Exploring the influence of meteorological conditions on the performance of a waste stabilization pond at high altitude with structural equation modeling

Long T. Ho, Duy T. Pham, Wout Van Echelpoel, Andres Alvarado, Juan E. Espinoza-Palacios, Maria B. Arevalo-Durazno and Peter L. M. Goethals

ABSTRACT

Algal photosynthesis plays a key role in the removal mechanisms of waste stabilization ponds (WSPs), which is indicated in the variations of three parameters, dissolved oxygen, pH, and chlorophyll *a*. These variations can be considerably affected by extreme climatic conditions at high altitude. To investigate these effects, three sampling campaigns were conducted in a high-altitude WSP in Cuenca (Ecuador). From the collected data, the first application of structure equation modeling (SEM) on a pond system was fitted to analyze the influence of high-altitude characteristics on pond performance, especially on the three indicators. Noticeably, air temperature appeared as the highest influencing factors as low temperature at high altitude can greatly decrease the growth rate of microorganisms. Strong wind and large diurnal variations of temperature, 7–20 °C, enhanced flow efficiency by improving mixing inside the ponds. Intense solar radiation brought both advantages and disadvantages as it boosted oxygen level during the day but promoted algal overgrowth causing oxygen depletion during the night. From these findings, the authors proposed insightful recommendations for future design, monitoring, and operation of high-altitude WSPs. Moreover, we also recommended SEM to pond engineers as an effective tool for better simulation of such complex systems like WSPs.

Key words | algal photosynthesis, high altitude, spatiotemporal variation, structure equation modeling, waste stabilization ponds

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INTRODUCTION

Waste stabilization ponds (WSPs) are large shallow lagoons surrounded by earth embankments, in which wastewater is purified by completely natural processes (Hosetti & Frost 1995; von Sperling 1996; Babu *et al.* 2010). Taking advantages of the photosynthetic aeration to reduce operation costs and potential risks from the emission of volatile organic compounds, WSPs are increasingly favored in numerous countries (Munoz *et al.* 2004; Dias *et al.* 2014). Indeed, due to their simplicity and low cost, WSPs are desirable in many developing countries (Mara 2004). However, contrary to their simple design and operation, processes happening inside the pond systems are complicated. These processes are characterized by complex interactions of bio-geochemical cycles, biochemical processes and reactions which are strongly dependent on climatic conditions and hydraulic patterns (Ho *et al.* 2017). Therefore, it is expected that the performance of WSPs can be greatly influenced by severe high-altitude meteorology, i.e. strong light intensity, low air temperature, great variation of temperature and low oxygen pressure (Juanico *et al.* 2000).

Until now, the number of studies concerning the efficiency of WSPs at high altitude remains low despite some reports on their poor effluent quality, e.g. Pearson *et al.* (1987b), Juanico *et al.* (2000) and Lloyd *et al.* (2002). More

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specifically, according to a study of Lloyd *et al.* (2002) on fourteen WSPs at the altitude of 2,675 m to 3,827 m in Mexico, adverse environmental conditions, such as large daily temperature variation from −4 °C to 30 °C and strong wind speeds, caused night-time thermal stratification and short-circuiting leading to the under-performance of these ponds. Indeed, these climatic conditions are also concluded as predominant controlling factors on the pond removal efficiency in the other two studies. However, since these studies only take into account the data from pond influent and effluent, their conclusions are relatively common and it is still unclear how high-altitude characteristics affect the pond performance. From that perspective, there is a lack of proper guidelines for pond designers and operators to deal with the distinctive features of high-altitude meteorology in order to ensure compliance with effluent quality standards (Ho *et al.* 2018). This paper aims at filling these gaps of knowledge. From three sampling campaigns thoroughly conducted in Ucubamba WSP system in Cuenca, Ecuador, an advanced multivariate data analysis, structural equation modeling (SEM), is applied to investigate the effects of climatic conditions on the efficiency of the pond system. More specifically, we focus on a distinguishing element of WSPs which differentiates it from conventional WWTPs, i.e. the involvement of algal photosynthesis. As such, the interaction between the high-altitude characteristics and the spatio-temporal variations of three indicators of algal photosynthesis (dissolved oxygen (DO), pH, and chlorophyll *a*) is meticulously analyzed. At the end, insightful recommendations on pond design, monitoring, and operation at high altitude are drawn.

MATERIALS AND METHODS

Study area

The WSP is located at Ucubamba (2°52′21″ S 78°56′30″ W) at altitude of 2,400 m a.s.l. and operated by the Municipal Company ETAPA. The largest WWTP in Ecuador is designed to treat the domestic effluent coming from more than 400,000 inhabitants in Cuenca. The average influent concentrations of organic matters and nutrients are biochemical oxygen demand (BOD_5) of 94 mg $O_2.L^{-1}$, chemical oxygen demand (COD) of 240.73 mg $O_2.L^{-1}$, total phosphorus (TP) of 5.18 mg $P.L^{-1}$, total Kjeldahl nitrogen (TKN) of 8.15 mg $N.L^{-1}$ (Alvarado 2013). The dry season is between June and December and the rainy season is between January and May with temperatures between 7 and 20 °C and 12 and 25 °C, respectively (Alvarado 2013). The WSP receives wastewater through a pre-treatment step including screening and grit chamber and, then, the wastewater is divided into two identical flow lines including an aerated pond (AP), a facultative pond (FP) and a maturation pond (MP) before being discharged into Cuenca river (see Figure 1). The total surface of the WSP is 45 ha with 11.5 days of theoretical hydraulic retention time (HRT), in which APs occupy 6 ha, FPs 26 ha, and MPs (Alvarado *et al.* 2012b).

Sampling campaigns

Three sampling events were implemented in the FPs and MPs of the two parallel lines on July 25–26, 2013, August 14–15, 2013 and August 26–27, 2013. To obtain

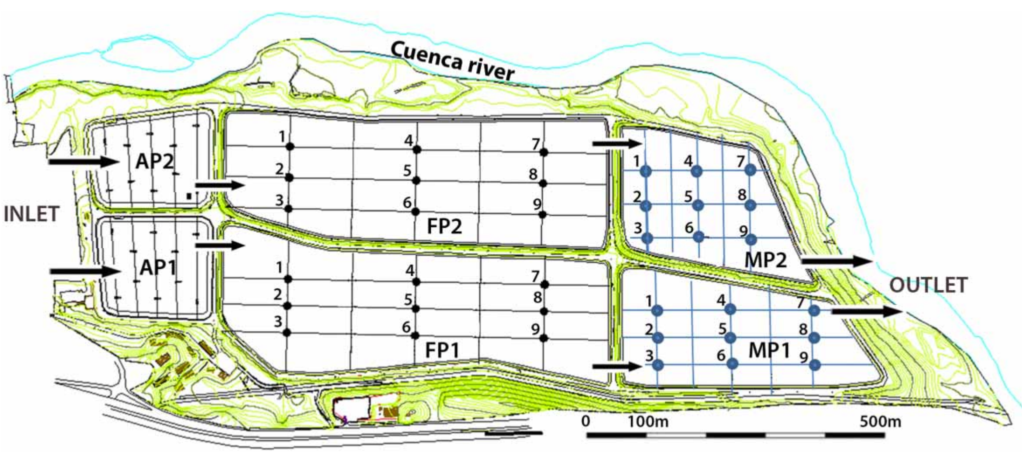

Figure 1 | Map of Ucubamba waste stabilization pond in Cuenca, Ecuador. Two parallel lines of WSP contain aerated ponds, facultative ponds, and maturation ponds. Grids were formed within the last two ponds in order to ensure that the collected samples are representative of variations along the ponds.

comprehensive insights into the spatial variation of water quality parameters, grids were formed by dividing FPs and MPs into six sections along the longitudinal direction and four sections breadthways. From the grids, samples were taken at nine different locations representing three zones of these ponds: influent (locations 1, 2, and 3), middle (locations 4, 5, and 6), and effluent (locations 7, 8, and 9) (Figure 1). In each location, samples were collected at two depths, 30 cm below the water surface and 15 cm above the sediment layer. Due to the sludge accumulation at location 1 and 2 in both FPs, only samples at 30 cm below the water surface were collected. Each sampling campaign lasted for two days as the sampling of one line required the period of one day, i.e. from 08.00 until 18.00. To investigate the diurnal dynamics of wastewater constituents, the samples of the bottom line were collected within a different period in the third campaign.

At each sampling location, temperature (°C), total dissolved solids (TSS, $g.L^{-1}$), pH (–), ammonium (mg NH_4^+-N. L^{-1}), chlorophyll *a* (μg *a*.L^{-1}), and DO (mg $O_2.L^{-1}$) were determined with two manual multi-probes, YSI 6600 V2 and YSI 6920 V1. These probes were carefully calibrated every three days by following their manual in order to ensure their accuracy. At the same time, the samples at three locations within one zone of the ponds were collected by Teledyne ISCO 6712 and then rigorously mixed. These homogeneous samples were analyzed for BOD_5 (mg O_2. L^{-1}), COD (mg $O_2.L^{-1}$), TP (mg $P.L^{-1}$), TKN (mg $N.L^{-1}$) and total solids (TS) (mg.L^{-1}) using the American Public Health Association methods (APHA 2005). Additionally, meteorological data, including air temperature (°C), solar radiation ($W.m^{-2}$) and wind speed ($m.s^{-1}$) were obtained from the Meteorological Station of CELEC Hidropaute located around 600 m away from the WSP.

Structural equation modeling and Kruskal-Wallis tests

One main objective of our research is to determine the key factors influencing pond performance, especially on the three indicators of algal photosynthesis, DO, pH, and chlorophyll *a*. To this end, SEM as an advanced statistical analysis tool for multivariate data was applied in R (Team 2010) using the lavaan package (Rosseel 2012). Principally, a hypothesized model was composed, including a theoretical covariance structure between random variables ($\sum^{(\theta)}$), which, subsequently, was compared to the covariance matrix of the actual data ($\sum$) (Sutton-Grier *et al.* 2010; Kline 2011). The agreement between these two covariance matrices was evaluated via the fundamental null hypothesis in SEM as follows (Equation (1)).

$$H_O: \sum = \sum(\theta) \quad (1)$$

where θ is a vector of all free parameters. Therefore, in the first step as model specification, we constructed a conceptual model or a path diagram as a pictorial demonstration of a system of simultaneous equations, based on the existing knowledge on the mechanisms of WSPs and our research questions. After model specification, the collected data were applied for model estimation by the most widely used fitting function, maximum likelihood (ML). After that, we followed three key aspects to evaluate the developed model, i.e. existing knowledge and research questions on the system, model fit indices, and model parsimony to evaluate the fitted model (Musil *et al.* 1998). Particularly, various fit indices were used to assess the goodness-of-fit and the parameter estimation of the hypothesized model. According to Hu & Bentler (1999), besides chi-square (χ^2) which was highly sensitive to sample size, other indicators should be applied to avoid the problems of sample size, i.e. comparative fit index (CFI), Tucker-Lewis index (TLI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR). Particularly, the recommended values were CFI and TLI >0.95, RMSEA between 0.05 and 0.08, and SRMR <0.08 to indicate a good model fit (Schumacker & Lomax 2015). The detailed formulas of these fit indices can be found in Hu & Bentler (1999). To achieve a parsimonious model which should not be more complicated than necessary for the description of the data (Omlin *et al.* 2001), the significance of simulated pathways among latent and observed variables was assessed via z statistic. Non-significant variables were removed in the final model, hence, allowing to identify the significant impacts of high-altitude characteristics on pond performance, especially on DO, pH, and chlorophyll *a*.

Together with SEM, a non-parametric statistical tool, Kruskal-Wallis test, was applied to determine the spatiotemporal differences of the measured wastewater constituents and climate conditions regarding the sampling time and the locations within a pond and among the ponds.

RESULTS

Spatial variations among and within the ponds

The spatial variations between different depths and ponds of the three parameters (DO, pH, and chlorophyll *a*) are demonstrated in Figure 2. The variations of other biochemical and meteorological parameters are shown in appendix 1 (available with the online version of this paper). Similar to the fluctuation of meteorological parameters, a wide variation of wastewater constituents was found among four ponds, which corresponded to very low *p*-values of Kruskal-Wallis tests in Table 1. Interestingly, even though the two flow lines were designed to be identical, their performances were highly diverse. The first line received around 20% higher pollutant concentrations, i.e. BOD, COD, TKN, TP, and TS, compared to the second line as demonstrated via low *p*-values of these pollutants between two FPs and two MPs in Table 1. Similarly, we also found a higher level of oxygen and pH in the first line compared to those in the second line, which was contrary to comparable concentrations of chlorophyll *a* between two lines. Between the surface and the bottom, the values of most biochemical parameters were relatively homogeneous, while DO, pH, and chlorophyll *a* were characterized by a high variability (*p*-values <0.01). As demonstrated in Figure 2, higher values in terms of both concentration and variation were found near the water surface. In contrast to the high variability of water quality parameters between two depths, pond zone had only a minor impact on the variations of biochemical parameters, except for oxygen level. Regarding the meteorological parameters, the climatic conditions intensively changed within a short period of time, which was confirmed by low *p*-values in all the cases in Table 1. Two exceptions were the values between two depths which were measured subsequently after each other and among the three campaigns where their similar ranges were observed.

For a further investigation on the spatial variation of DO, pH, and chlorophyll *a*, their concentrations and deviations in three different zones of the pond system are

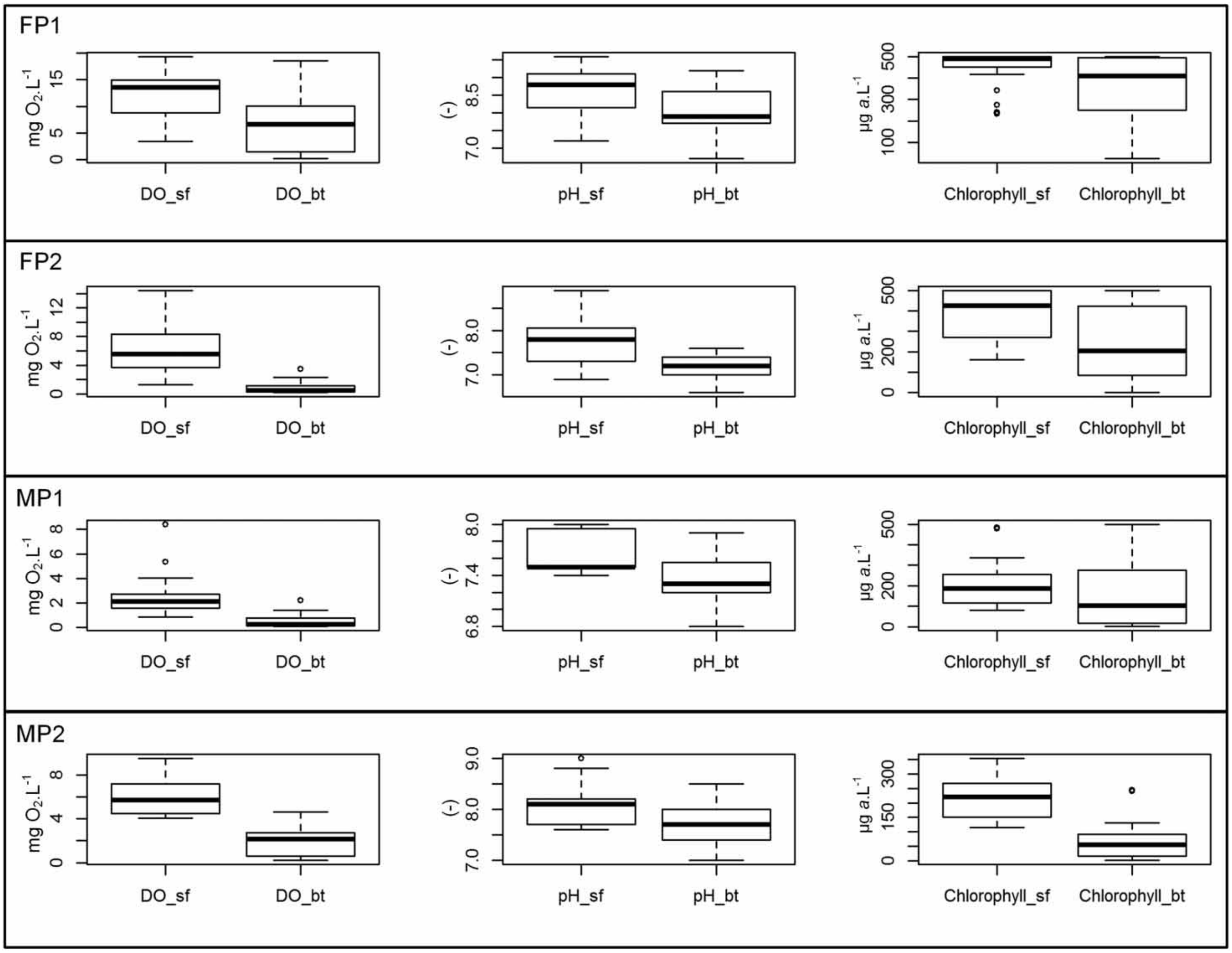

Figure 2 | Variations of DO, pH, and chlorophyll *a* between different depths and ponds. Sf: surface; Bt: bottom.

Table 1 | Summary of the *p*-values of the Kruskal-Wallis tests

Parameters	Different ponds	Between two FPs	Between two MPs	Between depths	Different zones	Different daytimes	Different campaigns
DO	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Chlorophyll *a*	<0.001*	0.0531	0.1824	<0.001*	0.7840	0.2049	<0.001*
pH	<0.001*	<0.001*	<0.001*	<0.001*	0.0914	<0.001*	<0.001*
BOD	<0.001*	<0.001*	<0.001*	0.0381*	0.6457	<0.001*	<0.001*
COD	<0.001*	<0.001*	<0.001*	0.0139*	0.7384	<0.001*	0.1642
TKN	<0.001*	<0.001*	<0.001*	0.3259	0.6191	<0.001*	<0.001*
TP	<0.001*	0.0107*	0.1353	0.7974	0.1315	<0.001*	<0.001*
TS	<0.001*	0.0003*	0.203	0.2006	0.3253	<0.001*	<0.001*
Solar radiation	<0.001*	0.5286	<0.001*	0.9064	<0.001*	<0.001*	0.3846
Air temperature	<0.001*	<0.001*	<0.001*	0.6345	<0.001*	<0.001*	0.8809
Wind speed	<0.001*	<0.001*	<0.001*	0.8030	<0.001*	<0.001*	0.7822

*: *p*-value ≤0.05 (threshold of illustrating a significant difference).

illustrated in Figure 3. As agreed with the results for the Kruskal-Wallis tests, the concentrations of the three parameters were homogeneous within one pond, but very different among them and between two depths. More specifically, despite having higher level of DO and pH in FP1 compared to FP2, these values of its consecutive pond (MP1) were lower than MP2. In fact, the oxygen level at the water surface dropped from 10 mg $O_2.L^{-1}$ in FP1 to around 3 mg $O_2.L^{-1}$ in MP1 while there was a slight increase in the upper line. This trend also occurred at the bottom layers of the ponds. Interestingly, the concentrations of chlorophyll *a* were relatively comparable between two lines and these values decreased by around 50% from the FPs to the MPs in both lines. This finding is in line with the study of Pham *et al.* (2014) on algal biodiversity of this pond system, which suggested that the algal abundance in the FPs was lower than in the MPs. It is also noteworthy that the standard deviations of DO and pH were much higher than those of chlorophyll *a*, which could be associated with stronger impact of climatic conditions on DO and pH leading to more fluctuation of their values.

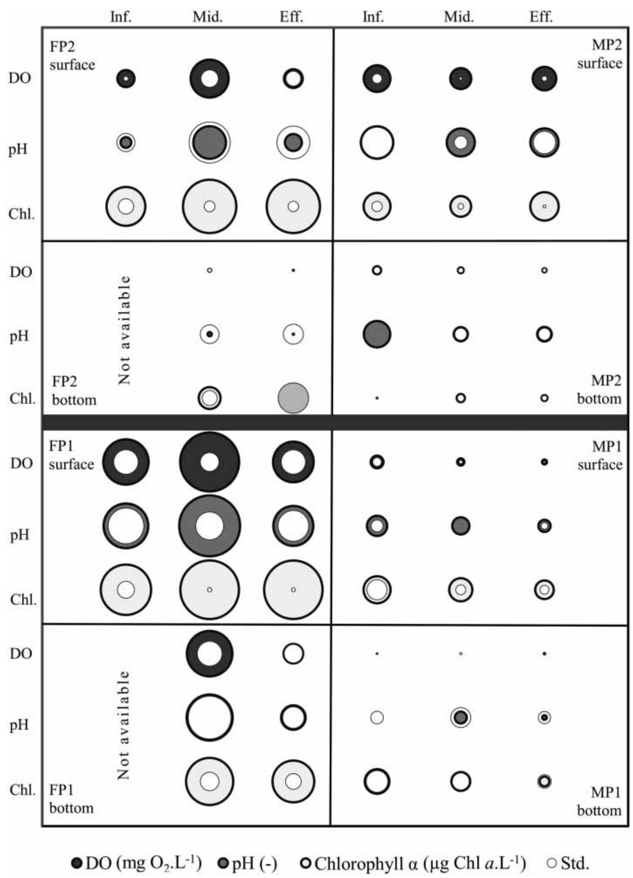

Figure 3 | DO, pH, and chlorophyll *a* (chl.) with their standard deviation (Std.) at the three zones of the ponds, influent (inf.), middle (mid.), and effluent (eff.). The order of the ponds in the graph is analogous to the real system, where the top four boxes correspond to flow line two and the bottom four boxes to flow line one. The normalized values of DO, pH, and chlorophyll *a* were calculated by subtracting the minimum value and then dividing by the difference between the maximum and minimum values (Aksoy & Haralick 2001). Due to the sludge accumulation, the values of the influent zone at the bottom of FPs were not available.

Temporal variations

Figure 4 demonstrates relatively analogous patterns of diurnal fluctuation of DO and pH, in which they were lowest at the early time of the day, increased during the day, and peaked from 13.00 to 15.00 when light intensity reached its maximum. These temporal fluctuations were in contrast with the static level of chlorophyll *a*. This difference was relevant with the obtained *p*-values of the three parameters regarding different daytimes in Table 1. During high

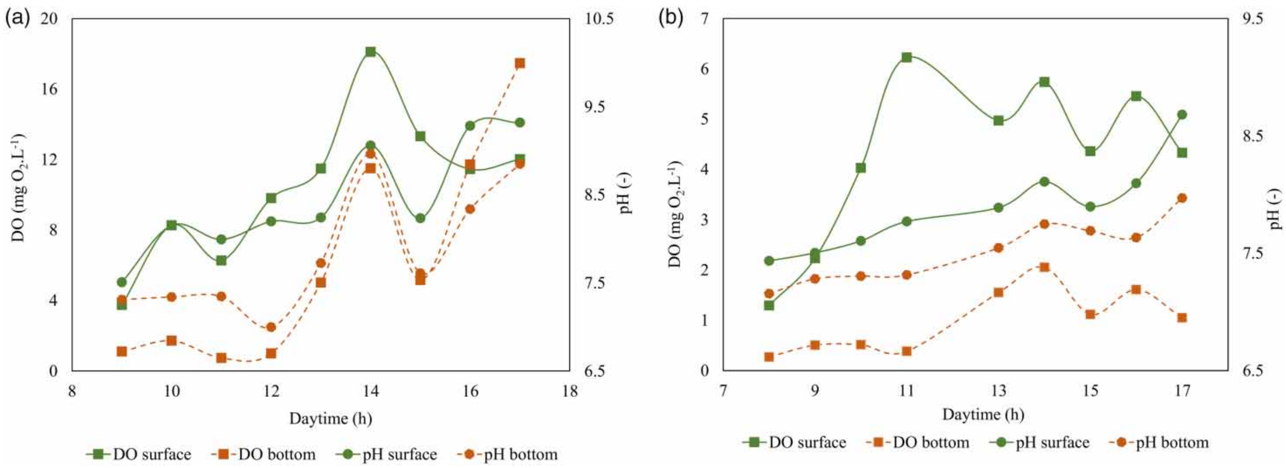

Figure 4 | Diurnal variations of DO and pH between two depths of FPs (a) and MPs (b).

light-intensity period, average oxygen concentrations and pH could reach above 20 mg $O_2.L^{-1}$ and 9 at the surface of the FPs while such high peaks were not found in the MPs. Much less expected is the extremely high concentration of oxygen at the bottom of FP1 around 16 mg $O_2.L^{-1}$ during the last 2 h of the afternoon in the first sampling campaign. pH at the surface of the ponds during the late afternoon remained at high values, around 9 for FPs and 8.5 for MPs, which was generally regarded as beneficial for the inactivation of fecal microorganisms and ammonia volatilization (Davies-Colley *et al.*, 1999). Regarding other water quality parameters and meteorological conditions, as indicated in the results of the Kruskal-Wallis tests, daytime also contributed significantly on their variations, which proved the crucial role of temporal aspects on the variations of the performance of the pond system.

SEM conceptual model and path analysis

The specification of the conceptual SEM model was composed, based on existing knowledge in literature and our research questions about the meteorological effects on pond performance, especially on the three parameters, DO, pH, and chlorophyll *a*. Four latent variables were chosen, i.e. meteorology, water pollution, time, and space, which included 14 observed variables from the sampling campaigns. The effects of time and space as two latent exogenous variables (ξ) was further investigated on not only the three parameters but also other two latent endogenous variables (η), meteorological conditions and water pollutants. Moreover, we also evaluated the direct correlations among the three parameters as well as the indirect effects of daytime on DO via meteorological conditions, i.e. wind speed, air temperature, and solar radiation. By allowing the estimation of these direct and indirect effects of the latent and manifest variables, the SEM model was able to provide a comprehensive overview of the interconnected web of biochemical processes and reactions happening inside the pond system. Indeed, thanks to its ability to simultaneously test theoretical relations among multiple variables, the complex interactions of the in-pond bio-geochemical cycles and meteorological characteristics were illustrated in Figure 5. This conceptual model can hence be applied to other WSPs systems as the first step of model specification.

Subsequently, the conceptual SEM model was fitted on the collected data, leading to a simpler model in which all non-significant pathways were removed (Figure 6). Particularly, the effect of water pollution on the three parameters was not significant (p-values >0.05), hence, none of its observed parameters is present in the fitted SEM model. The reason could be because of high oxygen concentrations as a result of the enhanced algal photosynthesis which was accelerated by strong solar radiation in this meridional high-altitude WSP system. Compared to this high production of DO, the amount of oxygen, which was consumed for bacterial mineralization and nitrification process, appeared to be inconsiderable. Moreover, nutrient concentrations in the influent also exceeded their required amount for the growth of algae, hence, their impact on chlorophyll *a* is not significant. Conversely, the latent variable, space, including depth and pond type, appeared to be greatly important for the variation of the three parameters. Pond location, however, was evaluated as a non-significant parameter which was relevant to the high p-values of Kruskal-Wallis tests (Table 1). Sampling campaign was also removed as a non-significant

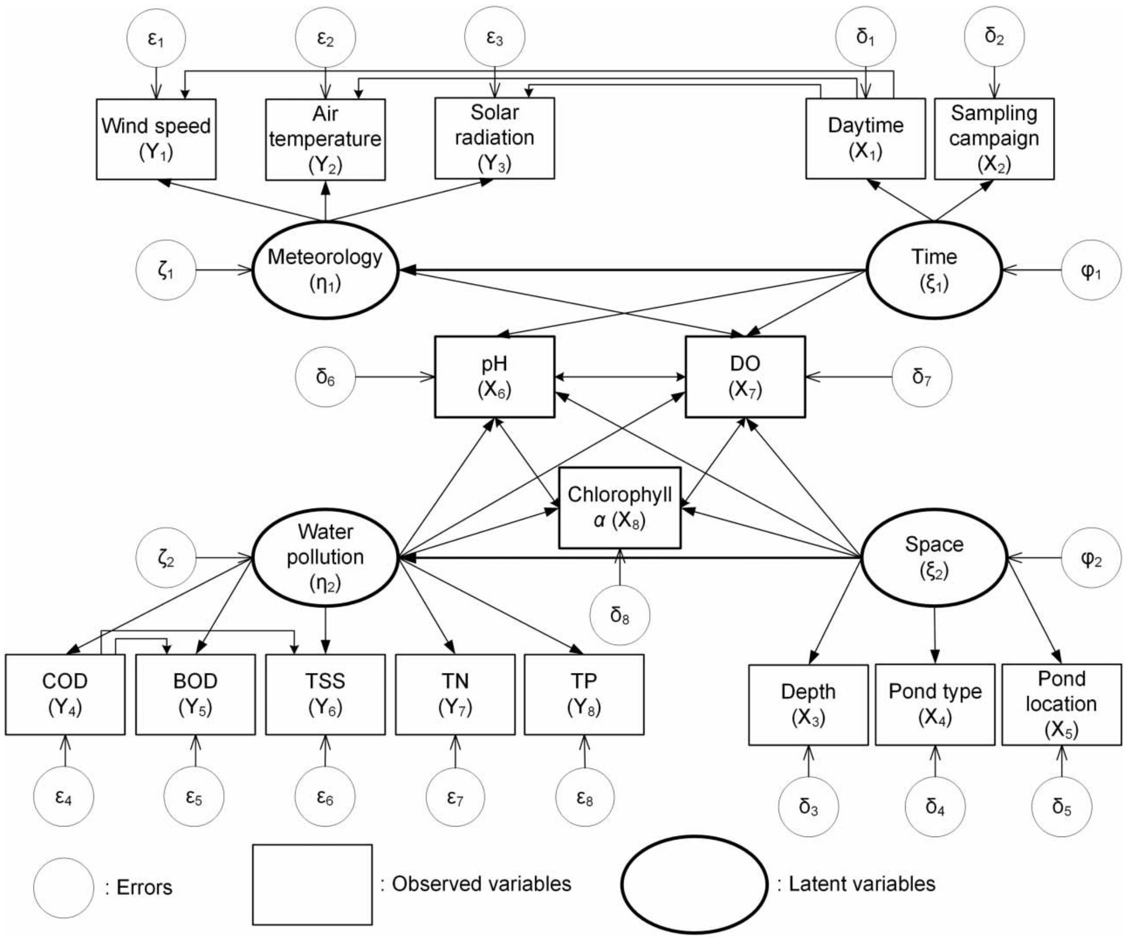

Figure 5 | Conceptual structural equation model (SEM) of a WSP. This SEM focuses on the influence of high-altitude characteristics on pond behavior, especially on the three parameters linked with algal photosynthesis, i.e. DO, pH, and chlorophyll *a*.

variable (p-value $= 0.136$), while daytime significantly affected the oxygen level via its impacts on meteorological conditions in both direct and indirect pathways.

From the path analysis of SEM, the space exerted the major impact on DO and pH with its high path coefficients of -14.898 and 0.196, respectively. Daytime was one of the most significant contributors to DO variations with its direct path coefficient of 2.509 and its significant indirect effect via meteorological parameters. These substantial impacts of space and daytime on the oxygen level were contradicted with non-significant effects of the water pollutants (p-values > 0.05). Among three observed meteorological parameters, air temperature had the greatest influence on the oxygen level while solar radiation played the least important role, which is relevant with the degree of the influence of daytime on these meteorological parameters.

Regarding the performance of the SEM, a good agreement was found between the model-implied covariance matrix and the sample covariance matrix of the collected data. According to the guide of Schumacker & Lomax (2015) for model-fit criteria, our SEM model has most of its fit indices in the acceptable range for good fit model, i.e. CFI: 0.982, TLI: 0.969, RMSEA: 0.074, and SRMR: 0.087. With respect to model parsimony, after fitting on the collected data, the final model became simpler than the conceptual structure, which clearly highlighted the crucial roles of meteorology, as well as time and space in the variations of the three parameters in the pond system.

DISCUSSION

Spatial variations among and within the ponds

WSPs are normally subdivided into two parallel lines so that both lines are able to have similar treatment performance.

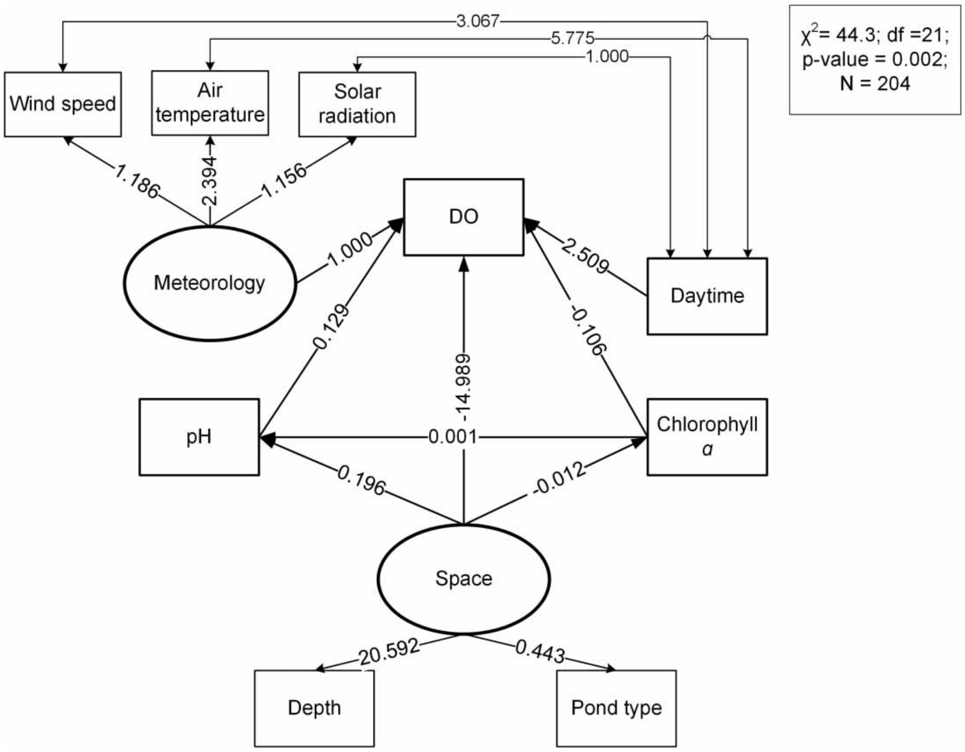

Figure 6 | Simple SEM model for Ucubamba WSP with only significant pathways among the latent and observed variables. χ^2: chi-squared test values, df: the degree of freedom, N: sample size.

However, the two identical flow lines of Ucubamba WSP performed differently, in which FP1 received higher pollutant loadings than FP2, especially organic matter. Indeed, their average surface organic loadings were up to 250 and 185 kg.ha^{-1}.d^{-1}, respectively, while the recommended limitations were 240 kg.ha^{-1}.d^{-1} for WSPs at tropical and subtropical regions and only 200 kg.ha^{-1}.d^{-1} for WSPs at altitudes above 2,400 m a.s.l. (Juanico *et al.* 2000; Ho *et al.* 2017). These high loadings were associated with the sludge accumulation, which was also the reason for unavailable data at the bottom of location 1 and 2 in FPs. According to the study of Alvarado *et al.* (2012a) in this pond system, the sludge volume of the FPs reached up to 34% of the pond volume which substantially reduced its active volume. More importantly, low temperature at high altitude from 7 to 20°C during our sampling campaigns could significantly reduce the growth rate of microorganisms involved in biological wastewater treatment (Zimmo *et al.* 2004). A much higher temperature was recommended for the optimum growth of nitrifying bacteria, i.e. about 35 °C, being similar to the recommended value for heterotrophic bacteria collected from WSPs (Mayo & Noike 1996). Indeed, air temperature was weighed as the most influential meteorological parameter on the fluctuation of the oxygen level in the SEM model.

Between the two depths, there was a wide disparity in the concentrations of DO, pH, and chlorophyll *a* caused by the algal stratification while pollutant concentrations were relatively homogeneous. This difference is also demonstrated in the fitted SEM as depth is the most influential factor with respect to space on DO, pH, and chlorophyll *a* while pollutants appear to be unaffected. This homogeneity of wastewater constituents was a result of sufficient mixing which can be influenced by the intensive temperature variation at high altitude, from 7 to 20°C, and strong wind. Wind speed also appeared in the fitted SEM model as the second most influential meteorological parameter affecting pond performance, especially the oxygen level. In the model, its positive coefficients, 1.186 and 3.067 for the direct and indirect effects, respectively, reveal its beneficial role on enhancing the oxygen level in the ponds via promoting the mixing efficiency, hence increasing oxygen reaeration rate. Note that the location of these ponds with negligible protection of surrounding tree encourages more exposure to wind turbulence from downstream to upstream Cuenca river, facilitating the mixing conditions. Indeed, the interaction between this external factors and pond configurations, such as design of input and output, can affect greatly the hydraulic performance of WSP systems (Passos *et al.* 2016). The vertical stratification of DO and pH were, however, induced by the movement of algal layer approaching the water surface in response to the light limitation caused by the water turbidity. This turbid condition was also demonstrated via a high TSS/BOD ratio in the FPs, around 5, while 1.5 is the recommended value from EPA (2011) for properly operated FPs. This high concentration of suspended solid can be caused by the overgrowth of algae and the loss of old sludge particles (EPA 2011). Strong solar radiation at high altitude and abundant nutrients in these ponds can promote algal growth as high algal biomass was recorded in our sampling campaigns, above 420 μg a.L^{-1} near the surface of the FPs. Old sludge age can be another reason for the high concentration of TSS.

Temporal variations

In Cuenca, daylight lasted from 06.00 until 18.00 with the peak of solar radiation between 13.00 and 15.00 when the maximum rate of algal photosynthesis and the highest DO and pH values occurred. The comparable variation of DO and pH in Figure 4 can be explained by the carbonate bicarbonate buffering system in WSPs. More specifically, CO_2 consumption via algal photosynthetic activity causes the increase of pH during the day while during the night or light limited conditions, respiratory processes generate CO_2, causing the drop of pH and oxygen level. More importantly, during this peak period, an extremely high oxygen level was recorded, more than 20 mg O_2.L^{-1} in our sampling campaigns and up to 39 mg O_2.L^{-1} in the sampling campaign of Alvarado (2013) on the same system. These abnormally high oxygen levels can be induced by immense light intensity, up to 1,500 W.m^{-2}, high algal biomass promoting the photosynthesis rate and low air temperature increasing gas solubility in water. Compared to Lake Van (Turkey) located at 1,648 m a.s.l. with 907 W.m^{-2} of the maximum solar radiation, the maximum oxygen concentration was merely above 10 mg O_2.L^{-1} in (Duzen & Aydin 2012; Stockhecke *et al.* 2012). Other climate conditions, such as rainfall, can considerably affect the oxygen level as a heavy rain with high wind speed, above 5 m.s^{-1}, was recorded in the first sampling campaign causing abnormally high oxygen concentrations at the bottom layers, up to 16 mg O_2.L^{-1}, in the last 2 h of the afternoon of the first sampling campaign. As such, additional sampling campaigns in rainy season are required for further study on the impact of rainfall or seasonal changes in other environmental conditions on WSP systems.

SEM evaluation

In contrast to the popularity of SEM in many research areas, such as sociology, psychology, medicine, political science, and economics, the application of SEM on ecological and environmental sciences remains limited (Arhonditsis *et al.* 2006). To the authors' knowledge, this is the first time SEM models are applied on a pond treatment system. Normally, when encountering with the complex interactions of multifaceted factors in ecological systems, ecological engineers are inclined to give away some degrees of generality for better realism and accuracy (Vepsalainen & Spence 2000). As such, regression models, as a simple description of collected data from laboratory experiments or sampling campaigns, are frequently a favorite choice of pond engineers. For instance, two well-known regression equations, Mara (1987) and Gloyna *et al.* (1976), are widely applied for designing and operating numerous pond systems. While useful for having a general idea of the performance of WSPs, these equations offer little insight on the complex interconnections between abiotic and biotic parameters within the pond system, which can cause many difficulties for engineers to extrapolate them on a global scale. As such, fourteen high altitude WSPs in Mexico experienced poor quality effluent because large daily temperature variation from −4 °C to 30 °C and strong wind speed caused night-time thermal stratification and short-circuiting at high altitude, which were probably omitted in their designs (Lloyd *et al.* 2002).

On the other hand, a SEM model of a complex pathway structure is capable of reflecting both direct and indirect interrelationships between observed variables and hypothesized variables in the presence of measurement errors and unexplained variations (Malaeb *et al.* 2000). Thanks to its ability to simultaneously evaluate multiple causal relationships, the mechanistic understanding of hierarchical ecological structure in different time and space scales can be illustrated in SEM models. Indeed, in our case, the conceptual SEM model accurately reflects the interactions among not only multiple inputs but also many kinds of inputs, i.e. biochemical, microbial, meteorological and spatiotemporal data. As such, unlike other descriptive models with limited ability for global extrapolation, pond engineers can apply this conceptual SEM model to describe the causal mechanisms inside other pond systems. After fitting the data, this SEM demonstrates the essential effects of meteorology on the performance of the pond treatment system via the spatio-temporal variations of the three parameters. The fitted SEM also proves its high goodness-of-fit via different evaluation criteria in the acceptable range for a good fit and parsimonious model. However, few limitations of the SEM model should be noticed. For instance, the effects of configuration characteristics related to hydraulic performance, such as the position of pond inlet and outlet or dead zones, on the flow efficiency as well as the pond performance, are not able to be simulated in SEM models. From this perspective, mechanistic models, which can include both hydraulic processes and biochemical reactions, can be a viable alternative.

Insights for pond design, monitoring, and operation at high altitude

The results from the fitted SEM model indicate the predominant role of climatic conditions at high altitude on the performance of the pond system, in which air temperature contributes the most among meteorological parameters. This confirms our expectations, as low temperature constrains the growth of biological community in the pond system which may reduce the removal efficiencies of treatment plants. Hence, in order to ensure compliance with the wastewater discharge standards, an extra safety factor of pond designs at high altitude should be considered. As such, longer HRT or a buffer system may be required at high altitude. Besides, wind speed is also evaluated as an essential affecting factor on pond efficiency, suggesting that engineers and plant owners should keep in mind its interactions with other parameters, such as inlet/outlet configurations, pond geometry, and hydraulic regimes in their designs. For this, a spatially explicit dynamic model, such as computational fluid dynamics (CFD) model, and more detailed hydraulic assessment are needed (Alvarado *et al.* 2012a; Passos *et al.* 2016).

Due to the strong solar radiation, the possibility of algal overgrowth at high altitude is much higher, especially in dry season as in our case. High algal biomass, above 420 μg *a*.L^{-1} near the surface of the FPs, was recorded in our sampling campaigns. Similarly, Pearson *et al.* (1987b) also found an extremely high level of chlorophyll *a*, up to 1,500 μg *a*.L^{-1}, in a high-altitude WSP in Mexico. This algal overgrowth generates the supersaturated DO condition during the day but, on the other hand, depletes the oxygen level due to their respiration during the night or light-limited conditions (EPA 2011). As a result, there can be a vast fluctuation of the pond performance at high altitude between early morning and mid-afternoon. Indeed, from the results of the Kruskal-Wallis tests and the SEM model, daytime proves its significant impacts, both direct and indirect, on the behavior of the pond system, especially on the three parameters related to algal metabolism, DO, pH, and chlorophyll *a*. To minimize these temporal influences and maintain a stable effluent quality, an extra aeration can be applied during the night for the oxygen consumption of aerobic heterotrophs to mineralize soluble organic matters and nutrients. However, in order to ensure a cost effective trade-off of this promising solution, optimal mixing performance with minimum number of aerators should be investigated via applying CFD models which were successfully employed by Alvarado *et al.* (2013) in the aerated ponds where the number of aerators reduced by factors of 2.5, without affecting the pond hydraulic behavior.

Pond operators should also take extra care on monitoring the three parameters and TSS/BOD ratio to control the algal biomass. More specifically, pH should be larger than 6.8 and chlorophyll *a* should be larger than 300 μg *a*.L^{-1} to avoid turning anoxic while measures should be taken to avoid the oxygen level dropping to zero during the night (König 1984; EPA 2011). Furthermore, it is important to keep in mind the spatial effect on the three parameters, which is clearly demonstrated in the high path coefficients between space and the three parameters in the final SEM model and extremely low *p*-values in the Kruskal-Wallis tests. These spatiotemporal variations suggest a need for different monitoring strategy for the three parameters which, according to previous guidelines for pond performance evaluation, i.e. Pearson *et al.* (1987a), Mara & Pearson (1998), and Shilton (2005), can be the same as other parameters. Particularly, instead of monitoring only the influent of pond system and the effluent of each pond, the determination of the three parameters should be measured daily at atleast at two depths, i.e. (i) 20–30 cm from the surface where the photosynthesis occurs and (ii) near the bottom. To evaluate the hydraulic efficiency, their samples should be collected monthly in different locations, as indicated in our sampling campaigns. Furthermore, we recommend that the samples of DO and pH should be collected daily at sunrise and again in midafternoon, to monitor algal respiration causing the oxygen depletion. From that, the necessity of extra aeration for compensation of oxygen depletion can be evaluated. Overgrowth of algae can be indicated by the high ratio between TSS/BOD which also suggests the problem of old sludge age as a result of high sludge accumulation. Since excessive solids buildup in the bottoms of ponds considerably reduce the active volume of the FPs, a regular schedule for physical solid removal is required. It is also important to keep in mind the seasonal effect on pond performance as we observed the great influence of heavy rain in combination with strong wind on the hydraulic performance of the two FPs.

CONCLUSIONS

An advanced multivariate data analysis, SEM model, is applied on the data collected from the three meticulous sampling campaigns in Ucubamba WSP to investigate the effect of severe meteorological conditions at high altitude on the pond performance. From the output of this first application of SEM on WSPs, it is concluded that low temperature is the main reason for an extra safety factor that should be taken into account in the designs of high-altitude ponds. Similarly, high wind speed can create a significant impact on flow efficiency; however, a further investigation of its interactions with other parameters, such as inlet/outlet configurations, pond geometry, and hydraulic regimes, is needed. Strong solar radiation can be both beneficial and detrimental to pond removal efficiency as it boosts the oxygen level during the day but also promotes algal overgrowth causing oxygen depletion during the night. From that perspective, extra care should be given to controlling the algal biomass via the three indicators, DO, pH, and chlorophyll *a*. More specifically, daily sampling at two different depths in early morning and mid-afternoon and monthly sampling at different pond locations as indicated in our campaigns are necessary for better evaluation of pond performance. Pond operators at high altitude should also record daily the variations of climatic conditions in terms of light intensity, cloudiness, precipitation and especially air temperature since extra measures are highly likely to be needed in unusual conditions at high altitude. More importantly, being able to illustrate the complex mechanisms of WSPs in different time and space scales, SEM models are recommended as an effective tool for better understanding and simulation to pond engineers and researchers.

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DECLARATION OF INTEREST

Conflicts of interest: none

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