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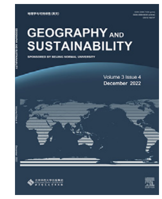

CLUE-S model based on GIS applied to management strategies of territory with oil wells—Case study: Santa Elena, Ecuador

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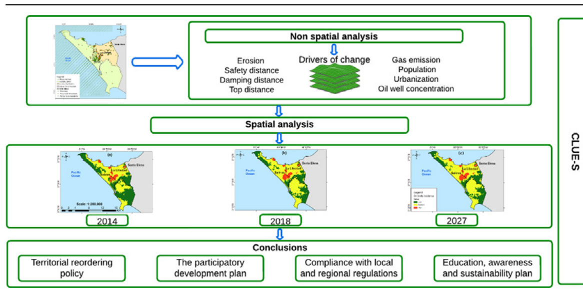
HIGHLIGHTS

- The concentration zone of wells affects land use and require territorial planning.
- The CLUE-S application is adapted to analyse oil wells' incidence in a territory.
- Using CLUE-S, the territory is projected (2027), a vital issue for decision-makers.

GRAPHICAL ABSTRACT



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ABSTRACT

Some cities worldwide have oil wells directly affecting the management of the territory. For example, La Libertad and Salinas districts contain 467 oil wells in urban areas representing a major land-use planning challenge. The objective is to apply the CLUE-S land use model in coastal cities with oil wells (Salinas-La Libertad), using geographic information systems considering environmental and security characteristics for territorial development. The stages of the study are: i) classification and categorisation of oil wells; ii) application of the GIS-CLUE-S method and visualisation of land use dynamics; iii) use the SWOT-TOWS matrix, for the analysis of the situation and the main factors affecting the territory. The results indicate high vulnerability in many urban sectors and those close to the coastline. Furthermore, the CLUE-S analysis shows that the population growth in the urban sector is close to oil well areas, making it a complex pole of human-industry interaction that impacts the management of the territory. This study synthesises three technical aspects: some oil wells do not comply with municipal ordinance regulations; identification of vulnerable zones due to environmental and security factors, which recommends a territorial reordering policy; as well as an education plan for the application of territorial ordering policies, with awareness and sustainability projections.

1. Introduction

The rapid global economic growth has affected the demand for oil in several countries, which causes an increase in the processes of oil activities such as exploration, extraction and marketing of oil (J. Chen et al., 2019; Jain, 2018; Saari et al., 2016). That led to the oil industry being one of the fundamental activities that sustain the economic income of several countries, such as Russia, Nigeria, Venezuela, Saudi Arabia, Norway, and Ecuador (Ambituuni et al., 2014; Benedictow et al., 2013; Buenaño et al., 2021; Taber, 2020; Tvinnereim et al., 2020). Therefore, this industry is considered one of the most important strategic sectors in the world, which drives a territory's modern economic, social and

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political development (Graham and Ovadia, 2019; Kamat et al., 2019; Kilian and Murphy, 2014).

Oil development in a territory involves the generation of oil fields and wells, transporting materials, drilling and other industrial operations. These processes occur in relatively populated settings, such as rural and urban sites in various regions (Mayer et al., 2018; Tran et al., 2020). The combination of oil and gas extraction in urban and suburban environments has generated petro-suburbs, residential areas that are home to active drilling and production structures in their midst (Haggerty et al., 2018). However, oil wells occasionally tend to be far from urban areas. Still, labour mobility, the demand for housing and essential services, and the execution of complementary works to oil projects contribute to expanding urban areas in oil production sites (Branch, 1972; Llerena-Montoya et al., 2021). In addition, the oil industry can alter land use and affect other activities close to oil fields, such as agriculture, which is oriented to satisfy the demand for food (Matemilola et al., 2018; Varjani and Upasani, 2019).

Land use by oil activity plays a vital role in developing cities based on hydrocarbon resources because it generates positive aspects such as economic development (Chen et al., 2019) and negative impacts on the population and the environment (Herrera-Franco et al., 2021b). For example, the proximity of the wells to the houses could generate risks of damage to health and the environment (Fitzgerald et al., 2020; Otchere-Darko and Ovadia, 2020). Health risks could present as symptoms of headache, respiratory tract involvement, eye and skin irritation, and diseases such as bronchitis, asthma and gastrointestinal. These risks depend on the mode, concentration and exposure time of the gases produced by the hydrocarbon activity (López et al., 2010). Therefore, it is necessary to apply scientific-technical methodologies for the efficient planning of the territory, which requires methods of land use for oil activity and its sustainable development.

There are various models of change in land use, which estimate the effects of the development of human activities on food, energy and housing needs (Kok et al., 2001; Schüngel et al., 2022). These models propose land use planning through geographical information systems (GIS) and remote sensing (Alawamy et al., 2020; Wang et al., 2020), associating the territory's economic, social and environmental factors with land use change (Acheampong et al., 2018; Demuzere et al., 2014; Verburg et al., 2002). For example, in Bucharest (Romania), they used a model of land use change called CLUMondo, for the projection of future demand for land use of living spaces, green spaces and agricultural areas to 2040 (Bacău et al., 2022), while in the Lake Tana basin (Ethiopia), used the CA Markov model, which considers the increase in erosion due to the effects of climate change (Getachew et al., 2021). Another example is the modelling of the effects of deforestation on an area of the territory, which led to rice fields and desertification in the last decade, in the Xiang River Basin in China (Wang et al., 2018). In addition, they used satellite tools to locate and design water source storage structures within the land use and cover framework (Bao et al., 2022). Among other models are: i) SECLAND, which projects 2050 climatic and socioeconomic factors in the interaction between agriculture and forest areas (Egger et al., 2022); ii) Dyna-CLUE, used to simulate urban growth limits in Quito, explains how urban sprawl consumes natural and agricultural land for housing (Salazar et al., 2020); and iii) the Conversion of Land Use and its Effect at Small Regional Extent (CLUE-S), applied to cases of future changes in land use concerning agricultural activity (Lambin et al., 2000), urbanization, and the abandonment of agricultural land in European landscapes (Huang et al., 2019; Verburg et al., 2006).

On the other hand, oil exploration and exploitation in coastal areas threaten the environment due to the emission of pollutants and possible oil spills that remain for long periods in intertidal coastal regions (Dai et al., 2020). For this reason, the socioeconomic vulnerability of coastal areas concentrates on commercial establishments, lodging services, natural areas and reefs, and the food sector, which are essential for adequately functioning the productive tourism chain in marine-coastal areas (Câmara et al., 2021; Escandón-Panchana et al., 2022).

Santa Elena-Ecuador oil province comprises three cantons: Salinas, La Libertad and Santa Elena. The built of the first well for oil exploitation in Ecuador was performed in 1911 (Lindsey and Lopez, 2015). Currently, in part of the southern area of the province, considered within the "Gustavo Galindo" oil field, it is common to see oil extraction wells near urban settlements with mobile rocker arms (Estrada, 2011). The spatial and temporal dynamics of land use due to housing needs in the study area (Verburg et al., 2011) are related to the oil industry because areas where oil wells locate previously corresponded to rural areas and are currently urbanised (Herrera-Franco et al., 2021a). In addition, land use changes are associated with the decrease in agricultural areas due to urbanisation in these coastal areas (Li et al., 2022). Salinas and La Libertad are considered tourism centres that contribute to the economic development of this province, where there are more than 450 wells installed in urban settlements and their surroundings, close to homes, which can cause risks to the health and integrity of people as well as the environment (Herrera-Franco et al., 2022; Rodríguez and Pilasagua, 2014).

In this context, the following research questions were raised: Is it possible to adopt an agricultural land use methodology for territorial planning proposals due to the presence of oil wells and their impact on the safety-environment of the area? How do we generate and propose development or territorial reorganization strategies depending on the degree of abandonment or location of the wells and the oil industry?

This work aims to apply the CLUE-S model of land use using spatial analysis (the geolocation of wells, well concentration, land use and well inventory) and non-spatial analysis (change factors, health perception and environmental pollution) to generate technical strategies that help decision-makers. CLUE-S is a suitable model for land use planning. Its structure proposes two spatial and non-spatial approaches. The non-spatial analysis determines the driving factors of change that present the dynamism of land use by oil activity. In addition, the application of surveys on the perception of population health and environmental pollution found threats and vulnerabilities in the sectors due to the proximity of oil wells. The spatial analysis included the geolocation of wells and the statistical spatial distribution, obtaining a map of the incidence of oil wells in the Salinas and La Libertad sectors. Finally, the SWOT matrix made it possible to define development strategies for decision-making for the population close to oil wells.

2. Materials and methods

2.1. Study area

The study area corresponds to the districts of Salinas and La Libertad, located on the Ecuadorian coast (2°11′1″S and 2°20′20″ S, 80°51′31″W and 81°00′41″ W), west of the Santa Elena province (Fig. 1). In 2020, Salinas and La Libertad had a population of 94,590 and 117,767 inhabitants, respectively (Instituto Nacional de Estadísticas y Censos (INEC), 2020), and a total area of 93.15 km^2 (Instituto Nacional de Estadísticas y Censos (INEC), 2010).

A rugged morphology characterises the area with the presence of peninsulas and headlands along the coastline (Dumont et al., 2014). Salinas is the most salient point or westernmost part of the Ecuadorian and South American coast (Fig. 1), a geographical feature that stands out in the study area.

The region's climate is dry, with rainfall patterns influenced by ocean currents (Humboldt Current), the Intertropical Convergence Zone (ITCZ), and Pacific oceanic phenomena (El Niño (warm)-La Niña (cold) phenomena) (García-Garizábal, 2017). Irregular and low rainfall has given rise to three vegetation types: coastal desert and semi-desert vegetation (*xerophytic woodland, thorn woodland, and arid scrub*), deciduous forest, and semi-deciduous forest (Pearsall et al., 2016). The foliage is coastal desert and semi-desert, typical of the asymmetric western coastal margin of the Santa Elena Peninsula.

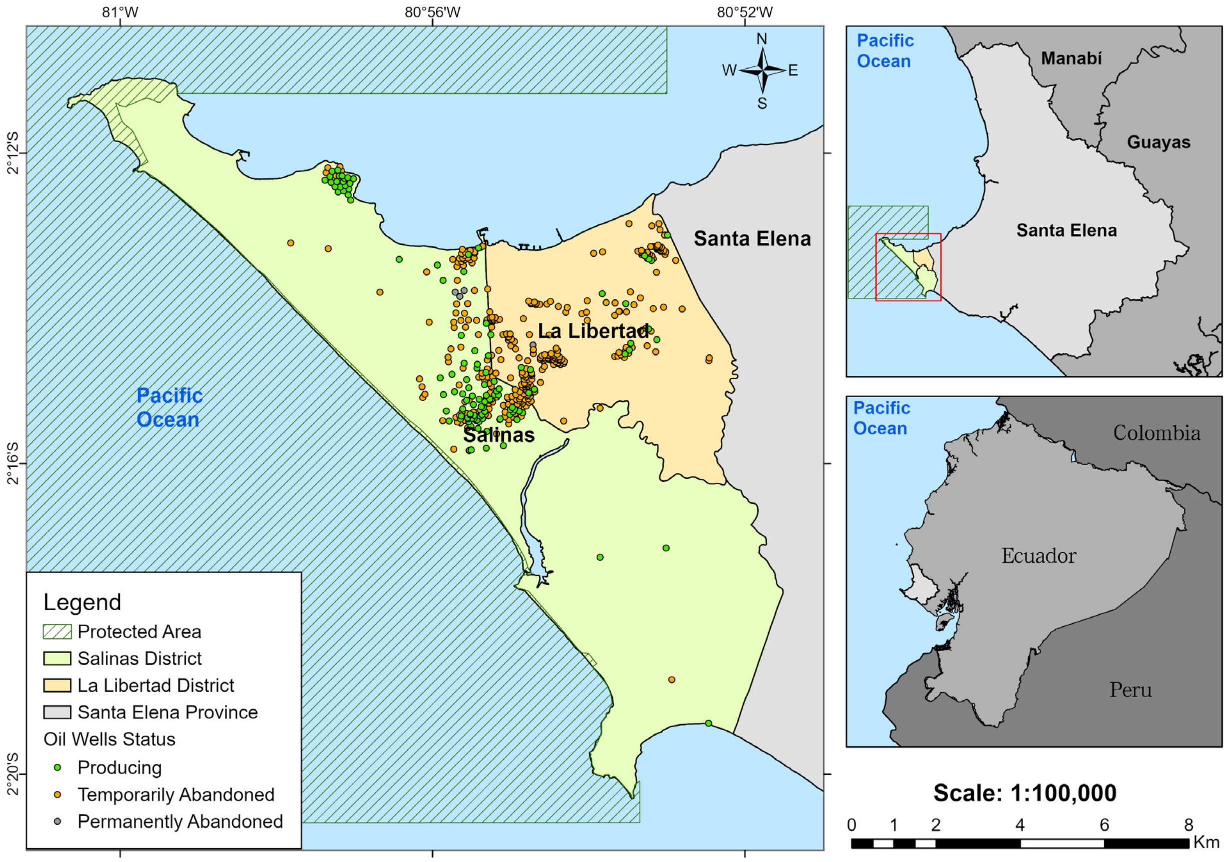

Fig. 1. Location of the study area.

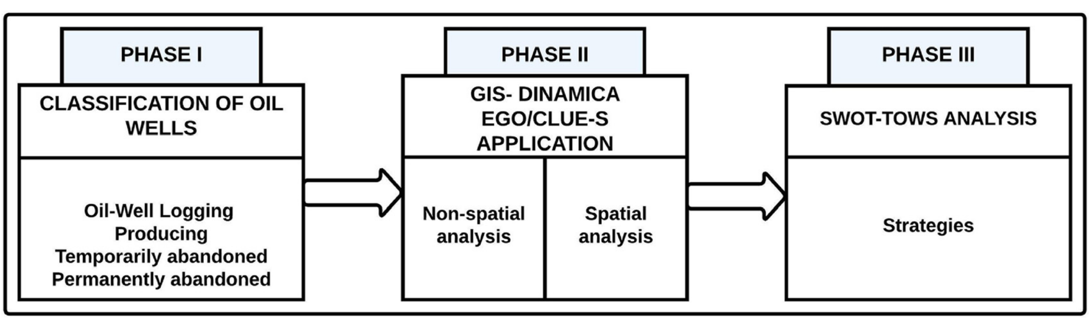

Fig. 2. Scheme of the process used in this study.

2.2. Geological setting

Regionally, the Santa Elena Peninsula is in the southwest of the foothills of the Chongon-Colonche Coastal Range and west of the Progress Basin. In this area, outcrops geological units ranging from Late Cretaceous to Quaternary alluvial deposits are dominant. These geological formations have NNW-SSE trending faults associated with the La Cruz regional fault and NE-SW trending faults contrary to the alignment of the Chongón Colonche Mountain Range (Ficcarelli et al., 2003; Lindsey et al., 2020; Lindsey and López, 2015; Luzieux et al., 2006) (Fig. S1).

2.3. Study phases

The process consists of three phases (Fig. 2): i) classification of wells; ii) application of the CLUE-S methodology to assess land-use dynamics; and iii) application of the SWOT -TOWS matrix, based on the opinion of experts in the field.

2.3.1. Phase I: classification of oil wells

This first phase comprehensively analysed all the oil wells under study through the wells' registration, geolocation and classification. The classification of wells allowed the identification of threats and vulnerabilities due to proximity between them, the proximity of the wells to urban areas and their possible effects on natural resources, such as water bodies and flora. In addition, this classification is considered oil well types depending on their current status: wells producing and temporarily and permanently abandoned.

2.3.2. Phase II: GIS-Dinamica EGO/CLUE-S application

The CLUE-S methodology is a model used for the dynamic analysis of land use in small regions. It analyses land-use changes and their relationship to drivers of change such as economic, political and socio-cultural factors in the Salinas and La Libertad districts. It allows for determining spatial connectivity (land use) and a set of variables (drivers of change) that specify the dynamics were occurring in these areas (Verburg et al., 2002; Zhang et al., 2016).

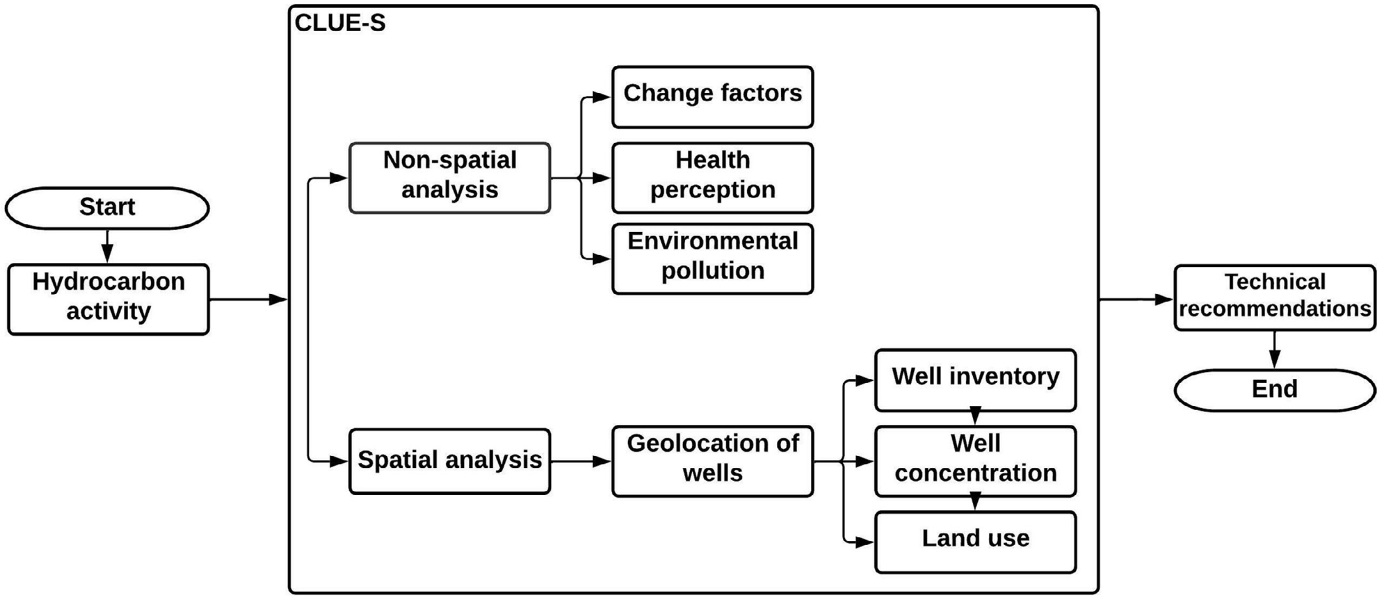

Fig. 3. Phase diagram of the CLUE-S methodology.

Fig. 3 shows the critical aspects of the CLUE-S methodology, which includes two phases in this research: the first consists of a non-spatial analysis of land use in the study area, and the second of a spatial analysis of land use.

2.3.2.1. Non-spatial analysis. In this step, the human activities or economic functions present in the territory of the Salinas and La Libertad districts made it possible to identify the land use and the drivers of change (Braimoh and Onishi, 2007; Pauleit et al., 2005). Table S1 presents the various land uses by hydrocarbon activity with their respective change factors, media and research techniques.

In the second semester of 2019, fieldwork and visits were carried out in the urban and rural sectors. In addition, the fieldwork found variables or drivers of change that dynamize land use, and evidence of the industrial oil activity and a detailed description of the relationships between population, economy and environment (Abu-hashim et al., 2015; Camacho-Sanabria et al., 2017).

The research technique used was direct observation and the information collected from the territorial development plans of the districts of Salinas and La Libertad. This recognised different uses of the land according to the activity carried out by the inhabitants, for example, the use of the land for commercial activity, infrastructure, presence of the sea and industrial activities (Cihlar and Jansen, 2010; Verburg et al., 2002).

In January 2022, through surveys, information collects from the population near the oil wells to determine the incidence of oil activities on health and environmental pollution. The survey consists of three parts: sociodemographic data, identification of risks and vulnerability, and the oil company-population-governance relationship. The representative sample used Eq. (1) (Alcaraz-Quiles et al., 2015; Lerma et al., 2021), with a probability of success (p) and failure (q) of 0.5, sampling error (ε) of 0.05 and confidence level of 95% (z=1.96). According to data from the Instituto Nacional de Estadísticas y Censos (INEC) (2010), the approximate population (N) of the study area is 164,617. Therefore, the representative sample (n) is a minimum of 383 people, corresponding to 65.23% of the urban area and 34.77% of the rural area. With the subjective data obtained, the next step determines the threats and vulnerabilities due to the proximity of the oil wells.

$$n = ((z^2)\times p\times q\times N)/((\varepsilon^2(N\text{-}1)+((z^2)\times p\times q))) \quad (1)$$

The perception of the population around the oil wells and information from the technical files of the wells determined the parameters of hazards and vulnerabilities based on compliance with local and national regulations (Azevedo et al., 2017; Elser et al., 2020; Gad Municipal del Cantón La Libertad, 2009; Gad Municipal del Cantón Salinas, 2008; Nelson and Grubesic, 2018). Risks such as distance from homes to oil wells and gas emissions were assessed (Hachem and Kang, 2022). Exposures include the presence of oil operations, contact with hydrocarbon spills and the absence of oil well signage (Presidencia de la República del Ecuador, 2010, 2018).

The threat assessment, according to the regulations, the perception of the respondents and the adaptation of sensitivity levels proposed by Marinho et al. (2021) determined three levels of high, moderate and low susceptibility: i) low probability of damage to the environment or the population; ii) moderate probability of damage with a moderate magnitude; and iii) high probability of damage with a critical magnitude. In addition, the assessment of vulnerabilities identified: i) low fragility and zero exposure; ii) moderate brittleness and high exposure; and iii) high frailty and exposure (Gollan et al., 2019).

Table 1 presents the threats and vulnerabilities due to proximity to oil wells, potential environmental and health risks, and the perception of soil contamination by the inhabitants. These threats and vulnerabilities negatively impact the environment (coastal marine) and the health of the sector's inhabitants (Andrews et al., 2021).

2.3.2.2. Spatial analysis.

(1) ***Geolocation of oil wells***

The georeferenced records of the oil wells in Salinas and La Libertad used visualisations and fieldwork. Consequently, ArcGIS Pro software created a project with UTM projection datum/spheroid WGS 1984 Zone 17S. Subsequently, all the wells classified according to their status were imported (Fig. 1), thus obtaining an updated and georeferenced inventory of wells (Díaz et al., 2015; Golla et al., 2019).

(2) ***Concentration of oil wells***

As Tobler's first geographical law points out, all attribute values on a geographical surface are related. Still, closer objects are more strongly related than distant objects, interrelated in spatial distribution, clustering, randomness and regularity (Sui, 2004; Tobler, 1970). The closer the distance, the closer the relationship. The exploratory spatial analysis of

Table 1
Threats and vulnerabilities due to the proximity of oil wells in the districts of Salinas and La Libertad.

Criteria	Parameter	High	Moderate	Low
Threat (Gad Municipal del Cantón La Libertad, 2009; Gad Municipal del Cantón Salinas, 2008; Presidencia de la República del Ecuador, 2010)	Distance from houses to wells	30 to 60 meters	Between 60 to 120 meters	Greater than 120 meters
	Presence of oil stains	The constant presence of oil stains	Not apply	It does not have oil stains
	Gas emission	Always	Sometimes	Never
Vulnerability (Presidencia de la República del Ecuador, 2010, 2018)	Soil granulometric structure	Little (granular)	Moderate (heterogeneous)	High (block)
	Affectation	High	Moderate	Low
	Well closure	There is no closure of the oil well	Not apply	There is a closure of the oil well
	Well signage	There is no signage	Not apply	There is signage
	Certainty of preventive/corrective maintenance by the oil operator	Presence of oil operations	Not apply	No oil operations
	Contact with oil spill	Always	Sometimes	Never

the oil wells used the Kernel Density Estimation (KDE) and considered the productive state of the wells in the study area. The KDE is a mapping and spatial analysis tool that determines the overall areal density of the location points based of the number of locations per unit area (Zuo et al., 2021). The method converted the sets of wells into continuous surfaces. Therefore, it found density maps of producing, temporarily abandoned and permanently abandoned oil wells (Fig. S2).

(3) ***Land-use***

This work uses three scenarios to determine the probability of spatial distribution by land use according to oil activity: scenario 1 (2014) is the local governments' absence of land-use planning policies; and Scenario 2 (2018) the existence of a land-use planning plan by the local government (Gad Municipal del Cantón La Libertad, 2014; Gad Municipal del Cantón Salinas, 2014). Additionally, these scenarios were choosen due to the availability of land use and land cover (LULC) data obtained from the geoportal of the Ministry of Environment, Water and Ecological Transition of Ecuador (MAATE, acronym in Spanish). Scenario 3 is a logistical projection of land use for 2027, applying the least-squares method.

This procedure determined an empirical analysis of the relationship between land use and its drivers of change. The connection is evaluated by logistic regression, a standard methodology in land-use transition, to establish the probability of a specific land use occurring according to its transition factors. The logistic regression mathematical model is as follows (Eq. 2):

$$\ln \left(P_i / 1 - P_i\right) = \alpha_0 + \alpha_1 X_{1,i} + \ldots + \alpha_n X_{n,i} \tag{2}$$

where:

P_i is the probability of land use;

X represents the change factors. Thus, the most relevant change factors influencing land use are selected (Huang et al., 2019; Verburg et al., 2002).

Fig. 4 shows that land use allocation is related to the dynamics of change factors, leading to a statistical analysis determining the probability of land use in the study area.

The odds ratio (OR) explained the logistic regression coefficients for several independent variables. The model allows probabilistic predictions compared using the receiver operating characteristic (ROC). The ROC values range from 0.5 to 1. The value of 0.5 for random assignment probability and 1 for a better simulation. If the ROC is less than 0.7, then the goodness of fit of the statistical model is poor, whereas, when the ROC is higher than 0.7, the integrity of fit of the statistical model is acceptable (Braimoh and Onishi, 2007; Huang et al., 2019; Verburg et al., 2002).

The statistical relationship is used to obtain the spatial distribution between change factors and land use types, thus indicating the likelihood of each land use occurring in a particular location (Huang et al., 2019). The probability of land use and the dynamic behaviour of drivers of change influence land-use allocation through decision rules, which determine the conditions for land-use change. According to Verburg et al. (2002), these rules are i) land uses are unlikely to be converted to another type of land use; ii) land uses are easily converted to a different kind of land use, depending on their change factors; and iii) profitability of land use may lead to another type of land use.

Table 2
Oil well rasters for data geoprocessing.

Oil wells	Rank		Rating	Weight		
				P	TA	PA
Productive (*P*)	0	10	1	3	2	1
Temporarily Abandoned (TA)	10	20	2			
Permanently Abandoned (PA)	20	30	3			
	30	40	4			
	40	50	5			
	50	60	6			
	60	70	7			
	70	80	8			
	80	90	9			
	90	100	10			
	100	110	11			

LULC maps obtained from the MAATE geoportal, corresponding to 2014 and 2018 (Fig. S3), were used for the exploratory spatial analysis (Ministerio del Ambiente, Agua y Transición Ecológica, 2022). Moreover, as a complementary part of the LULC, all the protected areas included in the National System of Protected Areas (SNAP, acronym in Spanish), located within Salinas and La Libertad, were considered. The data were also acquired from the MAATE Geoportal.

Finally, for exploratory spatial analysis, all preliminary results were integrated by year using the Raster Calculator tool to obtain the maps of oil well incidence for the 2014 and 2018 scenarios. This tool made it possible to relate the raster maps of well density, LULC and allocation of rating and weights according to the level of vulnerability. Table 2 presents the status of the oil wells with their respective KDE proximity range, rating and assigned weights. In addition, Table 3 shows the classification of land use with the associated rating and weights considered. A higher rating was given to the land uses related to housing areas, water collection and food production affected by proximity to the oil well.

(4) ***Use and coverage modelling for the future scenario***

Dinamica Environment for Geoprocessing Objects (Dinamica EGO) platform ran the LULC probabilistic simulation model for the 2027 scenario (Universidad Federal de Minas Gerais (UFMG), 2022). This tool has been used in several LULC future scenario modelling studies, such as detecting changes in LULC through image segmentation and GIS anal-

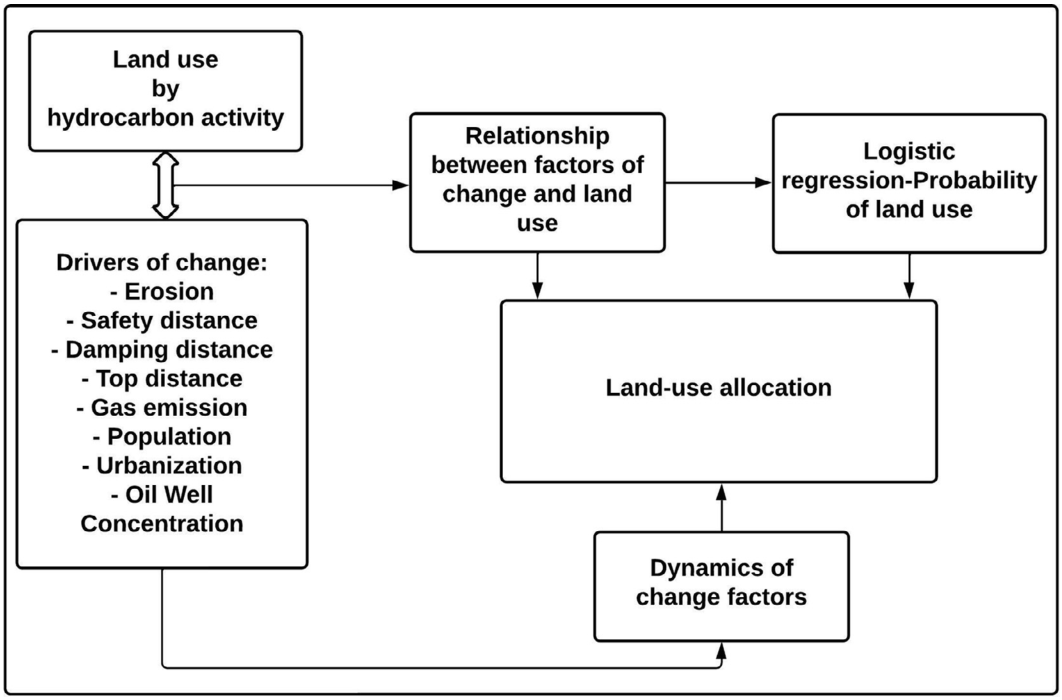

Fig. 4. Procedure for assigning land use.

Table 3
Land use rasters.

Variable	Use	Rating	Weight
Land use	Populated areas	7	5
	Natural (Water)	6	
	Artifitial (Water)	6	
	Buildings	1	
	Agricultural land	5	
	Forest plantation	3	
	Shrub vegetation	2	
	Herbaceous vegetation	2	
	Area without forest cover	1	
	Protected areas	4	

ysis to generate land use and land cover maps at current and future dates to obtain a cartographic database (Mas et al., 2017). In addition, it was used for the identification of spatial factors in land use dynamics, for the generation of past and future scenarios in agricultural and urban areas (Osis et al., 2019; Soares et al., 2020).

The simulation had four stages: i) selecting all land use categories to determine the probability of future land use occurrence; ii) LULC transitions for the simulation periods 2014–2018 and 2018–2027. The transitions that occurred in this model were: area without forest cover to populated place, shrub vegetation to populated area, area without forest cover to forest plantation, artificial area to forest plantation and area without forest cover to agricultural land. iii) Assignment of the weights of evidence of the model transitions, to represent the influence of the LULC classes on the spatial probability of each transition, using the Chi^2, Crammer index and standard uncertainty methods. The correlation between variables of significant LULC transitions is considered a factor greater than 0.5 according to the Crammer index. iv) Simulation and validation of models (Elz et al., 2015; Kabuanga et al., 2021).

(5) ***Model validation***

The modelled LULC scenario for 2027 was validated on the Dinamica Ego platform, using the period from 2014 to 2018. First, the transition rates for changes in land use were calculated (Table 3). Then, the expansion pattern allowed us to spatially assign the changes of the state through the patcher mode (Santos et al., 2022). Similarly, the Weights of Evidence method generated the transition probability maps, and Crammer's coefficient performed the correlation analysis between the variables (correlations ≥0.5) (de Oliveira et al., 2020). Finally, to validate the model, it is necessary to verify the similarity between the simulated and existing maps for the same scenario through of reciprocal similarity comparison technique (Piontekowski et al., 2019). Therefore, starting in 2014 was modelled the 2018 scenario. The result compares with the existing 2018 scenario, obtaining superior general accuracy of 90% (Elz et al., 2015; Kabuanga et al., 2021), which confirms the goodness of fit of the 2027 scenario simulated with this model.

2.3.3. Phase III: application of SWOT-TWOS matrix

The SWOT (strengths, weaknesses, opportunities and threats) matrix was applied. It is a versatile tool that made it possible to create strategies to guarantee optimal results and actions in decision-making (Brunnhofer et al., 2020; Carrión-Mero et al., 2018; Hajizadeh, 2019; Herrera-Franco et al., 2021). The SWOT analysis identified internal factors' strengths and weaknesses and examined the opportunities and threats of external factors related to the study variables. The TOWS matrix turns opportunities and weaknesses into strengths through strategies based on these relationships and their implications (Datta, 2020; Sahani, 2021). In addition, through the participation of experts in the field, they constructed the SWOT, which seeks the best development alternatives/strategies in the relationship between territory and oil wells. The focus groups included the participation of experts, who expressed their opinions regarding oil activity in the urban territory and its impact on society (Lavasani et al., 2015).

3. Results

3.1. Probability of spatial distribution

The statistical analysis determines the estimation of the contribution of the different potential factors of change to the correlation of a type of land use. Based on a logistic regression model, which specifies the

Table 4
Results of the regression of the spatial distribution of land use in the districts of Salinas and La Libertad in the Santa Elena province during 2014-2027.

Drivers of change α_n	Partial regression coefficient α_n			Exponential Coefficient Exp (α_n)			ROC value		
	2014	2018	2027	2014	2018	2027	2014	2018	2027
Erosion	-2.00	-1.89	-1.47	0.14	0.15	0.20	0.83	0.82	0.81
Safety-distance	-2.60	-2.64	-2.71	0.07	0.07	0.07			
Damping-distance	1.89	1.22	0.85	6.63	3.38	1.88			
Top-distance	-1.80	-1.80	-1.77	0.17	0.17	0.17			
Gas emission	2.44	2.45	2.45	11.59	11.62	11.60			
Population	0.38	0.41	0.52	1.46	1.51	1.66			
Urbanisation	0.55	1.21	1.49	1.74	3.38	4.18			
Oil well concentration	0.27	0.29	0.55	1.30	1.34	1.64			

Note: $\text{Exp}(\alpha_n)$ denotes the changes in the probabilities of land use over a unit change by the change factors (independent variables). If $\text{Exp}(\alpha_n) > 1$, then the chance increases relative to the increase in the value of any change factor. On the contrary, if $\text{Exp}(\alpha_n) < 1$, the probability decreases.

significant contribution of potential change factors (independent variables) in land use (dependent variable) by oil activity (Braimoh and Onishi, 2007; Luo et al., 2010; Verburg et al., 2002). Table S2 presents the distribution of variables involved in the logistic model with their respective descriptions.

Logistic regression models established the correlation between land use and a set of drivers of change. The regression of the spatial distribution analysed the use of land by oil activity for the years 2014, 2018 and 2027 (Table 4), where it shows that the change factors leading to the use of land by oil activity are: buffer distance, the emanation of gases, population density, urbanisation and the concentration of wells in the years 2014, 2018 and 2027, respectively. All of the above subjects have a high incidence in the probabilities of land use ($\text{Exp}(\alpha_n) > 1$).

On the other hand, the data found in 2014 specify the correlation between population density and the oil well concentration factor, meaningthat there is a nearby population concentrated in oil wells in the Salinas and La Libertad district sectors. The distance of this population is 30 to 50 meters (distance_buffer) concerning the oil well. Therefore, the urbanisation change factor is significant due to population density. 2018 presents the same scenario, a notorious increase delimited by the correlation between population density, wells' proximity, and public urbanisation policies. The decrease in the buffer distance of 2014 concerning 2018 responds to the increase in the upper distance factor from the well or production facilities to the urbanization area (a distance greater than 50 meters). In other words, the increase in population density for 2018 is in the buffer distances and upper due to campaigns to prevent irregular human settlements implemented by the national government of Ecuador (Gobierno de la República del Ecuador, 2012) and the municipal ordinance that regulates the use of land and urban development in areas of oil activity (Gad Municipal del Cantón La Libertad, 2009; Gad Municipal del Cantón Salinas, 2008).

However, 2027 presents a third scenario based on the predictions of the previous logistic regressions, demonstrating the exact correlation between the significant factors of change.

3.2. Strategies and solutions

According to the study area analysis, Tables 5 and 6 present the SWOT and TOWS matrices, respectively.

Primary strategic lines obtained by the SWOT matrix:

- Promote environmental education for awareness and empowerment of the use of oil wells.
- The local government agencies, the centres of educational institutions and the private company in charge of the hydrocarbon, should create specific joint programs on the environmental importance of the oil activity in the sector.
- Determine alliances between the different sectors to take joint actions within the framework of urban development.
- Establish control policies framed towards the improvement in infrastructure and conditioning of oil wells in production, closed and abandoned.
- Implement soil management plans, guaranteeing good land-petroleum management by population growth.
- Guarantee through regulations the preservation and protection of the geological and mining-industrial heritage.

3.3. Oil wells incidence map

Fig. 5 presents the thematic maps of oil wells incidence for 2014, 2018 and 2027. The maps facilitate identifying the geographical distribution and relate the spatial patterns of the oil wells' incidence change within the districts of Salinas and La Libertad. From the analysis of the thematic maps, it is possible to identify some alterations in the areas occupied by each level of oil wells incidence. Table 7 shows the area values in hectares (ha) and the percentage occupied by each oil well's incidence group for 2014, 2018 and 2027.

In the three scenarios, the north of the Salinas district, the northeast of La Libertad, and the study area's central part presented a higher incidence of oil. It is essential to highlight the presence of the La Libertad Refinery, located in the northeast sector of La Libertad, a territory exclusively used by the oil industry. However, the northern regions of the Salinas district and the central part of the study area are densely urbanised sectors, which overlap the identified areas of high oil incidence. Additionally, it is possible to observe that the 2018 and 2027 scenarios experienced a slight increase in areas of high oil wells incidence compared to 2014 (Table 7). This increase occurs in the central region of the study area, specifically within the territory of the Salinas district.

On the other hand, the 2018 scenario expanded areas with medium oil incidence. The change showed a variation from 4,556 ha (49.70%) to 5,570 ha (60.76%) for 2014 and 2018, respectively (Table 7). This change occurred mainly in the Salinas district, in the sectors located to the south, north and northwest of the community, associated with changes in land use. For the years 2014 and 2018, the average oil incidence of the district went from 3,125 ha (46.69%) to 4,075 ha (60.89%), respectively (Table 7). In addition, the south of Salinas went from the use of shrubby vegetation in 2014 to an area dedicated to agricultural use in 2018 (Fig. 5a and b). To the district's northwest, the 2014 scenario exposed soils without specific service, which changed to built-up areas and lagoons linked to the salt extraction industry for the 2018 scenario. Similarly, the north of Salinas experienced a displacement of the areas of herbaceous vegetation by populated areas in 2018 (Fig. 5a and b). The demand for population growth in the region justifies the more significant presence of agricultural activity and the urban regions in 2018, which alters the oil incidence map. It is important to note that the oil incidence projection for 2027 is similar to 2018, with a slight expansion in the areas of medium oil incidence. The change occurred

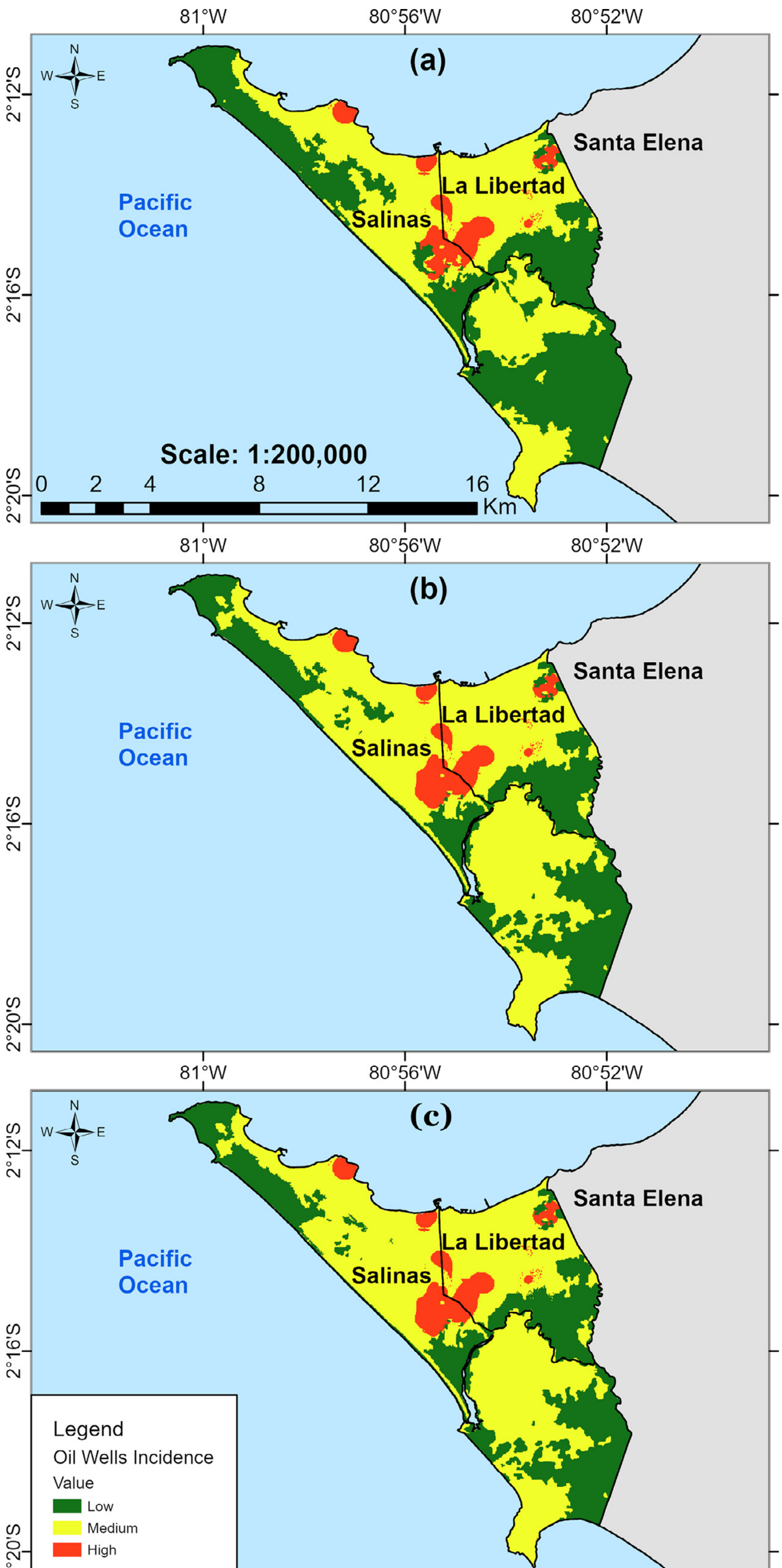

Fig. 5. Thematic maps of oil wells incidence, referring to the years 2014 (a), 2018 (b) and 2027 (c).

Table 5
SWOT Analysis of study area.

Internal		External	
Strengths		Opportunities	
S1	The oil industry is an economic factor for the area	O1	Santa Elena Peninsula Geopark Project, for its oil identity
S2	A geological and mining-industrial heritage exists in the area	O2	University projects constitute a means to take control and management measures for oil wells in urban areas
S3	Bituminous exudations are natural and historical and can serve as a site museum	O3	The institutions related to the themes can interact to provide solutions
S4	Unique ecosystem: a sea, coast, oil resources, paleontological deposits, sun and beach tourism	O4	Environmental education: educational campaigns, socialising the issue with the population
Weaknesses		Threats	
W1	Lack of signage and physical security perimeters of oil wells	T1	There is a presence of invasion of the area surrounding the oil wells
W2	The municipality must monitor the oil company regarding the signage since they are responsible for the exploitation and management	T2	Abandoned oil wells have other purposes
W3	The oil company is not committed to carrying out the signage	T3	Lack of coordination between the municipalities, the oil company and external organizations to take control and land-use channels
W4	The municipality does not apply the sites' regulations, control or rehabilitation	T4	Sectional agencies such as the Ministry of the Environment are not taking action
W5	Oil wells on public roads and close to homes	T5	Climate change affects and increases emissions and natural outcrops
W6	Lack of a detailed survey of environmental liabilities of oil wells		
W7	Lack of knowledge of the rate of gases in the environment		
W8	There is no socialisation, compliance or execution of ordinances regarding oil activity		

Table 6
TWOS strategies matrix.

S + O		S + T	
S1O1O2	Implement new initiatives for the development of the sector	S1T1T2	Implementation of development plans to improve the oil sector. Preservation and management of petroleum activities
S4O1O2	Application of regulations for the territorial development of the sector. Use of territory resources	S3T3T4	Design a plan to use of these geological-environmental sites to promote local and regional development
W + O		W + T	
W1O3	Improvement of physical security infrastructure for oil wells, through coordination of public and private sectors, for the development of the territory	W3T1T2	Delegate the obligation to the local oil company, the fulfilment of contractual obligations, for the environmental management of the sector
W6O2O4	Improve synergy with the university and other institutions for sustainable development in the territory-oil framework	W4T3T4	Issuance of regulations to apply a territorial ordering of the sector
W8O3	Legally apply territorial municipal ordinances for the optimal development of the sector	W8T3T4	Develop joint planning with public and private entities to monitor, control, and manage oil wells through community participation
		W6T4	Geoenvironmental diagnosis to define control and development strategies

Table 7
Oil wells incidence (areas and relative participation).

Oil wells incidence	Area (ha)								
	GLOBAL			Salinas			La Libertad		
	2014	2018	2027	2014	2018	2027	2014	2018	2027
Low	4104.27	3030.48	2972.43	3287.70	2277.36	2224.44	816.57	753.12	747.99
Medium	4555.98	5569.65	5626.80	3124.62	4074.84	4126.86	1431.36	1494.81	1499.94
High	505.89	566.01	566.91	280.35	340.47	341.37	225.54	225.54	225.54
Relative participation (%)									
Low	44.78	33.06	32.43	49.12	34.03	33.24	33.01	30.45	30.24
Medium	49.70	60.76	61.39	46.69	60.89	61.66	57.87	60.43	60.64
High	5.52	6.18	6.18	4.19	5.09	5.10	9.12	9.12	9.12

from 5,570 ha (60.76%) to 5,627 ha (61.39%) for 2018 and 2027, respectively (Table 7).

4. Discussion

Most of the CLUE-S methodology applications focus on the agricultural sector, where it combines the relationship of land use in different scenarios/territories. In this case, the CLUE-S methodology analysed a region whose main activity is the oil industry, recognising changes in land use due to the incidence of oil wells and other related activities (e.g., refinery and private oil companies).

This study shows land use's dynamic and spatial behaviour in an urbanised territory related to the oil industry through the CLUE-S methodology, a valuable and functional model in various spatial and non-spatial land-use scenarios. These two approaches determine the importance of the model because they relate the use of land by oil activity (e.g., oil wells, oil companies, extraction stockpiles, storage tanks for crude oil and derivatives), drivers of change and its spatial distribution (e.g., geolocation of wells, the concentration of wells related to population growth and urbanisation, and future prediction of land use). In contrast, specific activity models such as SWAT predict impacts of changes in land use, agricultural management and water quality in watersheds but present difficulties in optimising the land use pattern (Zhang et al., 2013). Likewise, the management tools for urban growth limits are oriented solely to planning and territorial ordering (James et al., 2013).

The change factors used by this model occurred based on the relevance and adequacy of the data. Population density and urbanisation are predominant socioeconomic factors in land use and coverage due to wells and oil infrastructure (Dami et al., 2014). Within the framework of this analysis, the trend of increase in population and surface of the urban area requires planning and ordering of the territory based on local and regional regulations, taking into account the variables that affect the change in land use, community participation and the commitment of government authorities. Other case studies use these factors to explain land use and land cover by agricultural activity (Gibreel et al., 2014; Huang et al., 2019; Zhang et al., 2016), watershed planning (Semadeni-Davies et al., 2020), spatial dynamics of wetlands under urban agglomerations (Peng et al., 2020) and prediction of mangrove habitat change (Wang et al., 2021).

The impacts caused by industrial activities (i.e., presence of oil wells) in the sector require the analysis of other factors of change. The structure of the CLUE-S model makes it possible to represent the change in land use related to the characteristics of various complex systems (Kucsicsa et al., 2019; Xu et al., 2013; Zare et al., 2017). For this reason, the proposed model applies to the oil system. One of the characteristics of oil activity is the emission of gas that produces environmental impacts due to toxicity (Ajilowo et al., 2011; Hoffman et al., 1982). In addition, the proximity and concentration of homes to oil wells determine vulnerability due to ecological and health risks. These variables require the establishment of use and change since they are determinants to explain land use differences (Matemilola et al., 2018). Table 4 shows that 60% of the driving factors of change (i.e., explanatory variables) positively influence the change in land use due to oil activity. Therefore, the buffer distance, gas emission, population density, urbanisation and concentration of wells increase the probability of land use by industrial action (Fry, 2013). In comparison, another study presented approximate percentages in using these explanatory variables to establish industrial/commercial land use (Braimoh and Onishi, 2007).

The spatial distribution of land use explained the drivers of change selected above because the ROC test statistic demonstrates the significant relationship between variables (ROC > 0.7). Several authors describe that the ROC value determines a robust correlation and a high capacity to explain the relationship between land use and its different change factors (Braimoh and Onishi, 2007; Huang et al., 2019; Luo et al., 2010; Zhang et al., 2016) . The ROC values for 2014, 2018 and 2027 are 0.821, 0.818 and 0.814, respectively. The decrease in ROC in 2018 compared to 2014 explains the increase in population and its relationship with urban growth due to land use in the Salinas and La Libertad sectors. For the 2027 scenario, the ROC value is a prediction that responds to the scenarios of previous years.

The logistic regression model indicates the strong relationship between change factors and land use. The spatial goodness of fit for oil activity for 2014, 2018 and 2027 is higher than other land uses (e.g., forest 0.79; rice crops 0.77) (Zhou et al., 2016). It implies that the CLUE-S model applied to oil activity presents a high prediction accuracy for land-use change in the study area projected at a time more significant than a decade.

Fig. 5 shows the simulation of the incidence of oil wells in the Salinas and La Libertad sectors for the years 2014, 2018 and 2027. It shows that the concentration of oil wells sitting by the increase in population significantly influences urbanisation. The future scenario for the year 2027 considered the same factors of change, where it stands out that the buffer distance has a tendency to decrease, which shows the incidence of oil wells in land use. The logistic regression reflects the behaviour trend in use and coverage of land by oil activity for the future 2027. The integration of simulation of various land uses, the possibility of proposing different scenarios, statistical relationships between land use and determining factors, and spatial re-presentation are advantages of the CLUE-S model in land use planning (Erdogan et al., 2011; Waiyasusri et al., 2016).

Oil activities contribute to the economic growth and development of a region. However, these activities are associated with significant local impacts on the soil, air, marine-terrestrial ecosystems and water (Uzoma and Mgbemena, 2015), and possible effects on human health (Fry, 2013; Hoffman et al., 1982). In addition, it affects the implementation of efficient land use planning for this industrial activity, which is helpful for economic development. Therefore, territorial planning must undergo continuous environmental, economic, political, and social evaluations to balance land use's economic and ecological benefits in sustainable development (Shu and Xiong, 2019).

The study's limitations are a) 467 identified wells correspond to those used in this work. In addition, the field trip verified that there are unsealed wells inside private infrastructures. Also, wells inside the salt production pools do not appear in the records. b) Another limitation is to verify the current status of the temporarily and permanently abandoned wells due to possible gas emanation. On some occasions, it is variable, influencing the concentration of gases in the sector. c) The data allow the evaluation of three years (2014, 2018 and 2027), but the influence of 2027 is an approximation since the last national census was in 2010. The uncertainties of the research are the reliability of the population's perception data and the statistical due process did not determine causal relationships.

Finally, the following challenges raise: 1) collect data from scenarios in uniform periods, allowing greater precision of the statistical work and contributing to timely decision-making; and 2) land use analysis according to other variables such as marine-coastal zones, natural areas, tourism, and industrial zones by salt extraction.

5. Conclusions

The CLUE-S model was applied to Salinas and La Libertad territories for detecting the influence of oil wells in modifying land use in the area. It demonstrates that the zone with a high presence of oil wells limits this use, due to the growing demand of urban areas, without considering the risks due to the industrial implications.

Oil and biodiversity coexist naturally in the sector, but the concentration of oil wells has an environmental impact in urban areas. In addition, with its associated infrastructures, the oil industry has a spatial and direct effect on the site.

This study recommends implementing participatory development plans and compliance with local and regional regulations to preserve oil resources without affecting the economic and environmental development of the sector. The legal aspect must complement new ordinances considerations and local and national policies, which promote local sustainability. For this reason, the monitoring, control and management of oil wells are recommended through joint planning by governments, the oil industry and the local community.

Ethical statement

This study did not require ethical approval. The research conducts following the principles of the Declaration of Helsinki regarding research with human subjects. With the respondents' consent, participation in the survey was voluntary and anonymous. The data provided treat confidentially.

Declaration of Competing Interests

The authors declare that there are no known competing financial interests or personal relationships that influenced the work reported in this paper.

CRediT authorship contribution statement

Gricelda Herrera-Franco: Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing, Validation, Project administration. **Paulo Escandón-Panchana:** Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing, Validation, Formal analysis, Visualization, Software. **F.J. Montalván:** Investigation, Methodology, Validation. **Andrés Velastegui-Montoya:** Data curation, Methodology, Software, Writing – review & editing, Visualization, Validation.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2022.11.001.

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