were notably restricted in scope when compared to those undertaken by Timilsina et al. [5] and Velasquez et al. [23]. The latter two evaluations demonstrated a comparatively thorough examination of the subject matter. As will be shown later, there has been a significant surge in high-quality investigations recently. It is therefore worth having an updated and more comprehensive review on the previous studies on GWVHT systems, particularly including the new studies which were not covered by the previous reviews [5,23,32,34,35]. This is the motivation for the present review on GWVHT systems, particularly focusing on the key components of the systems.

2. Overview of Past Studies on GWVHT Systems

The past studies on GWVHT systems were obtained through searching the Web of Science, Scopus, and Google databases using the key words 'gravitational', 'water', 'vortex', and 'turbine'. The search identified 91 studies, as summarised in Table 3. There are some studies on gravitational water vortex systems but without the use of any turbine. Such studies were excluded, as they are not in the scope of the present review, as no electricity would be generated.

Among these identified studies, 5 are reviews, 49 are journal papers, 36 are conference papers, and 1 is a master's thesis. The numbers of papers published in each year are presented in Figure 2, which clearly shows that the research on GWVHT systems has gained great momentum recently, indicating the importance of further extensive research on many aspects of GWVHT systems to significantly improve their performance. The numbers of papers involved experimental, numerical, and analytical studies are 49, 61, and 18, respectively, indicating that numerical studies are prevalent and that their prevalence has increased significantly in recent years, as shown in Table 3 and Figure 3. The analysis of GWVHT systems is difficult due to the complexity of vortex dynamics and turbulence, which limits the potential for analytical studies. The data in Table 3 and Figure 3 also show that turbines are the most studied component of GWVHT systems (42 papers), followed by basins (33 papers), while the studies on channels are significantly smaller (17 papers). As it is reasonable to argue that the performance of a GWVHT system is probably most affected by the turbine, and much less by the channel, such a distribution of the studies is rational.

It should be noted that the significance of studying GWVHT systems and the outstanding calibre of past research is underscored by these studies' publication in leading energy journals. Until 2019, no top energy journals had published any studies on GWVHT systems. However, since 2019, six papers have been published in *Renewable Energy* [36–41] and four papers have been published in *Energy* [42], *Energy Conversion and Management* [43], *Applied Energy* [44], and *Energies* [45], which are among the top journals in the energy field.

Table 3. Key information about past studies on GWVHT systems.

Ref.	Publication Type	Publication Year	Experimental Study	Numerical Study	Analytical Study	Basin Studied	Turbine Studied	Channel Studied	Study Type
[32]	Review	2017	+	+	+	+	+	+	Comprehensive review
[5]	Review	2018	+	+	+	+	+	+	Comprehensive review
[35]	Review	2020	+	+	+	+	+	+	Comprehensive review
[34]	Review	2020	+	+	+	+	+	+	Comprehensive review
[23]	Review	2021	+	+		+	+	+	Comprehensive review
[33]	Journal	2013	+	+		+			Parametric study
[46]	Journal	2013	+		+	+	+		Case study
[47]	Journal	2014	+			+	+		Case study
[22]	Journal	2015	+	+		+			Comparison study
[48]	Journal	2015	+	+					Validation
[49]	Journal	2016	+				+		Parametric study
[50]	Journal	2017	+	+					Case study
[51]	Journal	2018							Case & feasibility study
[52]	Journal	2019							Case & feasibility study
[43]	Journal	2019	+		+		+		Parametric study
[39]	Journal	2019		+			+		Parametric study
[53]	Journal	2019	+	+					Case study
[54]	Journal	2019	+	+			+		Case study
[7]	Journal	2019	+	+		+			Case study
[55]	Journal	2020		+				+	Case study
[36]	Journal	2020	+			+	+		Parametric study
[42]	Journal	2020	+		+		+		Parametric study
[56]	Journal	2020	+	+			+		Case study
[57]	Journal	2020	+	+			+		Parametric study
[40]	Journal	2020	+	+	+				Case study
[58]	Journal	2021	+	+		+			Parametric study
[59]	Journal	2021	+	+	+				Case study
[60]	Journal	2021		+					Case study
[61]	Journal	2021		+			+		Parametric study
[62]	Journal	2021		+		+	+		Parametric study
[63]	Journal	2021		+			+		Case study
[64]	Journal	2021							General design selection
[31]	Journal	2021	+						Case study
[45]	Journal	2021	+		+		+		Parametric study
[65]	Journal	2021		+		+			Case study
[66]	Journal	2021		+					CFD model validation
[67]	Journal	2021			+				Analytical model
[68]	Journal	2021		+			+		Comparison study
[38]	Journal	2022		+			+		Parametric study
[37]	Journal	2022		+	+	+		+	Optimization
[69]	Journal	2022		+			+		Parametric study
[70]	Journal	2022		+				+	Parametric study
[71]	Journal	2022		+			+		Optimization

Table 3. *Cont.*

Ref.	Publication Type	Publication Year	Experimental Study	Numerical Study	Analytical Study	Basin Studied	Turbine Studied	Channel Studied	Study Type
[72]	Journal	2022		+	+		+		Parametric study
[73]	Journal	2022	+						Case study
[74]	Journal	2022	+				+		Parametric study
[75]	Journal	2022		+			+		Parametric study
[76]	Journal	2022		+		+			Parametric study
[77]	Journal	2022		+		+	+		Parametric study, Optimization
[78]	Journal	2022		+			+		Parametric study, Optimization
[79]	Journal	2023	+	+		+	+		Parametric study
[44]	Journal	2023		+	+	+		+	Modelling, optimisation
[41]	Journal	2023	+	+					Case study, model scaling
[80]	Conference	2015	+	+	+	+		+	Modelling, Optimization
[81]	Conference	2016	+	+			+		Case study
[82]	Conference	2016							Case and feasibility study
[83]	Conference	2017	+				+		Case study
[84]	Conference	2017		+		+			Optimization
[85]	Conference	2017		+		+		+	Parametric study
[86]	Conference	2018	+	+			+		Parametric study
[87]	Conference	2018	+	+			+		Case study
[88]	Conference	2018	+					+	Parametric study
[89]	Conference	2019	+			+			Case study
[90]	Conference	2019		+		+			Parametric study
[91]	Conference	2019	+						Case study
[92]	Conference	2019	+				+		Case study
[93]	Conference	2020	+				+		Case study
[94]	Conference	2020	+						Case study
[23]	Conference	2020		+		+		+	Case study
[95]	Conference	2020	+	+	+				Model scaling
[96]	Conference	2020		+	+				Case study
[97]	Conference	2020		+					Case study
[98]	Conference	2020	+	+		+		+	Parametric study
[99]	Conference	2020	+					+	Case study
[100]	Conference	2020		+		+			Parametric study
[101]	Conference	2020							Feasibility study
[102]	Conference	2020	+				+		Case study
[103]	Conference	2020		+		+			Parametric study
[104]	Conference	2021							Concept design
[105]	Conference	2021	+						Case study
[24]	Conference	2021							Feasibility study
[106]	Conference	2021	+			+			Parametric study
[107]	Conference	2021			+		+		Case study
[108]	Conference	2022		+			+		Parametric study
[109]	Conference	2022		+					Case study
[110]	Conference	2022	+	+		+	+	+	Parametric study
[111]	Conference	2022		+		+			Parametric study, Optimization
[112]	Conference	2022		+			+		Parametric study

Table 3. *Cont.*

Ref.	Publication Type	Publication Year	Experimental Study	Numerical Study	Analytical Study	Basin Studied	Turbine Studied	Channel Studied	Study Type
[113]	Conference	2022	+	+		+			Case study
[114]	Thesis	2016	+	+		+	+	+	Parametric study, optimisation

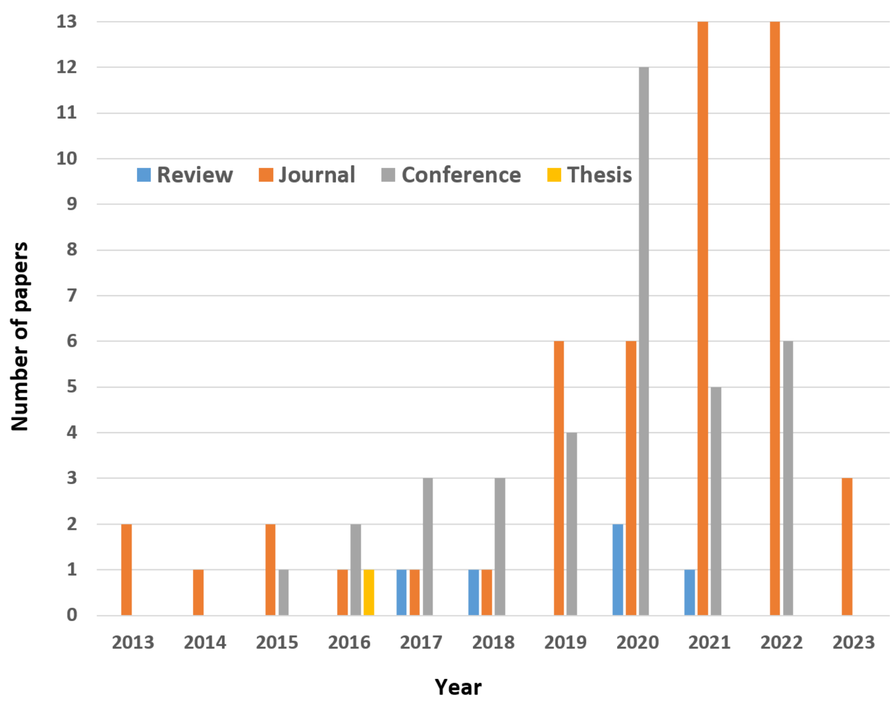

Figure 2. Number of papers for each year.

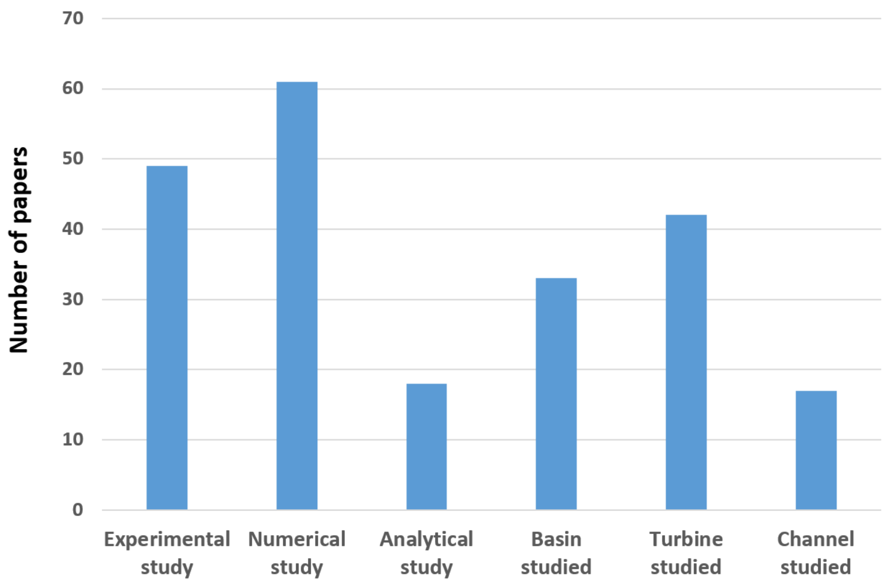

Figure 3. Number of papers for different types of studies and for different components studied.

3. Quantitative Analysis of the Performance of GWVHT Systems

The ultimate goal of a GWVHT system is to achieve optimal performance. In order to evaluate its performance, specific quantitative variables must be considered. When it comes to GWVHT systems, the power output and overall efficiency are crucial quantitative performance variables. However, due to its novelty and uniqueness in the hydropower generation field, these variables are not clearly defined yet. This lack of clarity is likely a big reason why there is such a wide range of efficiency in installed and studied GWVHT systems.

According to Williamson et al. [115], the performance variables for any power generation system with a turbine are the maximum turbine power obtainable P, overall turbine system efficiency η_v, flow rate Q, and gross head H_g. Two of them will need to be defined, with two unknowns. P relates to Q and H_g with the following equation [5],

$$P = \rho g Q H_g, \tag{1}$$

where ρ is the density of fluid and g is the gravitational acceleration. The two unknowns are determined using another equation derived from the further analysis of the turbine torque generation mechanism, which depends on the specific type of the turbine.

The GWVHT system is a combination of a reaction and impulse turbine [5]. When water flows into the basin, a vortex is created which drives the turbine blades in an axial direction. The water is then discharged through a hole at the bottom of the basin into the outlet passage. This system acts like a reaction turbine, similar to a Kaplan turbine, but with fixed blades and no spiral casings or vanes. See Figure 1 for a visual representation. In this case, Williamson et al. [115] gave the following equation to calculate P:

$$P = \eta_v \rho g Q (H_g - H_1 - H_2 - H_3), \tag{2}$$

where, for the GWVHT system considered, η_v is the efficiency of the vortex turbine, H_1 is the head loss along the radius, H_2 is the head loss at the orifice or intake, and H_3 is the kinetic energy of the outflow [5]. These head losses are functions of the speed of the water passing through the components and are dependent on the configurations and geometries of the components of the turbine system. In the case of a GWVHT system, these components are mainly the basin, the turbine (and its blades), the inlet and outlet passages, etc. From Equation (2), it can be seen that it is important to minimize the head loss between the upstream river water level and the approach to the vortex chamber as a first attempt to optimise the design [5]. By applying the principles of momentum, we can estimate the power generated by the shaft when water hits the turbine blades, which functions similarly to an impulse turbine (P_{out}) [5,20,115], leading to

$$P_{out} = T\omega, \tag{3}$$

where T is the torque generated on the shaft and ω is the rotation speed of the shaft, respectively. T can be approximated using a force generated on the impeller–water interface by estimating the difference between the initial velocity near the vortex core v_i and the blade velocity v_b, i.e., [5]:

$$T = \rho Q (v_i - v_b) r, \tag{4}$$

where r is the average impact radius. The efficiency of the turbine can therefore be determined by [5]

$$\eta_v = \frac{P_{out}}{\rho g Q H_g} = \frac{(v_i - v_b) r}{g H_g}. \tag{5}$$

It is apparent that η_v is strongly dependent on the speed of the impeller. Mulligan and Casserly [20] suggested that to achieve the maximum efficiency, the impeller speed should be maintained at half of the vortex core speed [5].

Among the publications listed in Table 3, almost 60% either did not provide the complete information for P, P_{out}, or η_v, particularly P and η_v, or just presented P_{out}, but with no, or else a vague or inconsistent, definition of P_{out}. Most of these publications are earlier studies, particularly some earlier conceptual studies, case studies, and numerical studies. For the remaining publications, almost all of them used Equations (1), (3), and (5) to calculate P_{out}, P, and η_v, respectively. However, the definition of H_g in the equations varies significantly, although a small number of studies also used different ways to determine

T. Many of these remaining studies did not provide the definition of H_g, just stating that H_g is the gross head or the head of water, or the available hydraulic power. These studies include [43,51,57,65,68,72–74,87,89,95,99].

In three different studies [38,41,62], the measurement of the height difference between the water surface and the basin bottom was referred to as H_g. These studies concluded that the kinetic head contribution is usually insignificant due to the slow velocity of open channel flows. Two studies [31,42] used the vortex height as H_g. Three studies [49,83,88] used the water height in the inlet passage as H_g. Three studies [56,72,94] used the basin height as H_g. Nishi and Inagaki [50] and Swami et al. [53] used the following equation to calculate H_g:

$$H_g = h' + h_3 + \frac{V_3^2}{2g} - h_4 - \frac{V_4^2}{2g}, \tag{6}$$

where h' is the height difference between the discharge hole at the basin bottom and the bottom of the outlet passage, h_3 is the height difference between the water surface in the inlet passage and the basin bottom, and V_3 and V_4 are the velocities in the inlet and outlet passages, respectively. However, Nishi et al. [40,59] also just used $h_3 + V_3^2/2g$ as H_g. Zamora-Juárez et al. [78] used the following equation to calculate H_g:

$$H_g = h_v + \frac{V_{in}^2}{2g}, \tag{7}$$

where h_v is the vortex height and V_{in} is the velocity in the inlet passage. Velásquez García et al. [112] used the height difference between the bottom of the inlet passage and the middle of the blades as H_g. By analysing the velocity triangles at the inlet and outlet of the blade and the relative stream velocity and angle, Haghighi et al. [39] obtained a quite complicated equation to calculate H_g which is not detailed here.

4. Vortex Dynamics

The vortex plays a crucial role in generating power from a GWVHT system, but it is the least understood component. Timilsina et al. [5] point out that the challenge arises from the air–water–turbine interface created in the basin of the GWVHT system, which adds an extra dimension to the process. Moreover, the flow regime within the system becomes turbulent due to the presence of the turbine, resulting in the generation of a complex flow. The turbine applies external torque on the fluid particle, causing it to rotate and creating a rotational flow field around its exit axis. This leads to a decrease in the initial water head pressure, which alters the flow field at the free surface flow region.

Timilsina et al. [5] listed several key questions about vortex dynamics in a GWVHT system, including the effect of the free-surface vortex on previously understood depth–discharge relationships for hydropower turbines; the location where the free-surface interacts with the turbine; the action on the free-surface when a load (torque) is put on the turbine; the velocity distribution across the blade–water interface; the optimum position, shape, size, and number of the blades; and the speed for the blades to be operated at to achieve the maximum efficiency.

Additionally, the generally turbulent nature of the vortex dynamics in the GWVHT system makes it extremely difficult to understand and quantify the characteristics of the vortex dynamics through simple theoretical analysis and experiments, although numerical simulations are able to do the job appropriately. The current poor understanding of vortex dynamics is most likely the major contributor to the relatively small power output and low efficiency of many installed and studied GWVHT systems.

Timilsina et al. [5] provided a comprehensive overview of various theoretical, analytical, and empirical models that characterize and measure the vortex flow field, pressure, and tangential velocity and the interaction between vortex and turbine. Mulligan et al. [116] indicated that a water vortex can be explained by the theory of conservation of angular momentum. Fluid particles moving radially and with a small inflow of tangential velocity generate a significant vortex structure close to the centre of the discharge. Fluid particles moving away from the centre have an angular momentum, resulting in a less angular velocity with a larger radius. When the particles move to the centre, the radius reduces; thus, to conserve the angular momentum, the angular velocity increases, which increases the vorticity or vortex.

The most important parameter in the vortex dynamics is the circulation parameter, which governs the flow and rotational strength and is defined as follows:

$$\Gamma = 2\pi r v_\theta, \tag{8}$$

where r is the radial position from the centre of rotation and v_θ is the tangential velocity of the free-surface vortex (in the absence of a turbine). This relation was reaffirmed by Guzman et al. [117] and Mulligan et al. [67]. It was obtained for an ideal fluid using the continuity and Navier–Stoke equations in the cylindrical coordinate system and by assuming a steady-state, axisymmetric, inviscid flow with negligible axial and radial velocities, which indicates that the tangential velocity becomes the dominant velocity component in the vortex field. This is because in an ideal fluid, there are no deformation rates and the fluid behaves irrotationally, although any real fluids will behave rotationally. This is the classical vortex velocity model for ideal irrotational flows.

Considering the physical significance of the free vortex model, some researchers modified the model and developed several modified vortex models, both with and without a turbine, with some summarised by Timilsina et al. [5]. The Rankine vortex model is considered to be the pioneering model for describing the vortex behaviour with a filament of a finite core radius containing constant vorticity [118,119].

In a GWVHT system, the turbine blades distort the generated vortex in the basin, thus decreasing the tangential velocity of the water vortex [43] whilst increasing the axial and redial velocities. The flow is discharged at the discharge hole at the basin's bottom by these main driving velocities. It is important that the flow is continuous to ensure a steady flow vortex at this point. However, Wang et al. [120] and Anh et al. [121] noted that after water strikes the blades, the flow becomes complex, so the velocities are affected, and inside the water vortex, an air core is formed at the centre of the water vortex. Depending on its behaviour, the vortex could be classified as a weak or strong vortex. The weak vortex field is dominated by the axial flow, whilst in the strong vortex, circulation is dominated by a stable continuous air core [116]. Apart from that, the steadiness of the primary water vortex field is affected by the secondary flow field and sub-vortices [118].

It should be particularly mentioned that Mulligan et al. [116–118,122,123] made some substantial contributions to the development of modified models for Γ for a GWVHT system. Mulligan et al. [118,123] showed that in a GWVHT system, the circulation parameter is in turn governed by the approach flow geometry, as follows:

$$\Gamma_v = \frac{2\pi r_{in} Q}{b h_{in}}, \tag{9}$$

where b and r_{in} are the inlet width and radius, respectively, and h_{in} is the depth of water at the inlet passage. This makes the inlet passage in the GWVHT system a key component which should be optimised to achieve the maximum efficiency. Mulligan et al. [118,123] further conducted an empirical study to obtain the following depth–discharge relationship to estimate the discharge (Q) in the GWVHT system:

$$Q = \frac{k_c}{(5cd/h_{in})^{n_c}} \sqrt{gd}, \tag{10}$$

where $c = r_{in}/b$ is a geometry parameter, d is the diameter of the discharge hole, and k_c and n_c are empirical parameters which are approximated by the following relations for $1.3 \leq c \leq 6.22$:

$$k_c = -0.12c^3 + 0.79c^2 - 0.62c + 0.36, \tag{11}$$

and

$$n_c = 0.05c^2 - 0.39c - 0.55. \quad (12)$$

Mulligan et al. [117] showed that the ideal tangential velocity Equation (8) for the case of a free-surface vortex (in the absence of a turbine) should be revised for the GWVHT system to account for the strong axial gradients near the air core in the system and gave the following empirical relation:

$$v_\theta = \frac{\Gamma_v}{2\pi r}\left[1 - \left(\frac{h}{5cd}\right)^{2r/d}\right]. \quad (13)$$

As shown above, the differences in the various vortex models strongly depend on the geometry, for example, the analytical study by Einstein and Li [124] and the experimental study by Vatistas and Koze [125], who conducted research on vortex formation in cylindrical tanks by comparing the height of the inlet channel and the bottom of the tank. Using a helical turbine with a hydrofoil profile, Marian et al. [46] showed that the vortex height improved the energy extraction, so they concluded that to improve efficiency, the vortex needs to be extended to the base of the discharge. Wanchat et al. [33] also confirmed that the vortex height was an important parameter in power extraction. Ruiz Sánchez [7] found that the conical geometry has an 11% higher tangential velocity than the cylindrical geometry has.

Since there is a complex air–water flow field around the vortex turbine, some phenomena are difficult to observe experimentally. Thus, numerical studies with computational simulations are needed in GWVHT systems, as indicated by Bajracharya et al. [116] and Mulligan et al. [57]. One example is that by Edirisinghe et al. [38], who conducted numerical simulations to understand the air core behaviour in terms of the turbine–vortex interactions, velocity, and pressure using different turbine configurations. They showed that horizontally curved blades had a slightly better performance than vertically twisted blades for the original design of the conical basin. However, when the discharge hole at the basin bottom was increased, the vertically twisted blades performed better, achieving an efficiency of 55.3% while maintaining a stable air core. Nevertheless, the actual effect of the air–water interaction is yet to be fully established. Few studies showed agreement between experimental and numerical results. Some studies only investigated turbines and did not study the hydro dynamics. Dhakal et al. [87] confirmed that parametric studies on turbines were few, and it is worth studying its reliability using computational simulations. Regarding the vortex flow field, Ullah et al. [43] observed that it varied significantly with and without the presence of the turbine blades in the basin. When the blades were presented, the vortex head dropped. However, in the absence of the blades, the inlet and outlet velocities were the same. It is therefore very difficult to determine if it is a free vortex or a forced vortex; thus, assumptions need to be made beforehand and tested. Nishi et al. [40] conducted a study on the influence of flow rates on the performance of a GWVHT system by conducting experiments and free surface flow analysis and found that the effective head and turbine efficiency increased as the flow rate increased; hence, the turbine output increased at a rate greater than the increase rate of the flow rate. Nazarudin et al. [109] carried out Solidwork simulations on the conical basin using the inlet velocities of 5 m/s, 9.9 m/s, and 13 m/s to study the effect on the outlet velocity, pressure, and vorticity. They noted that the the tangential velocity was higher than the radial velocity; the outlet velocity varied linearly with the inlet velocity, with the maximum outlet velocities of 17.09 m/s, 33.79 m/s, and 44.37 m/s, respectively; the corresponding pressures were 159 kPa, 618 kPa, and 107 kPa, respectively, and there was high pressure at the walls and decreased towards the outlet; the corresponding vorticities were 48.28 m/s, 91.66 m/s, and 120 m/s, respectively, and vorticity was affected by d/D (where d and D are the diameters of the discharge hole and the basin); vorticity decreased towards the centre, and it was weak near the blades and was linear with radius.

Timilsina et al. [5] also discussed some other characteristics of the turbine–vortex interaction in a GWVHT system and argued that the turbine in the system is partially a reaction turbine. They believed that the head difference generated by assuming the turbine in the GWVHT system to be a reaction turbine may be a good metric for the performance and power output estimation of the system, although they also remarked that there was still no research available that estimated this effect using the combined vortex models. The readers are referred to Timilsina et al. [5] for more details on this point.

5. Review of the Past Studies on the Main Components of GWVHT Systems

As shown in Table 3, out of the 85 journal and conference papers and one thesis, 39 carried out parametric studies (including optimisation studies), and the remaining publications carried out non-parametric studies, which include case studies, feasibility studies, conceptual designs, validation, modelling, etc. As discussed above, the main components of a GWVHT system include the basin, the turbine with multiple blades, and the channel (inlet and outlet passages). In the 39 parametric studies (including optimisation studies), 19 involve basins, 25 involve turbines, and 9 involve channels, while in the remaining non-parametric studies, only 9 involve basins, 12 involve turbines, and 3 involve channels. It should be noted that 23 publications did not involve (or provide information on) any of these three main components at all, which are mainly some case studies and/or feasibility studies [24,31,40,50–53,59,60,82,91,94,96,97,101,104,105,109], validation studies [48,66], analytical models [41,67,95], and concept designs [64,104]. It should also be noted that some publications involve more than one main component [23,36,37,46,47,62,77,79,80,85,110] and the thesis [114] involves all three main components.

As the studies solely focused on channels (inlet and outlet passages) are much fewer and generally associated with studies on the basins, in the following sections, the past studies on basins and channels are combined to be reviewed in a single section, and the past studies on turbines (along with the blades) are reviewed in a separate section.

5.1. Past Studies on Basins and Channels

Figure 4 presents the schematic of a cylindrical basin and a conical basin and their respective inlet channels, which are the two most commonly used basins in GWVHT systems. There are also several other basins with different shapes (such as concave and convex basins), which will also be reviewed.

5.1.1. Non-Parametric Studies on Basins and Channels

According to Mulligan et al. [21], there is a direct correlation between the size of a basin and the height of a vortex created in it when there is no turbine present. They also found that for the best formation of the vortex, the diameter of the opening at the bottom of the basin should be between 14% and 18% of the basin's overall diameter.

Dhakal et al. [22] conducted a study on two GWVHT systems—one with a cylindrical basin and the other with a conical basin. The systems were tested at a low head of 0.8 m and a small flow rate of 0.01 m^3/s. Their findings showed that the conical basin system had a higher power output and efficiency compared to the cylindrical basin system. The turbine position that produced the maximum power output was located between 65 and 75% of the basin's height from the top. However, the efficiencies were generally low, averaging at less than 40%, and the power outputs were small, with an average of less than 40 W. Dhakal et al. [47] also carried out an experimental study on the GWVHT systems with a cylindrical basin and a conical basin, but with two turbines which have different numbers of blades and blade radii. They found that the bottom-most position was the best position to place the turbine, as the velocity head increased with the increase in depth, resulting in higher efficiency. Their results also showed that the vortex formation was improved in the conical basin compared to that in the cylindrical basin, which in turn increased the efficiency of the GWVHT system with the conical basin. Dhakal et al. [47] further showed that the inclusion of the inlet diffuser increased the speed of flow in the turbine, indicating that the formation of the vortex velocity was significantly affected by the changes in the channel height, cone angle, and notch inlet width. It was recommended that the inlet notch length should be increased to the optimal length to minimize water losses [22]. With the proposed mathematical model and experiments, Marius-Gheorghe et al. [46] investigated the performance of a GWVHT system with three-stage turbines (i.e., there are three different turbines along the shaft) in a conical basin and found that when all turbines were operating, the energy performance was higher at the closest turbine to the discharge hole of the conical basin, which is similar to the results shown by Dhakal et al. [47]. They also showed that the swallowing capacity of the turbines was affected by the increase in the angle from the tip of the conical basin, and this effect was more accentuated at a higher water discharge.

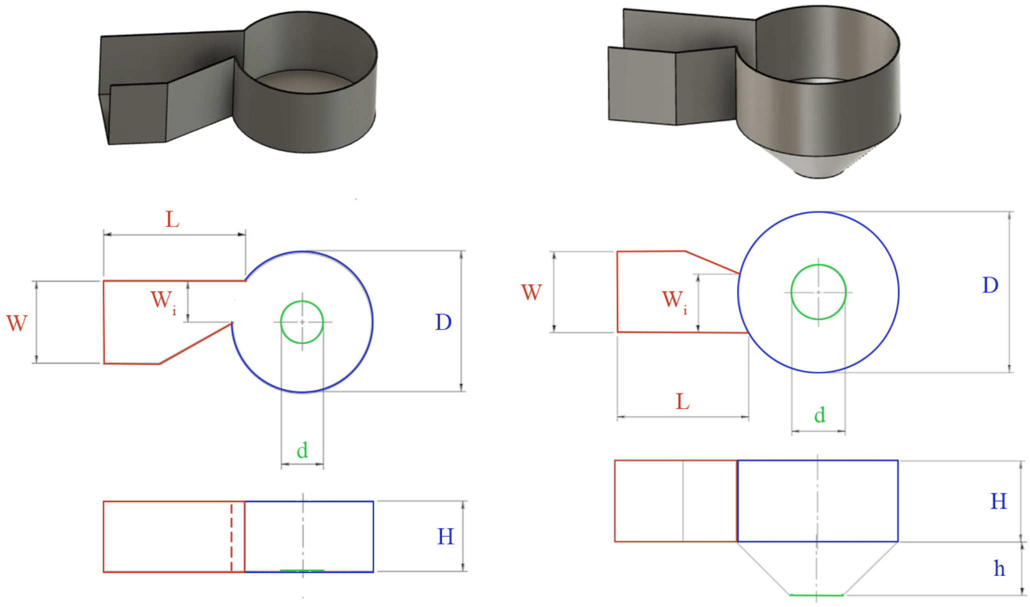

Figure 4. Schematic of a cylindrical basin (**left column**) and a conical basin (**right column**) and their respective inlet channels: 3D model (**top row**), top view (**middle row**), and side view (**bottom row**). Notations: D—diameter of the basin top; d—diameter of the discharge hole at the basin bottom; H—height of the basin; h—height of the conical section of the conical basin; L—length of the inlet channel; W—width of the inlet channel; and W_i—width of the opening to the basin.

Sánchez et al. [7] conducted both numerical and experimental studies on two GWVHT systems, one with a concave basin and the other with a convex basin. The findings showed that the concave basin system outperformed the convex basin system, producing power outputs of 0.37 W and 0.23 W, respectively. Additionally, Sánchez et al. [58] compared a GWVHT system with a conical basin to one with a cylindrical basin in terms of discharge hole size. The results indicated that the conical basin system performed better than the cylindrical basin system.

In a study conducted by Velásquez García et al. [23], the impact of inlet channels and basins on the performance of GWVHT systems was numerically analysed using ANSYS Fluent with the $k - \epsilon$ turbulence model. The study compared systems with cylindrical and conical basins and considered two inlet channels: tangential and wrap-around. The results showed that the conical basin produced a more symmetric vortex for both inlet channels and maximized the flow velocity on the water surface area.

Nishi et al. [40] conducted a study on the efficiency of the GWVHT system in a conical basin with a diameter of 0.49 m and a discharge diameter of 0.1 m. They used both experimental and numerical methods, including the ANSYS CFX 15.0 and the VOF method, to carry out a three-dimensional unsteady numerical analysis. Their findings showed that the turbine's efficiency was directly related to the flow rate.

In a study by Srihari et al. [89], they experimented with five different conical basins equipped with vortex intensifier nozzles. The basins were placed in various positions and orientations, and their results were compared to those obtained by Dhakal et al. [22]. The study found that the vortex formation in the basins was strengthened by the intensifying nozzles, resulting in increased turbine efficiency. The best basin configuration showed an increase in torque by 57.77%, power output by 54.42%, and efficiency by 54.41% compared to the configuration used by Dhakal et al. [22].

A study by Havaldar et al. [55] analysed GWVHT systems with two types of inlet channels: straight and curved. The results showed that the curved inlet channel had a higher average velocity, indicating that it performed better than the straight inlet channel.

The study by Burbano et al. [70] explored how the shape of inlet channels in GWVHT systems with a conical basin affects their performance. They analysed square and trapezoidal cross-section shapes, each with three different channel shapes (straight, partially curved, and fully curved). The researchers discovered that using a trapezoidal channel cross-section improved power output by reducing the impact of viscous forces on fluid velocity, causing it to accelerate. Additionally, changing the geometric parameters in the baffle zone was only beneficial for trapezoidal channels, as it narrowed the connection between the channel and basin, enhancing fluid velocity upon entry. In conclusion, the study recommended using trapezoidal cross-section channels for all applications.

A study by Huwae et al. [99] investigated how the inlet channel affects GWVHT systems. The researchers found that when the channel is too short, a surface wave can appear in a rectangular inlet channel, resulting in significant hydraulic loss and a decrease in power output. They varied the relevant parameters in their experiments to determine which ones affected the water surface at the inlet channel. They found that placing a strainer 5 cm away resulted in a 60% increase in output power by reducing the wave speed. However, they recommended further research on non-dimensional parameters, such as the Froude number, to optimise the performance of GWVHT systems.

The summary provided in Table 4 showcases several studies on GWVHT systems, including various geometrical configurations (updated from Velásquez et al. [23]). The table reveals that there is no consistent relationship between the power output and the different ranges of geometrical parameters. Surprisingly, the highest efficiency is not solely dependent on the maximum d/D. However, it is generally observed that GWVHT systems with conical basins tend to perform better than those with cylindrical basins. This conclusion aligns with the findings of other studies mentioned earlier.

Table 4. List of some past studies on the geometrical parameters of the basin and inlet channels in GWVHT systems (note: d, D, H, w, h, and L are labelled in Figure 4).

Reference	Basin Type	d/D	H/D	W/D	h/D	L/D	Power (W)	Efficiency (%)
[86]	Cylindrical	0.14	1.53	0.50	0.0	2.20	2.83–9.53	14.4–48.6
[126]	Conical	0.17	1.50	0.50	0.50			
[89]	Conical	0.50	1.42	0.5	0.5	2.83	33	42.4
[95]	Conical	0.22	1.06	0.32	0.16	2.08		
[36]	Conical	0.13	1.96	0.42	0.42	0.45		
[40]	Conical	0.20	0.37		0.33			55
[63]	Conical	0.14	0.43		0.57	2.14		75
[37]	Conical	0.16	1.84	0.59				
[37]	Cylindrical	0.18	1.57	0.36	0.0	1.51		
[71]	Concave	0.34	1.27	0.42	0.89	3.30	3.0	45
[71]	Convex	0.22	1.35	0.28	0.59	2.19	2.0	45
[108]	Conical	0.28	0.19	0.20				
[70]	Conical	0.13	0.57	0.5	0.43	2.14		

5.1.2. Parametric Studies on Basins and Channels

Wanchat et al. [33] conducted a study, both through experimentation and numerical analysis, on a cylindrical basin GWVHT system. They found that if the discharge diameter is less than or equal to 0.2 m, then there will not be enough angular momentum in the vortex to drive the turbine when the height is at 20% of the basin's diameter, as more water enters than is discharged. On the other hand, if the discharge diameter is greater than 0.4 m, the vortex height is too low, and there is not enough energy to spin the turbine. According to their model, the system produced a 60 W power output at 30% efficiency with a discharge diameter of 0.2 m.

Dhakal et al. [98] conducted a numerical and experimental study on the effect of d/D on the performance of the GWVHT systems with conical basins when d/D varies between 0.15 and 0.3. They carried out the numerical simulation by assuming a laminar flow, and their numerical results showed that the basins having d/D in the range of 0.2 to 0.25 produced the maximum output power, which was also confirmed by their experimental results.

Kim et al. [62] utilised the ANSYS CFX 17.2 package to analyse the effectiveness of a GWVHT system that comprised four turbines with varying numbers of blades in a conical basin. To enhance the basin's performance, they introduced three draft tube modifications: a straight draft tube, a conical draft tube with a divergent angle of 10C, and a height-increased conical draft tube. The results showed that adding a small draft tube to the basin boosted the system efficiency by nearly 3% and increased the overall efficiency by up to 60%. The researchers attributed this improvement to the draft tube's ability to gradually recover the low-pressure area from the basin's discharge hole to the outlet passage.

Velasquez et al. [37] explored how to improve the efficiency of a GWVHT system with a conical basin by optimising its geometry. The study found that the highest circulation and efficiency were achieved through specific ratios of geometric parameters, including d/D, H/D, W/D, h/D, L/D, and the wrap-around angle (α). The researchers used the response surface methodology to determine the optimal combination of factors and their impact on the system's performance. This technique enables the exploration of the relationship between independent variables and their combined effect on the outcome being studied. They used ANSYS Fluent to carry out 60 numerical simulations with 60 geometries with d/D, H/D, w/D, h/D, L/D, and α being in the ranges of 0.1–0.3, 0.5–2.0, 0.2–0.5, 0.2–0.6, 0.25–3.0, and 90–180°, respectively. They found that the highest circulation of 2.089 m^2/s was achieved when $d/D = 0.167$, $H/D = 1.84$, $w/D = 0.2$, $h/D = 0.599$, $L/D = 0.5$, and α = 179.976°. The study also revealed that the inlet passage structures are capable of affecting the tangential flow to the basin. More recently, Velásquez et al. [79] continued the study on the optimisation of the geometry of the GWVHT system which was studied in [37], but in this case, they developed a high-fidelity surrogate model to generate a multi-objective genetic algorithm which can search the optimal geometry of the inlet channel and the basin. Again, they considered the six same parameters, d/D, H/D, w/D, h/D, L/D, and α, in the same ranges of 0.1–0.3, 0.5–2.0, 0.2–0.5, 0.2–0.6, 0.25–3.0, and 90–180°, respectively, that were considered in [37]. They found that the values of the six variables which provide a compromising solution for maximizing the vortex strength and at the same time minimizing the volume flow rate were $d/D = 0.108$, $H/D = 0.565$, $w/D = 0.361$, $h/D = 0.599$, $L/D = 1.518$, and α = 92.141°, respectively.

In their laboratory experiments, Sarke et al. [106] compared two types of GWVHT systems: one with a cylindrical basin and one with a conical basin. They discovered that the system with the conical basin performed better, generating 21–23 W of power compared to the cylindrical basin's 17–18 W. The researchers also observed that increasing the diameter (d) of the cylindrical basin resulted in a higher power output than in the conical basin. Therefore, a cylindrical basin is preferable for a larger discharge outlet, while a conical basin is slightly better for a smaller one. Additionally, the team found that an increase in water flow led to a slight boost in power output for the cylindrical basin, but a more significant increase in power output for the conical basin. As a result, a conical basin is preferable in high-water-flow rivers.

Assuming a very small flow rate such that the flow is laminar, Vinayakumar et al. [77] used the finite element method in the COMSOL package to carry out a series of numerical simulations to perform a parametric study on several key parameters of a GWVHT system for optimisation, which include the height of the cylindrical basin, the number of curved blades, the length of the blades, and the tilt angle of the blades. They also constructed a physical GWVHT system and used the experimental results to validate the numerical simulations. However, they only provided the results for the effect on the speed of the rotor of these parameters and nothing else. In terms of the basin height, they only tested five basin heights (10 cm, 20 cm, 30 cm, 40 cm, and 50 cm) and found that the speed of the rotor increased when the basin height increased from 10 cm to 30 cm; after that, the speed decreased slightly.

Esa et al. [79] used Solidworks to carry out a numerical simulation study on a GWVHT system with dome-shaped (concave) basins to optimise the design of the system. In their numerical simulations, which were based on the assumption of a laminar flow, they studied two versions of the dome basins, that is, a wide dome basin and a narrow dome basin. The ratio of the diameter of the basin at its top and the diameter of the discharge hole at the basin bottom for the wide dome basin is 1.3:0.3, while the ratio for the narrow dome basin is 1:0.2. Both basins have the same basin height (0.25 m). Their numerical results showed that the optimised radius of the dome basin was between 0.6 m and 0.7 m, and the combination of a 0.3 m diameter of the discharge hole and a 0.6 m basin height produced the best results among all cases considered. They also found that the vortex velocity's development is directly proportional to the system's dome basin height. In addition, they constructed a dome basin GWVHT system and conducted some experiments. Their experimental results showed that the dome-shaped basins performed better with a discharge hole diameter in the range of 0.05–0.1 m and produced the highest overall efficiency of 31.77%.

Dhakal et al. [80] carried out a numerical and experimental study on optimising a GWVHT system with a conical basin by varying four design parameters of the basin, including the notch angle, the canal height, the notch inlet width, and the cone angle. A relationship among these design parameters with the water velocity for the optimisation of the system's performance was established and verified by the experimental results, with the values of the notch angle, the canal height, the notch inlet width, and the cone angle in the ranges of 10–70°, 0.1–0.4, 0.1–0.3, and 5–23°, respectively, and the maximum efficiency achieved was 74.35%. It should be noted that no units were provided for the canal height and the notch inlet width.

Chattha et al. [84] carried out a numerical study on the effect of the basin's geometry on the performance of a GWVHT system with a cylindrical basin. The numerical simulations were performed under the assumption of a laminar flow. Their numerical results showed that the vortex height and the gains in the tangential velocity, the air core, and the tangential, radial and axial velocities changed significantly when the basin geometry parameters such as the basin height and the discharge outlet diameter varied, and they concluded that to optimise the design parameters in order to improve the system efficiency, a strong vortex with an air core should be formed. The accuracy of the numerical simulations was not examined, and the assumption of laminar flow may not be appropriate for all simulations.

A study conducted by Rehman et al. [85] examined GWVHT systems and determined the geometrical features that lead to optimal system performance. Their findings showed that for optimal performance, the discharge hole diameter should be 40% of the basin diameter. Additionally, the rectangular passage should be at 60° with the pre-rotational plate at 30° to achieve the highest velocity. In another study, Rahman et al. [88] utilised a laboratory-scale GWVHT system to investigate the impact of the flow rate and inlet channel on efficiency. Their results revealed a polynomial relationship between flow rate and efficiency for flow rates ranging from 5.6 m^3/h to 8.8 m^3/h. They recommended using a tangential flow for the inlet to minimize distortions and losses. Inlet channels can either be tangential or scroll-type designs with flat basements, with the scrolling inlet being more commonly used, as it increases the discharge towards the exit [127].

Khan et al. [126] studied the effects of several geometry parameters in GWVHT systems on the tangential velocities and vortex formation, with D, W/D, inlet velocity, H/D, and d/D in the ranges of 0.4–0.8 m, 0.1–0.5, 0.1–0.6 m/s, 0.1–0.5, and 0.13–0.17, respectively. They noted that more water spilled out of the basin when d/D was increased, which reduced the vortex height in the basin; increasing W/D resulted in a larger mass flow, which led to overflow on the top of the basin; and increasing the basin diameter resulted in the decrease in the vortex height.

Jiang et al. [71] carried out a numerical study to optimise GWVHT systems using ANSYS Fluent by finding the location of the maximum tangential velocity and the optimal power output in a conical basin with different notch angles, conical angles, basin shapes, and diameters. They found that the optimised design parameters were a 1.0 mm basin diameter and 13° and 14° notch and conical angles, respectively.

An analysis was conducted by Thapa et al. [127] using numerical methods to compare the vortex flow pattern in GWVHT systems with different inlet channels. It was found that rectangular and circular channels had more symmetrical pressure variations than triangular and curved geometries. Another study by Rahman et al. [32] used ANSYS Fluent numerical simulations to show that the highest tangential velocity was achieved using an inclined inlet channel at 60° in a GWVHT system with a conical basin. The models studied also included horizontal and 30° inclined channels, and a constant inlet velocity of 3 m/s was used for each model. However, the types of simulation settings were not mentioned. Jha et al. [51] conducted numerical studies on GWVHT systems and found that the notch length should be within a certain critical value. If it is increased, it can cause disruptive turbulence, especially near the inlet area. Furthermore, they confirmed that the basin inlet channel is an important design parameter that may have an impact on power output. Velásquez Garcí et al. [128] studied the GWVHT systems with four geometries involving cylindrical and conical basins having tangential and wrap-around inlets, respectively. The VOF method was used in Ansys Fluent, and the $k-\epsilon$ turbulence model was selected using the inlet velocity of 0.1 m/s. The result was that the conical basin with a wrap-around inlet configuration showed a more symmetrical vortex, indicating a higher tangential velocity of 1.55 m/s at the radius of 0.22 m.

Tamiri et al. [110] combined numerical simulations and experiments to study GWVHT systems with five types of triangle-shaped diffusers which have various dimensions and with a conical basin with dimensions of 40 cm in diameter and 50 cm in height. They concluded that the inlet channel with a diffuser with a larger angle would maximize the flow of the water through the inlet channel, as the diffuser would act as an accelerator providing higher kinetic energy to the water to circulate around the basin, which can result in an increase in the turbine's efficiency. They also noted that the placement of the diffuser distorted the vortex profile, which developed a fully developed air core through the vortex height. When the diffuser angle was increased, there was an increase in the vortex profile. The increase in the vortex height will produce a greater vortex strength. Their results found that the most optimum position of the blades was when they were placed 35% above the basin, and the best-performing diffuser was that with the angle of 10° at the water height of 0.28 m.

In his master's thesis, Khan [114] conducted a detailed parametric study and optimisation on GWVHT systems with a cylindrical basin by carrying out numerical simulations using the ANSYS CFX package and via experiments. They considered four different blade shapes. To examine the effects of the parameters representing the inlet channel and basin geometries, i.e., D, d, H, and W, they carried out 25 numerical simulations over the ranges of 0.4 m $\leq D \leq$ 0.8 m, $0.13 \leq d/D \leq 0.17$, $0.1 \leq H/D \leq 0.5$, and $0.1 \leq W/D \leq 0.5$, respectively, and at the inlet flow velocity of 0.3 m/s. They found that increasing the flow rate into the basin resulted in a rise in the water level in the basin, leading to an increase in the tangential velocity. The vortex velocity reached its maximum when a full air core was formed; however, the air core and the vortex height could not be directly related to each other, as the air core's formation depended upon many other factors too. Increasing the flow rate by increasing the inlet depth was better than increasing the inlet width. The air core could be formed by increasing the outlet diameter if all other parameters were kept constant. When the basin diameter was reduced, the water level in the basin slightly increased; however, it also caused the air core to decrease until the air core eventually disappeared. When the basin diameter was increased from its optimal value, the vortex height decreased, resulting in a larger vortex strength, and thus a higher efficiency. Finally, water entry above the vortex's upper surface did not improve the power output. Based on their parametric study, they recommended that the optimal values for the basin and inlet channel parameters are $D = 0.5$ m, $H = 0.5$ m, $d = 0.08$ m, $W = 0.1$ m, and $H = 0.1$ m, respectively.

5.2. Past Studies on Turbines (Blades)

For a turbine in a GWVHT system, the major parameters representing the turbine characteristics include the shape, number, size (dimensions) of the blades, the orientation and position of the blades in the basin, and the diameter of the shaft and/or hub on which the blades are attached. All these parameters affect the system's overall performance. Numerous studies have been conducted with various types of turbines over wide ranges of these parameters to accommodate various applications. Table 5 summarizes some known values of these parameters and their respective efficiencies obtained from past research relating to turbines in GWVHT systems.

Figure 5 presents the schematic of the types of turbines with S-curved blades, curved blades, and flat (also called straight) blades, which are the three most commonly used types of turbines in GWVHT systems. There are also several other types of turbines with blades in different shapes (such as crossflow and twisted blades) or with different configurations, which will be reviewed below.

In the following review, some of the previous studies listed in Table 5 are further described with more details. In addition, the other remaining previous studies involving turbines are also described, with some details.

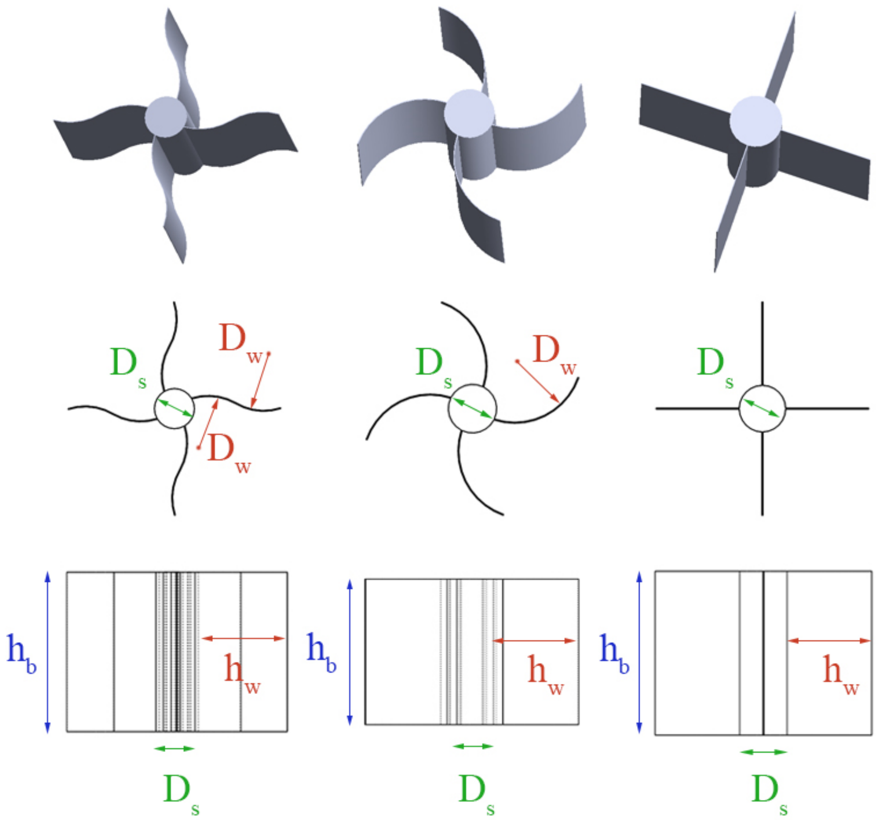

Figure 5. Schematic of the types of turbines with S-curved blades (**left column**), curved blades (**middle column**), and flat (straight) blades (**right column**): 3D model (**top row**), top view (**middle row**), and side view (**bottom row**). Notations: D_s—diameter of shaft (hub); D_w—curvature of curved blade; h_b—height of blade; and h_w—width of blade.

Table 5. Summary of the known values of the parameter relating to turbines in GWVHT systems reported by some previous studies.

Ref.	Basin	Blade Shape	Number of Blades	Shaft Diameter (m)	Blade Width (m)	Blade Length (m)	Flow Rate (L/s)	Power Output (W)	Efficiency (%)
[49]	Cylindrical	Flat	2, 4		0.075–0.2	0.25, 0.5	0.65	0.07–0.15	6–15
[129]	Cylindrical	Curved	5				40–60		25.7–37.9
[129]	Cylindrical	Curved with baffle	5				40–60		27.9–32.8
[130]	Cylindrical	Flat	3, 6	0.0075	0.017, 0.027	0.07	0.125–0.272		38.6–42.1
[83]	Cylindrical	Flat	4	0.1	0.4	0.5	11.19–15.47	0.0–16.42	0.0–22.2
[83]	Cylindrical	Curved	4	0.1	0.4	0.5	10.68–13.48	0.0–14.17	0.0–21.6
[50]	Cylindrical	Curved (crossflow)	20	0.09	0.091	0.091	2.85	0.8–1.52	19–34
[87]	Conical	Flat	6						26–46
[87]	Conical	Twisted	6						38–63
[87]	Conical	Curved	6						44–82
[87]	Conical	Curved	4	0.04	0.3	0.1	4	<14	31–71
[45]	Cylindrical	Curved	5	0.1	0.4–0.7	0.2–0.4	200–600		4.9–13.4
[45]	Cylindrical	Curved (crossflow)	24	0.4–0.7	0.1	0.3	200–600		1.4–21.9
[86]	Cylindrical	Flat	3		0.146		1.56–2.44		7–28
[62]	Conical	Curved	5–10	0.09	0.05	0.091			44–57

5.2.1. Non-Parametric Studies on Turbines (Blades)

An experimental study was conducted by Dhakal et al. [47] to determine how the number and radius of turbine blades affect the performance of GWVHT systems in both cylindrical and conical basins. They discovered that the most effective position for the turbine was at the bottom of the basin, where the velocity head increased with depth. They also found that fewer blades resulted in increased efficiency, as larger numbers caused significant vortex distortion. Additionally, increasing blade radius decreased efficiency due to friction at the basin's inner surface. Using a conical basin enhanced vortex formation, leading to a maximum efficiency of 29.63% being achieved in the experiments. To increase power extraction from GWVHT systems, Gautam et al. [81] suggested adding a boost turbine in series with the main turbine, placed near the discharge hole in a conical basin. Due to the basin's shape, the boost turbine was smaller than the main turbine. They conducted numerical and experimental studies to determine how different booster turbine parameters, such as inlet and outlet blade angles, impact angle, taper angle, number of blades, and turbine height, affected the system's performance. Their numerical simulations were performed using the ANSYS Fluent 16.2 package. The main turbine had five blades (their shape was not specified), while two of the boost turbines had three curved blades and the other one had six curved blades. They found that under the optimal conditions, the addition of a boost turbine can increase the system's efficiency by 6%. This study was continued by Dhakal et al. [54], who carried out a very similar numerical and experimental study. In this case, the main turbine studied had five curved blades while the boost turbine had five blades with four different shapes and sizes. They found that, overall, the GWVHT system with the best boost turbine produced an increase of 3.84 W in power output, which corresponds to an increase of 20.4%, compared to the system using only the main turbine. Yadav et al. [75] also studied the effect of adding a boost turbine to a GWVHT system with a conical basin through three-dimensional numerical simulations using the ANSYS 2020 R2 package. Both the main turbine and the boost turbine had four curved blades and the same shape, with the boost turbine placed below the main turbine along the same shaft. Their research focused on the effect of the gap between the main and booster turbines in order to obtain the optimal gap. They found that the optimal power output could be achieved if the distance of the main turbine's bottom position was fixed at 16.72% of the distance between the top of the conical basin and the top position of the booster turbine.

Sharif et al. [56] carried out a numerical and experimental study on the performance of a GWVHT system with a conical basin. Their numerical simulations were performed using the ANSYS CFX package. The turbine they investigated had five curved blades, and the dimensions of the turbine were 0.2 m in diameter, 0.067 m in height, and 0.03 m in hub diameter. The curved blades with an angle of 167° were placed at 65–75% of the height of the conical basin from the top position. Their results showed that with the flow rate of 2 L/s, the power output and the efficiency were in the ranges of 3.89–6.17 W and 33.19–52.64%, respectively.

In a study by Warjito et al. [68], the impact of turbine blade shape on a GWVHT system with a conical basin was analyzed using the Ansys Fluent 18.1 package and two turbulence models: $k-\epsilon$ and SST $k-\omega$. The researchers assessed three types of turbines, each with six blades: vertically flat, tilted flat, and curved. The results showed that tilted flat blades had the highest performance, with a maximum efficiency of 36%. This was 3% and 6% better than the vertically flat and curved blade designs, respectively. The researchers attributed this to the more stable pressure distribution area and the better vortex flow formation of the tilted flat blades compared to the other two designs.

Kueh et al. [83] tested two different turbines in a cylindrical basin. The first turbine had four flat, vertical blades that were 0.45 m wide and 0.5 m long, while the second turbine also had four vertical blades, but each blade consisted of a flat section that was 0.45 m wide and 0.4 m long and a curved section that was 0.45 m wide and 0.1m long at the bottom of the blade. The researchers discovered that the turbine with flat blades generated power outputs between 0.0 and 16.42 W and had an efficiency range of 0.0–22.2% at flow rates between 11.19 and 15.47 L/s. Meanwhile, the turbine with curved blades generated power outputs between 0.0 and 14.17 W and had an efficiency range of 0.0–21.6% at flow rates between 10.68 and 13.48 L/s.

The influence of turbine blade length and number of blades on the performance of GWVHTs in a cylindrical basin was experimentally investigated by Rahman et al. [130]. Four turbines were tested, with two having three vertically flat blades and the other two having six vertically flat blades. Two different blade lengths were used, and vortex profiles were obtained for each turbine configuration. The study found that the maximum vortex tangential velocity occurred at a head of 0.12 m. The highest efficiency of 43% was achieved with a three-blade turbine and a discharge diameter of 0.027 m. Interestingly, the study also found that the highest rotational velocity did not necessarily result in the highest efficiency, which aligns with the conclusions drawn by Dhakal et al. [47].

Wichian et al. [129] conducted a numerical and experimental study to investigate the effect of the baffle blades in a GWVHT system with a cylindrical basin. The baffle blades were specially designed, with semi-curved metal plates with different widths added horizontally at the bottom and the top of the vertical curved blades. The baffle plates generally have the same or similar shape as the curved blades and were used to direct or restrain flow. For the experimental study, two turbines with and without baffles having five curved blades were used in the cylindrical basin, which is 1 m in diameter and 1 m in height, and operated at flow rates from over 0.04 m^3/s to 0.06 m^3/s. For the numerical study, five models of the five-blade turbines with ratios of the area of the baffle plate to the total area of the blade of 0% (no baffle), 25%, 50%, 75%, and 100%, respectively, were numerically simulated with a CFD package with the $k-\epsilon$ turbulence model (but no specific package was specified). The results showed that the model with the ratio of 50% produced the maximum efficiency and the largest torque, with increases of 4.12% and 10.25%, respectively, and the larger baffle plates at the 75% and 100% ratios created greater inertia and thus reduced the torque and efficiency significantly.

Nishi and Inagaki [50] conducted a numerical and experimental study on the performance of a GWVHT system with a cylindrical basin and a turbine with 20 curved blades. They carried out the numerical simulation using the ANSYS CFX 15.0 package, coupled with the Volume of Fluid (VOF) method to deal with the air–water interface dynamics. The SST turbulence model was selected. Based on the comparison of the results obtained numerically and experimentally in terms of the produced torque, power output, and efficiency, they concluded that after considering the free surface using the VOF method, the experimental results agreed well with the numerical results. They also showed that when the rotational speed increased at the turbine inlet, the forward flow area enlarged, but when the air area decreased, the backward flow area also enlarged. Nishi et al. [40] continued this study and studied the effect of flow rates on the performance of the GWVHT system through experiments and a free surface flow analysis. With their analysis results, they proposed a loss analysis method and quantitatively assessed the hydraulic loss. They noted that the effective head and the turbine efficiency increased as the flow rate increased; thus, the power output increased at a rate larger than the increase rate of the flow rate. The results further showed that the tank loss and tank outlet loss were the most dominant of all losses, followed by the friction loss inside the tank, while the turbine loss and friction loss in the turbine were small. In addition, Nishi et al. [59] conducted a detailed numerical study to analyse the behaviour of the vortex structure with respect to the flow in the rotary and stationary regions in a GWVHT system and the effect of the blade directions on vorticity and its related flow path between the blades. The loss of the vorticity path was noted. To understand the loss, the loss coefficients of the rotational and stationary regions were defined and analysed. They found that the vortex structure was relatively small in the optimised turbine due to the swirling flow, and the loss due to the tip leakage vortex and the vortex near the turbine outlet hub were suppressed. Ruiz Sánchez [7] also revealed some loss generation mechanisms by determining that the sources of loss were due to the increase in the flow rate, which increased the turbine head and efficiency linearly, thus affecting the turbine output, as the water zone expanded at the blade inlet.

The optimal number of blades in a vortex-type turbine depends on the strength of the formed vortices and several other factors, especially the friction losses. Ruiz Sánchez et al. [63] studied two turbines of a GWVHT system numerically based on their generation of torque with H-Darrius and flat blades in a cylindrical basin. Using Ansys 2019 R3, the models were configured at constant operating conditions. They found that the torques were 0.76 N and 0.16 N for the turbines with the flat blades and the H-Darrius blades, respectively, indicating that the flat blades were more favourable compared to the H-Darrius blades in this case. Wardhana et al. [131] conducted a detailed study on GWVHT systems using propeller-type impellers having various blade cords, shapes, lengths, and numbers of blades. The result showed that the turbine with three twisted blades was the most efficient, with an efficiency of 54.4%. It was also shown that the number of blades was inversely proportional to the efficiency. They also studied the effect of enhancing the vortex strength using water nozzles on five different types of conical basins. The result showed that the turbine with fix nozzles of 0.050 m in diameter, separated 0.15 m from the upper surface, produced a power efficiency of 54.42%. The results agreed with those of Dhakal et al. [22], who found an efficiency of 54.41%. The nozzles strengthened the vortex formation and increased the efficiency.

5.2.2. Parametric Studies on Turbines (Blades)

Handoko et al. [102] experimentally investigated the effect of the arc angle of the curved turbine blade in a GWVHT system with a conical basin. The turbine has five curved blades with the dimensions of 0.08 m and 0.16 m for the blade width and length and 0.1 m and 0.012 m for the diameters of the hub and the shaft, respectively. The blades are inclined by 60°. Three blade arc angles (75°, 90°, and 105°) were studied. The experimental results showed that, overall, the blade arc angle of 90° produced the largest power output.

A parametric study was conducted experimentally by Power et al. [49] to examine the GWVHT performance in terms of various geometries and turbine parameters. The experiment consisted of a cylindrical basin of 0.7 m in height, 0.5 m in diameter, and a central outlet hole of 0.025 m in diameter. The turbines used in the experiments had two and four vertically flat blades with two lengths (0.25 m and 0.5 m) and four widths (0.075 m, 0.1 m, 0.15 m, and 0.2 m). Their experimental results showed that the size and number of the blades have a similar effect on performance, with their increase resulting in lower vortex heights but larger power outputs and higher efficiencies. Thus, further optimisation studies should focus on the use of larger blades and more blades.

Ullah et al. [43] analytically and experimentally investigated the performance of a multi-stage GWVHT system with a conical basin. There were three turbines in series, but each of them generated power independently through a telescopic shaft arrangement. The blades of each turbine were curved. The effects of key parameters, including the rotor ratio, the offset distance between neighbouring turbines, and the intra-staging and inter-staging of two-stage and three-stage GWVHT systems, were studied. They found that in a multi-stage GWVHT system, the profile of the blades of the upstream turbines produced minimal vortex distortion, indicating that the power generation capacities of the downstream turbines are ultimately increase, as the performance of the latter turbines strongly depends on the head utilization capacity of the former turbine. They also found that turbines with tilted blades were best suited to the position near the basin's bottom, whereas the cross-flow blades should be at the top position. Furthermore, their results showed that the rotor ratio of the neighbouring turbines should be selected in such a way that the two turbines have the same rotor-to-basin diameter ratio with the optimal offset distance. They concluded that multi-stage GWVHT systems, which combine the effect of solid-body rotation and a free vortex, present a significant improvement in the overall performance compared to that of single-stage GWVHT systems. Ullah et al. [36] further expanded this study by carrying out more experiments with some other configurations of the multi-stage GWVHT systems. However, this study essentially did not provide more new information, but it did recommend that further mathematical performance prediction models and flow visualisation techniques should be developed and used to explore the intrinsic physics involved in multi-stage GWVHT systems to obtain a deeper understanding of the systems to achieve optimisation.

Haghighi et al. [39] developed a hydrodynamic design method and carried out numerical simulations of a GWVHT system. Their design procedure was developed based on classical free vortex theory, which determined the hydrodynamic features at the turbine blades' radial sections and formed the selected hydrofoils with appropriate stagger angles and chord lengths in each section. They then carried out a steady-state, homogeneous, two-phase numerical analysis using the ANSYS CFX 15.0 package and incorporating the SST turbulence model to obtain the turbulence structures and validated their numerical results with experimental data. They used the simplified Rayleigh–Plesset equation to determine the bubble growth rate in the homogeneous two-phase model to explore the cavitation phenomenon in different states of turbine blade opening angles and rotational speeds. The maximum efficiencies for most of the turbine positions are more than 80%. They suggested that future research should focus on seeking an appropriate method for the transient simulation of a GWVHT system in an open channel and optimising different parts of the system.

Bajracharya et al. [57] carried out a comprehensive parametric study numerically and experimentally on the effects of turbine blade geometry on GWVHT systems with a conical basin. They identified seven geometrical parameters for the turbine design and investigated their effects on system efficiency. These parameters are blade height, blade angle in the vertical and horizontal planes, impact angle, taper angle, cut, and the number of blades. Their three-dimensional numerical simulations were performed using the ANSYS Fluent package with the SST $k-\omega$ turbulence model with curvature correction, as this turbulence model performs well for flows involving adverse pressure gradients and rotating and separating flows, which are exactly what are involved in GWVHT systems. Their experiments were conducted in the GWVHT system with similar basins, channels, shafts, hubs, and dimensions to those in [22] and with the gross head of 0.27 m and the flow rate of 0.0065 m^3/s kept unchanged throughout all cases studied. They studied 22 turbines with different combinations of blades with the variations in the seven parameters. Based on their detailed results and analysis, they recommended the following values for the turbine blades' geometrical parameters for the optimisation of the turbine design in GWVHT systems with a conical basin: a turbine height to basin height ratio of 0.31–0.32; a taper angle conforming to the basin cone angle and impact angle of 20°; the blades should be curved when viewed from the top only, with a blade angle in the range of 50–60°; and a cut ratio smaller than 15%. They also recommended that further studies based on vortex flow theory and multiphase numerical simulations should be carried out to improve understanding of the performance of GWVHT systems and further optimise the turbine designs.

In addition to their study on optimising the design of dome-shaped (concave) basins, Esa et al. [79] also investigated six different turbines. Two turbines had four flat blades with 30° and 90° drums attached, two turbines had four curved blades with 30° and 90° drums attached, and two turbines had curved blades with small 30° and 90° mountings attached. They found that the larger blades reduced the turbine's rotational speed, thus reducing efficiency, and increasing the weight of vertically installed blades also reduced the overall system performance. They found that the optimised location for placing the turbine was close to the discharge hole at the basin's bottom.

Saleem et al. [92] conducted an experimental study on the effects of several key parameters, including flow rate, vortex height, hub diameter, blade position, notch angle, and blade shape, in a GWVHT system with a cylindrical basin. The turbine had four blades, which have three different shapes: a curved one with a radius of curvature of 0.05 m, another curved one with a radius of curvature of 0.1 m, and a flat one. Several inclinations of these blades were studied. They found that the maximum power output could be generated when the vortex height was large and the blades were placed close to the basin's bottom; the power output increased approximately linearly with the radius of curvature for various vortex heights when the chord length of the blades was kept constant; inclined blades generally enhanced the performance; the diameter of the hub on which the blades were fixed affected the vortex significantly, with a smaller hub having less effect, whereas a hub with a diameter larger than the air core's diameter disturbs the vortex shape, so it is better to use the least possible hub diameter; and an optimised ratio of the width to the height of the blades existed for certain basin designs and flow rates, but more work needs to be conducted on this. Saleem et al. [42] expanded this work by carried out further experiments to present a much more detailed performance evaluation of the GWVHT system with a cylindrical basin with the help of mathematical considerations and expressions. The experimental results further confirmed that the vortex height and a good vortex shape with a fully developed air core were key parameters dictating the system performance. They concluded that the performance could be enhanced between the minimum and maximum load conditions by using the minimum possible notch angle and hub diameter, which creates the least disturbance in and minimum distortion of the vortex formed, and by using inclined blades with zero curvature (i.e., flat blades) fixed near the bottom of the basin.

In a study by Irwansyah et al. [61], both analytical and numerical methods were used to compare curved and flat turbine blades for a GWVHT system with a conical basin. The blade geometry and performance were determined using analytical methods, while the internal flow in the turbine was analysed using the ANSYS Fluent 18.1 package with the SST $k-\omega$ turbulence model. Both turbines had five blades, and the results showed that there was no significant difference in efficiency between the flat and curved blade turbines, with both achieving around 63% efficiency. However, by placing the blades in the optimal position (about one-third of the basin height from the bottom), the efficiency could be increased up to 84%. This is because, at this position, the kinetic energy converged the best, indicating that blade location is more important than the type of blade used.

In addition to the study on the effect of adding a small draft tub eto the conical basin, Kim et al. [62] also used the ANSYS CFX 17.2 package to investigate the effect of the number of blades on the performance of a GWVHT system with a conical basin using four turbines which have 5, 6, 8, and 10 vertically twisted blades. For each blade, the twist angle was 30° between the top and bottom blade profile, where the twist was gradually increased from the top to the bottom of the blade. They noted that the eight-blade turbine performed the best, with an efficiency of 57%, so for the eight-blade turbines, the exposure area to the vortex is optimal while maintaining a stable air core propagation. Turbines with fewer blades caused water to splash due to the impact of a massive water mass against a single blade, whereas turbines with a larger number of blades easily blocked the outflow of water and therefore propagated back pressure.

Sritram and Suntivarakorn [45] investigated the performance of GWVHT systems with both crossflow turbines and propeller turbines using experiments and the response surface methodology (RSM) method. The RSM method has been widely used in many laboratory experiments to determine the correlation between independent and dependent factors by forming equations to numerically simulate the experiment, and additionally, it is able to provide better levels and degrees of independent factors with satisfactory accuracy. A cylindrical basin with a diameter of 1 m and a height of 0.5 m was used in the experiments. The discharge hole at the basin's bottom was 0.2 m in diameter. The water flow rates for the experiments were in the range of 0.2–0.6 m^3/s. Two types of turbines were tested: one is the propeller turbine and the other is the crossflow turbine. For the first one, 12 propeller turbines with five curved blades each were produced and tested, which have three different heights (0.2 m, 0.3 m, and 0.4 m). For each height, there were four different turbines with the diameters of 0.4 m, 0.5 m, 0.6 m, and 0.7 m, respectively. For the second turbine, eight crossflow turbines at the height of 0.3 m were produced and tested, with four of them having 24 blades with the diameters of 0.4 m, 0.5 m, 0.6 m, and 0.7 m and four of them having 12 blades, 18 blades, 30 blades, and 36 blades at the same diameter of 0.4 m. Curved blades were used in all these crossflow turbines as well. The authors' major conclusion is that the crossflow turbine could perform better, generating more power output than the propeller turbine. More specifically, they found that at the same flow rate of 0.02 m^3/s, the 5-blade propeller turbine with a 0.4 m height and a 0.7 m diameter achieved 13.92% efficiency, while the 18-blade crossflow turbine with a 0.3 m height and a 0.4 m diameter achieved 23.01% efficiency at the same water flow rate. Based on the experimental results, they obtained an efficiency equation using the RSM method in terms of the flow rate, blade height, and turbine diameter. They also concluded that a turbine with five blades was the most appropriate to use and that the right distance between the blades of the turbine could maximize the exertion of the water flow rate. The RSM method was also used by Faraji et al. [72] in their study on the effects of speed, hub–blade angle, number of blades, and turbine profile in a GWVHT system with a cylindrical basin. Their numerical, analytical, and experimental study involved both flat blades and curved blades, and they obtained the relations for the efficiencies for both types of blades in terms of the turbine speed, hub–blade angle, and the number of blades.

Edirisinghe et al. [38] expanded their earlier work [108] to numerically carry out a parametric study on the effects of different configurations of turbine blades in a GWVHT system with a conical basin using the ANSYS CFX 17.2 package. The configuration parameters representing the turbine blades are the blade inclination, turbine height, vertical twisting, and horizontal curving. They studied five different turbine models; the first (basic) model consists of five flat blades with 0.5 m in diameter and 0.5 m in height; the second one is a modification of the basic model with the blades inclined to the basin at a conical angle of 41° with the same turbine height at 0.5 m; the third one is another modification of the basic model with the turbine height changed but at the same conical shape; and the fourth and fifth models are modified versions with the turbine blades modified with vertical twisting and horizontal curving, respectively, where the vertical twist angle was determined using the relative angle between the top and bottom blade profile, while the twist length was determined by the vertical twisting length. The numerical simulations were carried out using the SST-CC (SST with circular correction) turbulence models and the VOF method. They analysed the relationship between the flow behaviour and the system performance in detail for each case in terms of the air–water interface, pressure, and velocity fields. They noted that increasing the air core would result in maintaining low pressure behind the blades, thus increasing power output. They also found that the twisted vertical turbine, which has full exposure to a wide area at the vortex area, did not propagate a significant air core, and only when the air core outlet drain was increased was the air core allowed to propagate easily while maintaining the low-pressure region behind the blades, thus increasing pressure difference for power generation. They concluded that the blade inclination, similar to the conical basin inclination, produced improved performance, and the bottom-most position inside the vortex basin was the optimal position of the basic turbine model as the vortex strength was high at the discharge hole. The horizontally curved blades produced a slightly higher efficiency than the vertically twisted blades. However, when the discharge hole size increased, the latter had better performance, at the 55.3% efficiency while maintaining a stable air core. This is a very comprehensive study of the vortex dynamics in a GWVHT system with different turbine configurations, which provided very detailed information about the characteristics of the vortex dynamics, making a significant contribution to the understanding of the complex vortex dynamics. It represents one of several pioneering studies on vortex dynamics and the latest development of high-quality studies on GWVHT systems as well as the appropriate use of advanced numerical simulation tools (such as [36,37,39–44,66,71,132]). It should be recommended as an exemplar for future studies on GWVHT systems.

Aziz et al. [69] conducted a numerical study using SolidWorks on the GWVHT with a conical basin with the turbines of different numbers of flat blades at both vertical and horizontal orientations. The selected numbers of the blades are 8, 12, and 18, and the blades were tilted at 25°, 45°, 75°, 90°, and 120°, respectively. The results showed that comparable tangential forces were able to be extracted. In terms of the turbine orientation, the vertical turbine produced better performance, as reviewed by Timilsina et al. [5]. The study also found that increasing blades resulted in the reduction in the tangential force due to the small gaps in between the blades, so there was no sufficient contact with water.

As mentioned earlier, Vinayakumar et al. [77] used the finite element method to carry out a series of numerical simulations to perform a parametric study on several key parameters of a GWVHT system for optimisation, which include the height of the cylindrical basin, the number of curved blades, the length of the blades, and the tilt angle of the blades. In addition to the results about the optimal basin height, which is 0.3 m, they also obtained the optimal blade length, number of blades, and tilt angle of the blades through a parametric study by varying these parameters.

In a study by Zamora-Juárez et al. [78], the vortex formation and its interaction with turbine blades were analysed using both analytical and numerical methods. The aim was to determine the most efficient geometric configuration for a turbine. The numerical model was based on a two-phase flow system. The results indicated that a turbine with a radius coefficient of 0.8 and eight blades had the best performance, achieving an efficiency of up to 64.23%. The study also found that a blade submergence between 90% and 95% resulted in a braking effect on the rear surfaces of the blades, leading to reduced efficiency.

Velásquez García et al. [112] numerically studied the optimal position of the turbine in a GWVHT system with a spiral inlet channel and a conical basin. There were four curved blades in the turbine, and the numerical simulations were performed by changing their positions in the basin. Three positions (at 0.4H, 0.5H, and 0.6H, where H is the height of the basin) were studied. They found that the maximum efficiency (44.15%) was achieved when the turbine was located at 0.6H. But they stated that the optimal model needed experimental verification and recommended that further studies be carried out to establish the optimal turbine design for GWVHT systems in terms of all parameters representing the turbine.

As mentioned above, the thesis work by Khan [114] also included the study of the effect of the turbine blades, in addition to their detailed parametric study and optimisation in terms of the geometries of the inlet channel and the basin. They considered four different blade shapes: inverted conical blades, crossflow blades, curved flat blades, and twisted blades. They found that the turbine with the crossflow blades was the most efficient, with a maximum efficiency of 68.84% achieved under the operating conditions considered.

6. Review of the Past Studies on Other Matters Related to GWVHT Systems

6.1. Efficiency Improvement with New Materials

Changing the material will increase the power/weight ratio, the life span, and the modularity of a GWVHT system [79]. Sritram et al. [133] was the first to evaluate the materials used for turbine blades used in GWVHT systems. They conducted experiments with two types of blade materials, namely aluminium and stainless steel, over a range of flow rates and electric loads. Aluminium was found to produce the maximum efficiency of 34.79%, while for steel, it was 33.56%, indicating that the light-weight materials used for the turbine blades were favourable. Similar results were obtained by Jiang et al. [71], who conducted a numerical study on various geometries of turbines to optimise the power output of a GWVHT system and revealed that light materials of magnesium alloy performed well at a very low equivalent stress compared to other materials and could withstand high hydraulic loads and provide a longer lifetime. Similarly, Velásquez et al. [23] revealed that materials such as plastic, aluminium, or composite materials can be used to manufacture turbine blades because they are lightweight materials. Nevertheless, Zariatin et al. [93] obtained the opposite conclusion. They conducted an experimental study on the effect of the rust-resistant materials used for turbines in a GWVHT system with a cylindrical basin. They considered three different turbines with four flat blades, with each made of stainless steel SAE-304, aluminium alloy AA-5057, and Polyvinyl Chloride (PVC). The flat blades had a thickness of 0.002 m, a width of 0.115 m, and a height of 0.4 m. They noted that at the same operating conditions, the maximum efficiencies of the turbines made of SAE-304, AA-5057, and PVC were 31.8%, 27.7%, and 26.4%, respectively. They then concluded that the blades made of materials with larger densities would generate a larger power output.

More recent studies have been conducted to test new materials for turbine blades. A new superhydrophobic coated material was tested using numerical simulations for GWVHT systems, and it was found that an improvement in efficiency of 4% could be achieved in the design phase [39,134]. Superhydrophobicity is a surface property caused by the combination of nanostructured roughness and low surface energy [39,134].

It is apparent that more comprehensive research work is needed regarding the effect of materials used for turbine blades, along with that for other components of GWVHT systems.

6.2. Turbulence Models and Multiphase Models Used in Numerical Simulations

Numerical simulations are necessary for studying the vortex dynamics in GWVHT systems due to the turbulent nature of the flows, although laminar or transitional flows may occur in a very small portion of the systems. Free surfaces at the air–water interface within the vortex also need to be modelled in such simulations. While experiments are the most reliable way to understand the characteristics of the vortex dynamics and determine the system's performance, they can be challenging and costly, and they may interfere with flow behaviour, affecting the accuracy of the results. Numerical simulations have become more popular due to the availability of CFD packages like ANSYS Fluent and CFX, as well as improved computer power and capacity. Top journals in the energy field have published high-quality studies on GWVHT systems utilizing numerical simulations, providing detailed insights into vortex dynamics. It is expected that numerical simulations will be the primary research method for studying the performance of GWVHT systems.

It has been noted in the review of previous studies that many numerical studies, particularly those early studies on GWVHT systems, assumed the flows involved to be laminar, which, for most cases or operating conditions, is not correct, as the flows should be turbulent. Therefore, appropriate turbulence models must be used in the numerical simulations. In addition, many studies did not take into account the free surface at the air–water interface in the vortex using appropriate multiphase models. All these factors significantly affected the accuracy and reliability of the numerical simulation results, which in turn produced large errors in the prediction and quantification of the performance of GWVHT systems. This also explains why some of such previous studies showed larger differences between the numerical simulation results and the experimental results.

For the majority of turbulent flows, including those in GWVHT systems, there are several popular turbulence models available. The most common ones include the standard $k-\epsilon$ turbulence model and its variations such as the RNG $k-\epsilon$ turbulence model and the realizable $k-\epsilon$ turbulence model, the standard $k-\omega$ turbulence model and the shear stress transport (SST) $k-\omega$ turbulence model, and the Reynolds stress model. In addition, large-eddy simulation (LES) has quickly become a popular numerical simulation method for turbulent flows, although, so far, no previous study has been found to use LES to conduct numerical studies on GWVHT systems.

The two common multiphase models used for the numerical simulations of GWVHT systems are the VOF method and the Eulerian–Eulerian method, as described by Powalla et al. [66]. The VOF method is a simple multiphase flow model capable of resolving the interface between the phases of the mixture by adding a volume fraction transport equation. It is a transient surface-tracking technique designed for two or more immiscible fluids, where the position of the phase-to-phase interface is of interest. For the two phases (air and water in GWVHT system), only one volume transport fraction is calculated, and no interface interaction is assumed, so all phases share the same velocity, pressure, and temperature fields. It is an efficient method but less accurate than the Eulerian–Eulerian method, with which the momentum and continuity equations for each phase are solved.

There are many previous studies on GWVHT systems which included turbulence models and/or properly dealt with the free surfaces at the air–water interface in the vortex with multiphase models. Some of them are listed in Table 6. The most commonly used turbulence models are $k-\epsilon$ models and $k-\omega$ and SST $Kk\omega$ models. The most commonly used multiphase model used to deal with the free surface at the air–water interface is the VOF method. In general, the numerical simulations in these studies were performed using the commercial package of ANSYS Fluent or CFX.

A study by Burbano et al. [70] compared the effectiveness of four turbulence models in numerically simulating flows in GWVHT systems with six different basin and inlet channel configurations, along with a Savonius rotor. All simulations utilised the ANSYS CFX package, with the VOF method applied for the air–water interface. The four turbulence models tested were the baseline (BSL) $k-\omega$ model, the SST $k-\omega$ model, the realizable $k-\epsilon$ model, and the baseline (BSL) Reynolds stress model (RSM). The results showed that the BSL RSM generated the most torque, while the realizable $k-\epsilon$ model performed the least effectively. The two $k-\omega$ models performed similarly well.

6.3. Fish-Friendly Intake Structures

In any water-based technology, the security of the water system is an important external design consideration. Hydropower schemes must extract water in reliable and controllable ways [135]. GWVHT systems fall under the auspice of small hydropower technology and thus require low head applications. From the biological perspective, designing fish-friendly intake and turbine structures should follow sets of guided criteria. The design guidelines for Very Low Hydro Turbines (VLHTs), including GWVHT systems, were laid out by Fraser and O'Neil [136]. Quaranta et al. [134] also identified some basic criteria such as the maximum velocity of the blades, velocity gradient, optimal efficiency, and ranges of inlet and outlet velocities proportional to fish species of the locality.

Timilisina et al. [118] and Mulligan et al. [5] revealed that for a GWVHT system, selecting a high head is not the priority when selecting an intake further upstream, since the system does not necessarily depend on the full head pressure to operate; rather, it depends on the internally induced dynamic forces from the vortex energy. However, a high diversion intake–weir arrangement may be optional depending on site conditions. Tamiri et al. [137] revealed that the purpose of intake diversion in this case is for the purpose of water transfer convenience, fish-friendly water diversion, and a type of fore–bay structure. This was further confirmed by Velásquez et al. [23] in that the intake is needed for water resource assessment and selecting and identifying suitable environments for the installation of GWVHT systems. There is not enough data to fully understand the use of energy in river systems for GWVHT system design [126]. Rahman et al. [32] warned that even though the GWVHT systems are capable of low-carbon energy production, they can still be environmental unfriendly if not properly designed, as their intake may lead to depleted water resources for marine life.

Guzman and Glasscock [67] proposed three models of intake arrangement, including a river with an inclination, a river with a sudden drop, and a canal bypass. But they did not provide additional information. The models may be incorporated with designs with biological considerations. In any hydropower system calculation, the head loss must be accounted for, especially in the application of reactive turbines. The head loss assessment may be considered as the initial step in the optimisation of GWVHT systems [115].

Table 6. Turbulence models and multiphase models used in some previous studies using numerical simulations (NA—not available/specified/mentioned).

Ref.	Turbulence Model	Multiphase Model	CFD Package	Note
[48]	NA	Eulerian–Eulerian	ANSYS Fluent 14.0	Differences of -2% to 7% from experiments
[50]	SST $k-\omega$	VOF	ANSYS CFX 15.0	Good agreement with experimental results
[7]	BSL Reynolds Stress	NA	ANSYS CFX 19.1	Difference of -3.2% from experiments
[66]	SST $k-\omega$	VOF	Star-CCM+	Average differences of <15% from experiments
[40]	SST $k-\omega$	VOF	ANSYS CFX 15.0	Relatively satisfactory agreement with experimental results
[37]	RNG $k-\epsilon$	VOF	ANSYS Fluent	No direct comparison with experimental results
[72]	SST $k-\omega$	NA	ANSYS CFX 17.0	Good agreement with experimental results
[71]	$k-\epsilon$	NA	ANSYS Fluent	Differences of <5% from experimental results
[38]	$k-\omega$	Eulerian–Eulerian	ANSYS CFX 17.2	Maximum difference of about 4.2% from experimental results
[78]	RNG $k-\epsilon$	VOF	ANSYS CFX 2021 R2	No comparison with experimental results
[39]	SST $k-\omega$	Eulerian–Eulerian	ANSYS CFX 15.0	Differences of <3.2% from experimental results
[62]	NS	Eulerian–Eulerian	ANSYS CFX 17.2	Differences of <5% from experimental results
[44]	RNG $k-\epsilon$	VOF	ANSYS Fluent	No comparison with experimental results
[41]	SST $k-\omega$ with circular correction	Eulerian–Eulerian, VOF	ANSYS CFX	Noticeable differences from experimental results
[77]	RNG $k-\epsilon$	COMSOL Multiphysics	COMSOL	Differences of <10% from experimental results
[59]	SST $k-\omega$	VOF	ANSYS CFX 15.0	Noticeable differences from experimental results
[132]	Realizable $k-\epsilon$	NA	ANSYS Fluent 18.1	No comparison with experimental results
[97]	$k-\epsilon$	COMSOL Multiphysics	COMSOL	No comparison with experimental results
[57]	SST $k-\omega$	NA	ANSYS Fluent	Significant differences from experimental results
[90]	RNG $k-\epsilon$	VOF	ANSYS Fluent	Good agreement with experimental results
[41]	SST $k-\omega$ with circular correction	VOF	OpenFOAM	No comparison with experimental results

7. Implementation of GWVHT Systems in Developing Countries: A Case Study in Papua New Guinea

Table 2 reveals that the majority of the installed GWVHT systems are located in developed nations, with only a few situated in developing countries such as Nepal, India, and Peru. Given that GWVHT systems are the most viable and appropriate means of electricity generation for impoverished, remote, and rural areas in developing countries, it is anticipated that there will be significant research and development conducted on GWVHT systems specifically tailored for such regions.

The lead author of this review (Nosare Maika) and his team in Papua New Guinea (PNG) designed, constructed, and installed a pilot GWVHT system in a village [31], at the cost of about 4300 US dollars per kW of power. The system consisted of a mini-catchment dam, a closed head race, a cylindrical basin with an extended draft down channel, and a four-blade axial Kaplan turbine coupled with a generator. The cylindrical intake basin was 1.35 m in diameter, 1.0 m in height, and the water discharge outlet at the centre of the basin bottom was 0.23 m in diameter. The basin was constructed using metal sheets. The top of the basin was open to the atmosphere. The selection of the discharge diameter was made based on the previous study by Mulligan et al. [21], in which d/D has to be within 14–18%. The installed GWVHT system was designed to produce 2 kW of power using flow rates from 30 L/s to 100 L/s at a head of 1.5 m. The entire system was tested in a small creek near the village. The water flow rate was recorded daily using a digital flow meter at the steady head. The volt-meter and the current-meter readings were recorded hourly using the multimeter. The tests were conducted continuously for a period of 2 weeks. The data were recorded and evaluated in terms of flow rate, power output, and efficiency.

The GWVHT system's power output and efficiency are displayed in Figure 6, showing a typical day's performance. The results demonstrate that both power output and efficiency follow a nearly sinusoidal pattern, peaking at around 5 pm. The power produced ranges from 800 W to 1700 W, with the highest efficiency at approximately 70% and an overall efficiency of around 51%. The decline in power output and efficiency after their peaks may be due to increased household water demand, leading to a decrease in water volume capacity.

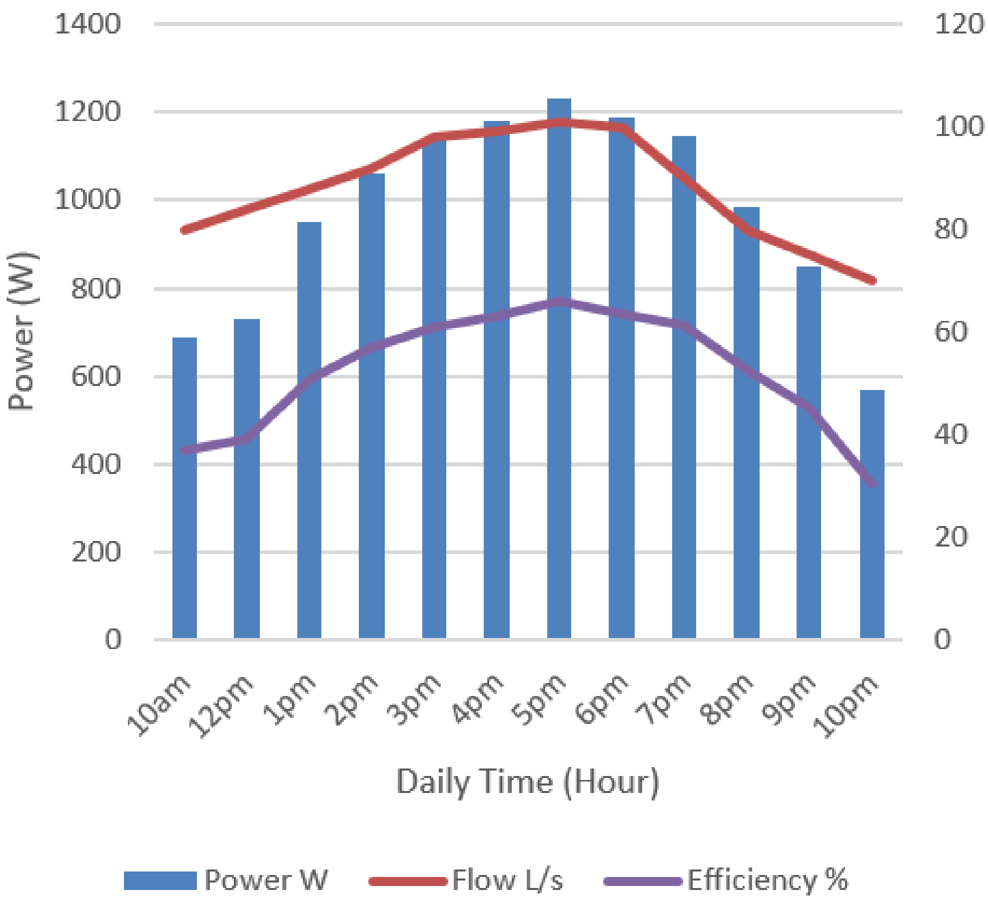

Figure 6. The power output and efficiency during a typical day produced by the GWVHT system in PNG.

8. Major Issues and Challenges and Recommended Future Work

The interest in and research on GWVHT systems have quickly increased, as such low-head sustainable energy generation devices are particularly suitable for remote and rural regions in developing countries. Although strong efforts have been made, particularly in the past several years, to understand the various mechanisms for this relatively new technology and the optimisation of their designs, there is still a long way to go to optimise and standardise the designs of GWVHT systems over a wide range of scales and with different configurations under various operating conditions so as to significantly improve the system performance, which has generally been very poor. This is mainly due to the current lack of in-depth understanding of the various mechanisms and characteristics of the vortex dynamics involved in GWVHT systems, which requires a concerted and comprehensive research effort covering all aspects of GWVHT systems using combined experimental, analytical, and numerical techniques.

Based on the above review of the previous studies on GWVHT systems, some major issues and challenges have been identified, as summarised below:

- The major issue is the poor understanding of the various mechanisms and characteristics of the vortex dynamics involved in GWVHT systems, which differ substantially under different configurations and under varied operating conditions. Due to the complex nature of the vortex dynamics involved in GWVHT systems, where the flows are in general turbulent or transitional (although for a very small portion of the systems, the flows may be laminar), analytical solutions are generally not available, even though some simple analytical solutions can be obtained as an approximate estimation for some operating conditions under which laminar flow dominates. Traditional experimental techniques face challenges to fully understanding the various mechanisms and characteristics of the vortex dynamics involved, as they are unable to provide all the details of the whole flow field. The interference of the measuring elements (like probes) placed in the flow may significantly change the vortex dynamics, thus changing the overall performance of the system under investigation. In addition, the rotation of the turbine makes the appropriate placement of the measuring elements difficult. This may explain why, until now, there has not been any experimental study on GWVHT systems providing the details of the flow field through the measurement of the relevant parameters using measuring elements. All past experimental studies have only measured data for parameters which represent the overall performance of a GWVHT system. Numerical simulation techniques have demonstrated to be very promising, feasible, and probably the only method able to provide all required details of the whole flow field. In addition, numerical simulations do not have any issue regarding interference with the flow field, so they do not change the vortex dynamics. The use of numerical simulations with appropriate turbulence and multiphase models in some previous studies to investigate the performance of GWVHT systems has produced some very promising details of the flow field, which has helped to improve the understanding of the various mechanisms and characteristics of vortex dynamics. Nevertheless, this kind of numerical simulation is just the beginning, and there have been many issues and challenges in numerical simulations of GWVHT systems (these will be further elaborated below), which should be properly addressed before their wide use in the study of GWVHT systems.
- Although there have been numerous parametric studies on GWVHT systems, as reviewed above, they are generally over very limited ranges of the relevant parameters and with very few data points. More importantly, they are very specific to a particular GWVHT system under specific operating conditions. The results and conclusions obtained from such parametric studies are usually not applicable to other GWVHT systems or under different operating conditions.
- The definition of the gross head, as reviewed above, has been very inconsistent and vague, which should be one major contributor to the wide range of differences in efficiency reported by different studies. Such inconsistency in the definition of the gross head makes it challenging and infeasible to compare the overall performance between different GWVHT systems or between GWVHT systems with different configurations. It also poses a big challenge to optimising and standardising the designs of GWVHT systems.
- Previous studies have utilised various turbulence models and multiphase models for numerical simulations. However, some of these simulations were not properly validated against experimental results and were only assessed based on general perfor-

mance parameters like torque, power output, and efficiency. This lack of experimental data on flow parameters in the field presents a significant challenge for producing valid and precise numerical results and for fully understanding the dynamics and characteristics of vortex mechanisms. Furthermore, there has been limited research on comparing the effectiveness of different turbulence and multiphase models for various types of GWVHTs across a broad range of operating conditions.

- A comparison in the performance between laboratory-scale and practical-scale GWVHT systems has seldom been carried out in previous studies. In addition, it has been noted that there are large discrepancies in the performance obtained between laboratory-scale and practical-scale GWVHT systems, as reported by a few previous studies. The major reasons for these are due to the small number of the practical-scale GWVHT systems installed and very limited data which can be obtained from them, as well as the very big challenge in constructing a laboratory-scale GWVHT system which can meet all required geometrical, kinematic, and dynamic similarities between it and its practical-scale counterpart.
- Although there have been many previous studies which stated that the optimisations of the designs for some specific GWVHT systems have been achieved, it should be pointed out that such statements are debatable. The major challenge for the optimisation of the design of a GWVHT system is due to the very limited parametric studies on GWVHT systems, as reviewed above, which are also generally over very limited ranges of the relevant parameters and with very few data points and are very specific to a particular GWVHT system under specific operating conditions. The overall performance of a GWVHT system is governed by all components, particularly the basin, the inlet and outlet channels, and the turbine and the attached blades. Without systematic and comprehensive parametric studies on the effects of all relevant parameters representing the configuration, geometry, operating conditions, etc., over a wide range of the respective values for each parameter, to accommodate GWVHT systems at different scales, it is impossible to achieve the optimisation of the designs for GWVHT systems. In addition, the configurations and geometries of the basins, inlet and outlet channels, and the turbine considered in previous studies, particularly the shapes and dimensions of the basins and the shapes, orientations, locations, numbers, and dimensions of the blades on the turbines, have still been very limited.
- Although it is vital to optimise a GWVHT system by achieving the best performance, which is usually represented by the maximum efficiency, it is also very important to take into account of the costs of the materials used for various components of the system and their manufacturing. Sometimes, a compromise has to be made between the maximum efficiency and the costs. There have been very few previous studies on the material aspect of GWVHT systems, and cost analyses have been very rare as well.

Accordingly, the following topics are recommended for future research work on the performance of GWVHT systems:

- The maximum research effort should be made to substantially improve our in-depth understanding of the various mechanisms and characteristics of the vortex dynamics involved in GWVHT systems with different configurations and under different operating conditions. Numerical simulation should be the major tool used to achieve this purpose, but some key experimental studies should also be carried out, mainly to validate the numerical simulations. However, these experimental studies should be conducted using advanced, non-invasive experimental techniques, such as the particle image velocimetry (PIV) technique, which is an optical method of flow visualisation to obtain instantaneous velocity measurements and related properties in fluids and does not interfere with the flow, so the vortex dynamics will not be affected by the experiments [138]. Nevertheless, studies should mainly be carried out using numerical simulations with advanced numerical methods. For the majority of GWVHT systems, the flows are dominated by turbulence, so appropriate turbulence models should be used, together with appropriate multiphase models to take into account the free surface at the air–water interface in the vortex. These can continually be achieved by using the commonly used turbulence models, such as the standard $k - \epsilon$ turbulence model and its variations such as the RNG $k - \epsilon$ turbulence model and the realizable $k - \epsilon$ turbulence model, the standard $k - \omega$ turbulence model and the shear stress transport (SST) $k - \omega$ turbulence model, and the Reynolds stress model, and using multiphase models such as the Eulerian–Eulerian method and the VOF method, as reviewed above. There are other turbulence models and multiphase models available as well, and these models should also be tested to evaluate their performance in predicting the vortex dynamics. For some small-scale GWVHT systems, the flows are mostly at low Reynolds numbers, so direct numerical simulations (DNS) can be carried out which directly solve the full governing equations (continuity, Navier–Stokes, and other relevant equations) without the use of any turbulence model or any simplification assumption [139]. Another very promising numerical simulation method is large-eddy simulation (LES). In LES, the smallest length scales, which are the most computationally expensive to resolve, are ignored through the low-pass filtering of the Navier–Stokes equations. This low-pass filtering is a time- and spatial-averaging, which effectively removes small-scale information from the numerical solution. For flows with larger length scales, the mean flow is obtained by directly solving the full Navier–Stokes equation without any simplification assumption. In this way, the cost and time associated with the LES simulations are dramatically reduced compared to the DNS simulations, but more accurate and detailed information about the whole field can be obtained than the numerical simulations using turbulence models.

- Substantial research effort should be made to carry out systematic and comprehensive parametric studies on GWVHT systems with generic configurations and under generic operating conditions, over a wide range of all parameters involved and with many data points. In this way, the results and conclusions obtained from the parametric studies can be universally applicable to any GWVHT system under different operating conditions.
- A consistent and universal definition of the gross head should be decided so that it can be feasible to compare the overall performances between different GWVHT systems or between GWVHT systems with different configurations based on the same ground. It will also provide great help to optimising and standardising the designs of GWVHT systems.
- Any numerical simulations using turbulence models and multiphase models must be validated against the corresponding experimental results to ensure the accuracy of the numerical results. The validation should be made by comparing the results of parameters in the flow field (such as velocities, pressure, turbulent kinetic energy, etc.), in addition to comparing the results in terms of the overall performance parameters such as torque, power output, and efficiency. Thus, it is essential to obtain the experimental results from some corresponding experiments which are able to provide the measured data of these parameters in the flow field. In addition, extensive comparative studies on the performance of various turbulence models and multiphase models for different GWVHTs under a wide range of operating conditions should be conducted, too.
- The effort to compare the performance between laboratory-scale and practical-scale GWVHT systems should be significantly increased. The comparison studies (both experimental and numerical studies) should be conducted in such a way to ensure that the laboratory-scale GWVHT system meets all required geometrical, kinematic, and dynamic similarities between it and its practical-scale counterpart. The results and conclusions obtained from studies on such laboratory-scale GWVHT systems can then be scaled up to be applicable to practical-scale GWVHT systems.
- Based on the systematic and comprehensive parametric studies on GWVHT systems with generic configurations and under generic operating conditions, over wide ranges of all parameters involved and with many data points, optimisations should be achieved by obtaining the optimal configurations, geometries, and dimensions for all components, particularly the basin, the inlet and outlet channels, and the turbine

and the attached blades, under various operating conditions so that the results and conclusions will be able to accommodate GWVHT systems at different scales. In addition, the configurations and geometries of the basins, inlet and outlet channels, and the turbine, particularly the shapes and dimensions of the basins and the shapes, orientations, locations, numbers, and dimensions of the blades on the turbines, multi-stage turbines should be significantly expanded to develop more innovative and efficient GWVHT systems with the best performance.

- It is important to put significant effort into researching alternative materials for every component of GWVHT systems. A thorough cost analysis should also be conducted to ensure the construction of cost-effective systems with exceptional performance.

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