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Wind Resource Assessment for Wind Energy Utilization in Port Harcourt, River State, Nigeria, Based on Weibull Probability Distribution Function

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Abstract- The development and sitting of wind energy conversion systems, for electrical power generation and other applications, in various states of the Federal Republic of Nigeria demand proper wind resource assessment of the project sites. This paper therefore presents an assessment of wind resource for wind energy utilization in Port Harcourt, River State, Nigeria. The average monthly wind velocity data, obtained from the Nigerian Meteorological Agency, Port Harcourt, River State, Nigeria, was used, in conjunction with the logarithmic profile equation, to determine wind velocity data at a desired hub height, and with the Rayliegh probability distribution function, a form of Weibull probability distribution function, to determine wind velocity and energy distribution. The results obtained include the wind velocity distribution, wind energy distribution, and the optimum average wind velocity of 17.75 m/s at an altitude of 50 m, which corresponds to the optimum power density or yield of 1370.13 W/m^2. The results also revealed a maximum power density or yield of 10731.08 W/m^2. This amount of energy corresponds to a maximum average wind velocity of 35.25 m/s beyond which the power density drops off. These results are quite adequate and indicative of high wind energy potentials for Port Harcourt, River State, Nigeria.

Keywords- Wind Resource, Wind Energy Studies, Wind Energy Conversion System, Port Harcourt, River State, Nigeria

1. Introduction

In recent times, there are emphases on renewable energy sources such as wind, geothermal, bio-mass, tidal and solar energies all over the world. This has been attributed to the alarming situations of global warming, continuing fossil fuel price rise, political opposition to the strengthening of nuclear power in many parts of the world, and the generally accepted limited nature of the earth's fossil fuel resources.

Renewable energies are climate friendly and clean alternative energies. Amongst these energies, wind energy, which could be harnessed by means of wind energy conversion systems, is globally of particular interest. This interest is further motivated by advances in aerofoil theory, material science, techniques of wind turbine blade design and manufacture, and in the technology of power electronics and variable-speed systems, which has brought about wind energy conversion systems being on the verge of achieving global market competiveness. Again, it has been highly expressed in the technical and historical records [1-8] on the global trends in motivation, design, development and utilization of wind power technologies for electrical power generation and storage, and for driving small-, medium- and large-scale industrial machineries. According to Stiebler [5], Europe leads in wind power systems development and utilization followed by North America, and then, Asia. Africa (including Nigeria), middle East, Oceania and South Africa are yet behind the scene, even though they are likely to have greater potentials for wind power utilization.

An analysis of the present Nigeria situations reveals over dependence on hydro-power and unsustainable conventional power generating systems. Worst still is epileptic electrical power supply, which have caused incalculable damage to every sphere of human life in Nigeria. Hence, these and other limitations not mentioned called for effective utilization of the country's renewable energy resources, particularly, wind energy resource, to augment the current dependence on hydro-electric and conventional energy systems for electrical power generation. Efforts are now being made by many concerned Nigerians toward exploitation of renewable energy resources. However, more efforts are needed in order to harness these free energy resources.

The main purpose of this work, therefore, is to evaluate the wind energy resource in the country to determine its potentials for wind energy utilization with particular interest in the potential sites at the Choba Banks of the New Calabar River, Port Harcourt, River State, Nigeria. It entails analysis of the obtained average monthly wind velocity data measured at a reference height from the Nigerian Meteorological Agency, Port Harcourt, River State, Nigeria, using the logarithmic profile equation to determine the average monthly wind velocity data at the desired heights. It also involves the use of Rayleigh probability distribution function to determine the wind velocity and energy distribution, and subsequently, the average wind velocity and maximum power density. These data are required in order to establish the potentials for wind energy utilization in the selected sites.

2. Wind Resource Assessment

Wind is the movement of air from regions of higher pressure to regions of lower pressure. It exists due to uneven distribution of heat of the sun on surface of the earth including land, water and atmosphere. That is, as the hot air rises, cold air moves to fill the void given rise to wind. As long as the sun shines and produces heat, by convection, there must be wind, and as long as there is wind its power is always available to be harnessed through its conversion systems for the benefit of mankind.

According to RETScreen and Stiebler [5, 9], wind resource assessment is the first and most important step in the development of wind energy conversion systems. It basically entails determining the wind velocity distribution and its average, and the wind energy distribution for an installation site using wind velocity data of the site measured with anemometer at a reference height.

Wind energy resource assessment can be undertaken by noting that, the wind regime at a particular location is influenced by the regional and local effects. It depends on the seasonal and short time variations. Boles and Cengel [4] reported that, regions with average wind velocity of 6 m/s or 13 mi/h and above are potential sites for economical wind power generation. The actual wind regime can be determined by measurement using anemometer, preferably at the height of the wind turbine mast. However, from Stiebler [5] this is not often possible as data collections show significant variations when different years, months and days are considered at the given location. Therefore, a standard for selecting appropriate hub heights for wind turbines is required.

Hesling [10] noted that wind speed and quality generally will increase with height as the effects of surface roughness, and the associated friction and turbulence decrease as height increases. Wind turbulence is created in the lee sides of obstacles, such as trees and buildings. Therefore, it is important to locate wind turbines in zones of low turbulence, and at acceptable hub heights to maximize wind energy capture potentials in order to increase turbine life as wear and tear are also reduced due to minimized unnecessary yawing. The suggested standard proportions of the region of turbulence to be used for wind turbine hub height selection are twice the height of the tallest obstacle.

Schmidt showed in [5] that the variation of wind speed with height has been shown to follow a logarithmic profile, and therefore, the proposed logarithmic profile equation is of the form:

$$v_2 = v_1 \frac{lin\left(z_2/z_0\right)}{lin\left(z_1/z_0\right)} \tag{1}$$

This equation can be used to determine the wind velocity $v_2\ [m/s]$ at height $z_2\ [m]$ given a reference velocity $v_1\ [m/s]$ at height $z_1\ [m]$. The roughness length defined as $z_0\ [m]$ depends on the country; as given in Stiebler [5], conventional parameters 0.03 m for farm lands, 0.1 m for heath scattered shrubs and trees and 0.5 – 1.6 m for forests are acceptable standards.

Stiebler [5] noted that in practice wind velocity distribution may be approximated by a Weibull probability distribution function, which is also known as the Rayleigh probability distribution function, if a form factor of k = 2 were used. This function is given in the form:

$$h_i(v) = \frac{\pi}{2} \frac{\Delta v}{v_{av}} \frac{v_i}{v_{av}} e^{\left(-\frac{\pi}{4}\frac{v_i^2}{v_{av}^2}\right)} \tag{2}$$

Note that, $h_i\ [\cdots]$ is the fraction of time the velocity $v_i\ [m/s]$ occurs and $v_{av}\ [m/s]$ is the average velocity for each velocity class $\Delta v\ [m/s]$. Stiebler [5] also reported that, the power distribution has been determined using the power density equation given in the form:

$$p_i(v) = 0.3675 v_i^3 \tag{3}$$

Note that, $p_i\ \left[W/m^2\right]$ is the power density or yield of each wind velocity class, and that, the wind velocity and power distribution vary and are unique from site to site.

In this work, the standard proportions of Hesling [10] were used to specify the wind turbine hub height. The logarithmic profile equation of Schmidt in [5] was used to determine the average monthly wind velocity regime at the specified hub height based on the wind velocity data measurement at anemometer or reference height, as obtained from the Nigerian Meteorological Agency (NIMA), Port Harcourt, River State, Nigeria. The Rayleigh probability distribution function of Stiebler [5] was used to determine the wind velocity and energy distribution. All computations were performed in MS Excel 2007 environment, and the results obtained are presented, and then, discussed in the next section.

3. Results and Discussion

The average monthly wind velocity data obtained at anemometer height of 3.7 m from NIMA, Port Harcourt, River State, Nigeria for a period of five year was plotted as shown in Fig 1. For the proposed site, the region of turbulence due to oil palm trees measuring 15 - 20 m high, that is, the tallest obstacles around the Choba Banks of the New Calabar River, was accounted for by specifying a hub height of 50 m amongst the standard hub heights given as 10, 20, 30, 40, 50, 60, 70 and 80 m. Also, the site's terrain of heath scattered shrubs and trees was accounted for by using a roughness length of 0.1 m.

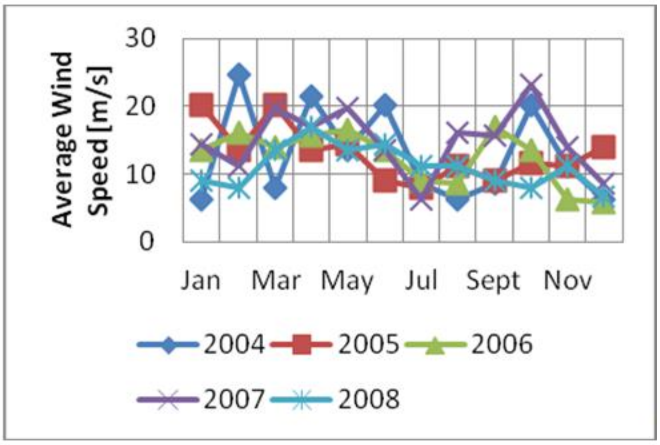

Fig. 1. Average Monthly Wind Speed for Port Harcourt, River State, Nigeria, at a Height of 3.7 m Obtained Using the Logarithmic profile Equation

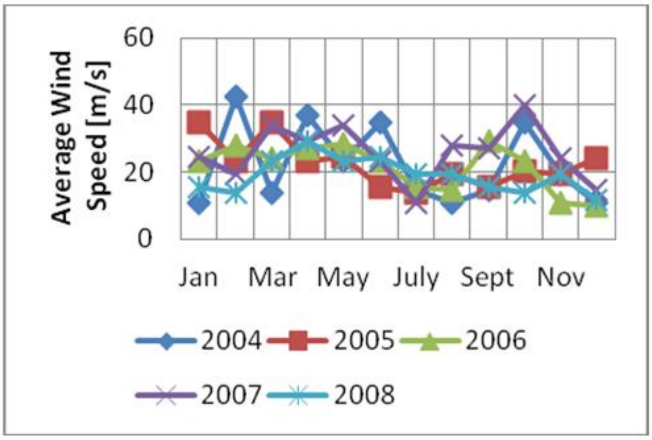

Fig. 2. Average Monthly Wind Speed for Port Harcourt, River State, Nigeria at a Height of 50 m (Source: Port Harcourt International Airport by NIMA)

These data were therefore used in the logarithmic profile equation (1), and after computing, gave rise to the average monthly wind velocity data at a height of 50 m, which was therefore plotted as shown in Fig 2. The average yearly wind velocity data at heights of 3.7 m and 50 m were equally computed and plotted as shown in Fig 3 for the purpose of comparison.

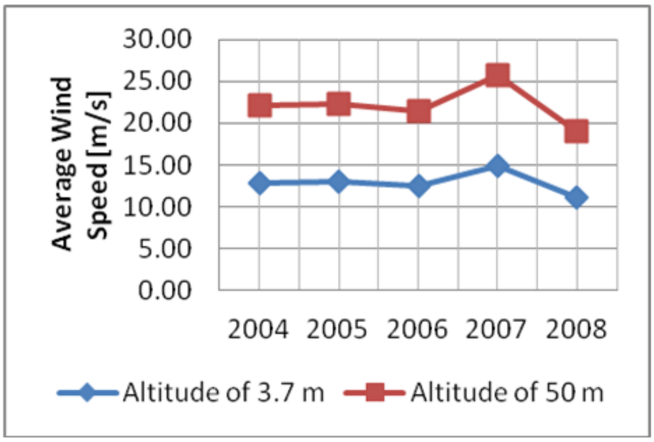

Fig. 3. Average Yearly wind Speed for Port Harcourt, River State, Nigeria, at heights of 3.7 m and 50 m

In Figs 1 and 2 it is shown that the maximum average monthly wind velocities of 24.60 m/s and 42.34 m/s at the heights of 3.7 m and 50 m, respectively, occurred in February, 2004. It is also shown that the minimum average monthly wind velocities of 5.82 m/s and 10.02 m/s at the heights of 3.7 m and 50 m, respectively, occurred in December, 2008. In Fig 3, it is shown that the average annual wind velocities are higher at the height of 50 m than at the height of 3.7 m. The maxima of 14.91 m/s and 25.66 m/s at the heights of 3.7 m and 50 m, respectively, occurred in the year 2007, whereas, the minima of 11.03 m/s and 18.99 m/s at the heights of 3.7 m and 50 m, respectively, occurred in the year 2008. The observed seasonal changes conform to the prior mentioned wind formation mechanism of which heat of the sun is a major agent. It varies amongst region in a given season of the year, hence the variation of the wind speed and energy. The seasonal changes are important consideration for applications where electricity is time dependent for short term energy planning [11]. They are strong showing that Port Harcourt environment is a potential site for wind energy utilization.

From the wind velocity data shown in Fig 2, the estimated wind velocity class size is 0.33 m/s, and that of the average wind velocity v_{av} is 22.1 m/s. These data were therefore used in the Rayleigh probability distribution function (2) and power density function (3), and after computing, for wind velocities in the range of 0 - 100 m/s, gave rise to the wind velocity and energy distribution data. These were, respectively, plotted as shown in Figs 4 and 5.

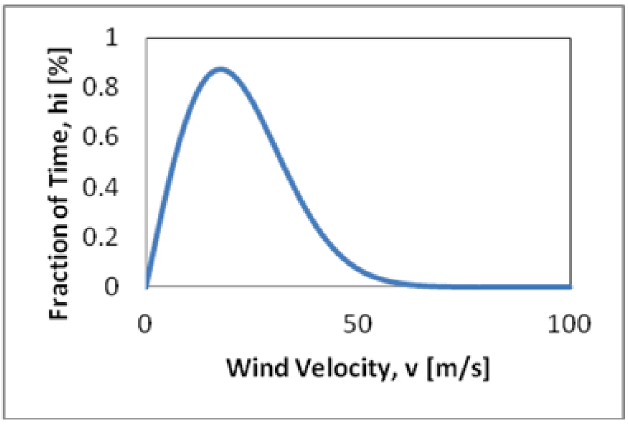

Fig. 4. Wind Velocity Distribution for Port Harcourt, River State, Nigeria Obtained using the Rayleigh probability distribution function.

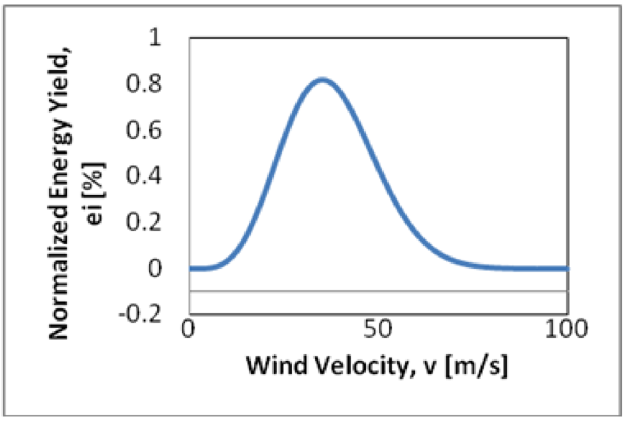

Fig. 5. Wind Energy Distribution for Port Harcourt, River State, Nigeria Obtained using the Rayleigh probability distribution function.

In the wind velocity distribution shown in Fig 4, it is found that, a wind velocity of 17.75 m/s occurred at a maximum percentage fraction of time of 0.875296. This velocity represents the optimum average wind velocity at a height of 50 m corresponding to the optimum wind power density or yield of 1370.13 W/m^2, which is available for conversion by an installed wind energy system in the site. Also, from the wind energy distribution shown in Fig 5, it is found that, a wind velocity of 35.25 m/s occurred at the maximum percentage normalized energy density or yield of 0.816469. This velocity represents the maximum average wind velocity at a height of 50 m corresponding to the maximum wind power density or yield of 10731.08 W/m^2, which is the highest available for conversion by an installed wind energy conversion system in the site beyond which the energy density drops off.

Besides, for more elaborate results, similar computations were performed on the entire range of the standard hub heights of 10, 20, 30, 40, 50, 60, 70 and 80 m given as requirement for small, medium and large scale wind turbines in Al-Shemmeri [12], and the data obtained given in Figs 6 and 7, as optimum wind data and Figs 8 and 9 as maximum wind data (also see tables the appendix). These results confirm the claim of Hesling [10] that wind velocity and power density increase with increasing hub height as a result of decrease in the effects of surface roughness, friction and turbulence with increasing altitude. The relationships are nonlinear, and therefore, described by logarithmic trend equations of the form given as notes in the figures. The figures also show that, the predicted and computed results are closely in agreement as revealed in the values of R2.

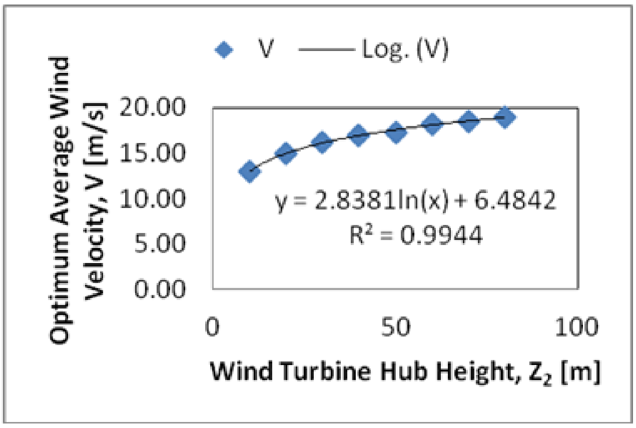

Fig. 6. Variation of the Optimum Average Wind Velocity with Hub Height as determined from Wind Velocity Distribution [Note: $v = 2.838 \ln z_2 + 6.484$; $R^2 = 0.994$]

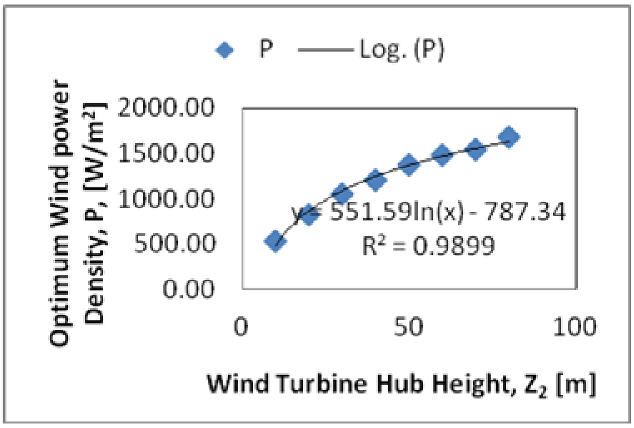

Fig 7. Variation of the Optimum Average Wind Power Density with Hub Height as determined from Wind Energy Distribution[Note: $p = 551.5 \ln z_2 - 787.3$; $R^2 = 0.989$]

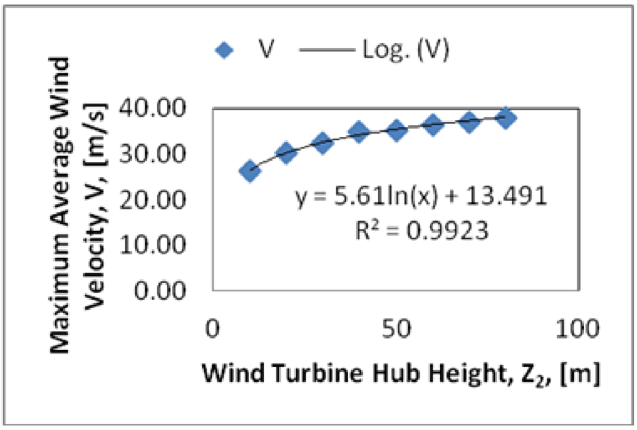

Fig. 8. Variation of the Maximum Average Wind Velocity with Hub Height as determined from Wind Velocity Distribution [Note: $v = 5.61 \ln z_2 + 13.47$; $R^2 = 0.992$]

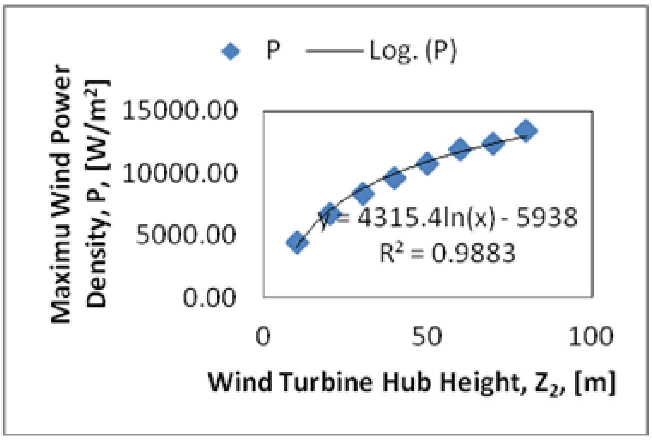

Fig. 9. Variation of the Maximum Average Wind Velocity with Hub Height as determined from Wind Velocity Distribution [Note: $p = 4315 \ln z_2 - 5938$; $R^2 = 0.988$]

The above results confirm that, the selected site has high potential for wind energy utilization. Its optimum average wind velocity of 17.75 m/s, at a height of 50 m, is greater than 6.0 m/s reported in Boles and Cengel [4] to be the average wind velocity for a potential site. Considering the economic, social, and environmental benefits to be derived and some of the limitations to be overcome, the site can be developed for wind energy utilization, that is, for electrical power generation and other applications, to augment the current hydro-power, and also, to minimize the numerous limitations of the conventional energy resource. Therefore, follow-up studies on the development of small, medium or large scale wind energy conversion systems, for electrical power generation and supply to specific or groups of utility areas in Port Harcourt, and economics evaluations to justify their feasibility for the wind energy utilization are recommended and possibly would be pursued in the next communications.

4. Conclusion

Problems are created in attempt to solve one. Success in the fossil fuel resource utilization has been a great solution, highly conventional, to electric power generation all over the world. Problems such as global warming, pollution of atmospheric air and water bodies, health hazards, and world and national politico-economic rancor are greatly associated with the current use of fossil fuel energy resource for electric power generation. Renewable energy resources are the new, non-conventional or clean alternative energy solutions that may overcome most of the above limitations, and of course, with its own limitations needing attentions. This work considers the first step in wind energy resource utilization for electric power generation in Port Harcourt, River State, Nigeria. The results suggest that, the selected site has high potential for wind energy utilization, which can be developed considering the various economic, social, and environmental benefits to be derived and some of the limitations to be overcome.

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Appendix

Table 1: Variation of Wind Data with Hub Height as determined from Wind Velocity Distribution Data

z_2 $[m]$	v_{av} $[m/s]$	Δv $[m/s]$	v $[m/s]$		p $[W/m^2]$		h $[\cdots]$
			Computed	**Predicted**	**Computed**	**Predicted**	
10	16.38	0.24	13.00	13.02	538.27	482.58	1.160961
20	18.84	0.28	15.00	14.99	826.88	864.85	1.012120
30	20.28	0.30	16.25	16.14	1051.30	1088.46	0.944888
40	21.30	0.32	17.00	16.95	1203.69	1247.12	0.903533
50	21.10	0.33	17.25	17.59	1370.13	1370.18	0.875296
60	22.75	0.34	18.25	18.10	1489.21	1470.73	0.854208
70	23.29	0.35	18.50	18.54	1551.25	1555.75	0.837732
80	23.77	0.35	19.00	18.92	1680.46	1629.39	0.824600
Note: (1) $v = 2.838 \ln z_2 + 6.484$; $R^2 = 0.994$, and (2) $p = 551.5 \ln z_2 - 787.3$; $R^2 = 0.989$							

Table 2: Variation of Wind Data with Hub Heights as Determined from Wind Energy Distribution Data

z_2 $[m]$	v_{av} $[m/s]$	Δv $[m/s]$	v $[m/s]$		p $[W/m^2]$		e $[\cdots]$
			Computed	**Predicted**	**Computed**	**Predicted**	
10	16.38	0.24	26.26	26.41	4431.53	3997.65	1.101595
20	18.84	0.28	30.25	30.30	6781.76	6988.58	0.957207
30	20.28	0.30	32.50	32.57	8410.39	8738.17	0.889742
40	21.30	0.32	35.00	34.18	9629.48	9979.51	0.846854
50	21.10	0.33	35.25	35.44	10731.08	10942.38	0.816469
60	22.75	0.34	36.50	36.46	11913.65	11729.10	0.793163
70	23.29	0.35	37.00	37.32	12409.99	12394.26	0.774448
80	23.77	0.35	38.00	38.07	13443.64	12970.44	0.759166
Note: (1) $v = 5.61 \ln z_2 + 13.47$; $R^2 = 0.992$, and (2) $p = 4315 \ln z_2 - 5938$; $R^2 = 0.988$							