MODELING ROAD ENVIRONMENTAL IMPACT USING A STANDARIZED SITE QUALITY MULTIVARIATE INDEX

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ABSTRACT

La aplicación de medidas de mitigación durante el desarrollo de un proyecto carretero busca reducir el impacto ambiental sobre el sistema. Los sistemas muestran una tendencia de deterioro o recuperación, asociada a la presencia humana, por lo que se estimó un índice de presencia humana (IPH) para evaluar el impacto del proyecto bajo distintos escenarios.

Se desarrolló una metodología con base en indicadores ambientales e imágenes de satélite, para evaluar la calidad ambiental de unidades de paisaje a lo largo de carreteras. Utilizando PCA se definió un índice de calidad ambiental multivariado con el que se clasificaron, mediante un análisis de Cluster, las diferentes clases de calidad ambiental en un mapa de la carretera.

Se estimaron relaciones lineales entre indicadores ambientales y el IPH para identificar tendencias en el nivel de participación de éste en la calidad ambiental de cada indicador. Éstas junto con el incremento poblacional en la zona, fueron utilizadas para modelar el comportamiento de la calidad ambiental sin el proyecto, con el proyecto sin mitigación y con el proyecto con mitigación, modelando escenarios al corto (2015), mediano (2020) y largo plazos (2030).

Esta metodología mostró ser útil para representar gráficamente, las variaciones en la calidad ambiental por la construcción del proyecto en un escenario cambiante.

1. INTRODUCTION AND OBJECTIVES

According to Mexico's environmental law, all road projects are required to apply for and obtain an environmental impact authorization and a land use permit. This requires the presentation of an Environmental Impact Statement (EIS); a document which deals with the impacts of construction and operation, the environmental mitigation, control and compensation measures to the satisfaction of authorities having environmental jurisdiction. It is a document that points out project properties, landscape features, construction and operational problems (impacts) arising from its execution, following certain guidelines. Within this document, possible damage on the environment is revised and mitigation or remediation measures suggested to be done during project execution or after the road construction is completed. Project effect on the ecosystems has to be revised under thee circumstances: 1) ecosystem changes without the road project, 2) the construction of the project without any mitigation measure (worst case scenario) and 3) the estimated effect of the project in this environment, considering all of the proposed mitigation measures.

The application of suggested mitigation measures is intended to reduce the environmental impact of roads on different system components. Nevertheless, these systems have their own recovery or deterioration tendencies, strongly related to human actions like urban growth, expansion of agricultural activities, and the presence of other types of roads in the area. Under these circumstances, sometimes the real effect of a road project is diminished in comparison to the strong deterioration induced by other factors (mostly human) within the system, and therefore, related to the increase in human presence within the area.

When estimating environmental consequences of a road project in time, we should not consider it to cause its effects on a static environment; we must address it to a changing landscape. To evaluate a project impact under the worst scenario (without any mitigation measures) and under the real scenario (considering mitigation actions as stated in the environmental impact statement), it is necessary to depart from a basic scenario of the system at present, but also consider its tendency for change (recovery or deterioration) in the future, independently from the projected road.

The objective of our work was to develop a quick and easy to follow procedure to adjust a multivariate statistics methodology to be able to estimate and predict environmental site quality loss in time, due to the construction and operation of a road, in a human induced changing landscape. Such methodology has been applied in several environmental impact assessment studies for the evaluation of time effects of road projects in Mexico with good results.

2. PROCEDURE AND RESULTS

This methodology was developed to model road impact scenario based on standardized environmental indicators and GIS satellite images. The main assumption of the model is that landscape changes along short time periods, few decades, are mainly due to human actions rather than landscape evolution itself.

2.1. Site quality

Study area was delimited in a GIS, considering thematic map overlapping and regionalization procedures. A buffer zone of different size, from 2 km to 40 meters, corresponding to the right of way of several roads was defined, and uniform surfaces (polygons) were delimited within such buffer to separate areas with different site quality; basically identified by vegetation cover and land use differences along each road project.

A multidisciplinary group of experts defined a set of indicative variables for each environmental factor to be evaluated at each polygon, considering field observations and measurements, as well as bibliographic references and image interpretation (table 1). Indicative variable's evaluation criteria was established and standardized at the initial stages of the study, considering gradual deterioration criteria under an ordinary scale of 1 to 9; where 1 represented the worst factor quality condition at a certain polygon and 9 represented the best. All of the environmental variables were considered in each polygon and factor quality for current conditions was evaluated. Standardization was useful to reduce skeweness as each expert assigned a certain quality value to each polygon, reducing subjective decisions. A multivariate site quality matrix was developed for each road (table 1).

Table 1 - Example of a site quality matrix, considering indicative variables for each polygon along the road project in 2010. Values were based on a standardized scale from 1 to 9 and qualification considered field, image recognition and GIS data.

POLYGON	ABIOTIC FACTORS								BIOTIC FACTORS					
	AIR QUALITY		GEO-MORPHOLOGY		SOIL			HIDRO-LOGY	VEGETATION	HABITAT FOR FAUNA				
	Gas emissions	Dust emissions	Morphometry	Rock intemperism	Diversity	Structure	Erosion	Water quality	% of vegetation cover	Large and medium mammals	Small mammals	Birds	Reptiles	Amphibians
1	7.0	7.0	7.0	7.0	7.0	8.0	8.0	8.0	9.0	5.0	7.0	7.0	7.0	3.0
2	7.0	7.0	5.0	5.0	4.0	4.0	5.0	5.0	6.9	5.0	7.0	7.0	7.0	3.0
3	6.0	6.0	5.0	5.0	4.0	4.0	4.0	4.0	1.2	5.0	7.0	9.0	7.0	3.0
4	7.0	7.0	6.0	6.0	5.0	5.0	5.0	5.0	7.8	5.0	7.0	9.0	7.0	3.0
5	7.0	7.0	6.0	6.0	5.0	5.0	5.0	5.0	9.0	7.0	9.0	9.0	9.0	5.0
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
148	6.0	6.0	5.0	5.0	5.0	5.0	5.0	6.0	4.8	5.0	7.0	7.0	7.0	3.0

Once all indicative variables were qualified, a multivariate statistical analysis (PCA) was run or variable reduction and variance maximization, which was obtained considering the first three components (for a 75 to 80% of the total cumulative variance). Selected components represent an integrated multivariate orthogonal index of variables distribution in space. A cluster analysis of the three components helped classify all polygons along road buffer zone within 7 site natural quality classes based on vegetation cover; from very good site quality (vegetation cover from 9 to 8; 100-80%), to very poor quality (vegetation cover values from 1 to 0; 10 to 0%). Some sites had no vegetation cover remaining, and showed different intensities of human presence. At those sites, there are different ways in which human activities affect natural processes; therefore, jointly with such classification for vegetation cover for natural environments, a gradient of human presence evaluation was included. Moderately modified sites showed average negative site quality from 0 to -10; highly modified sites where those with average negative site quality from -10 to -20 and very high modified sites, to even urban, were those showing average site quality lower than -20. A map of actual site quality for each polygon along the buffer zone was drawn (example figure 1).

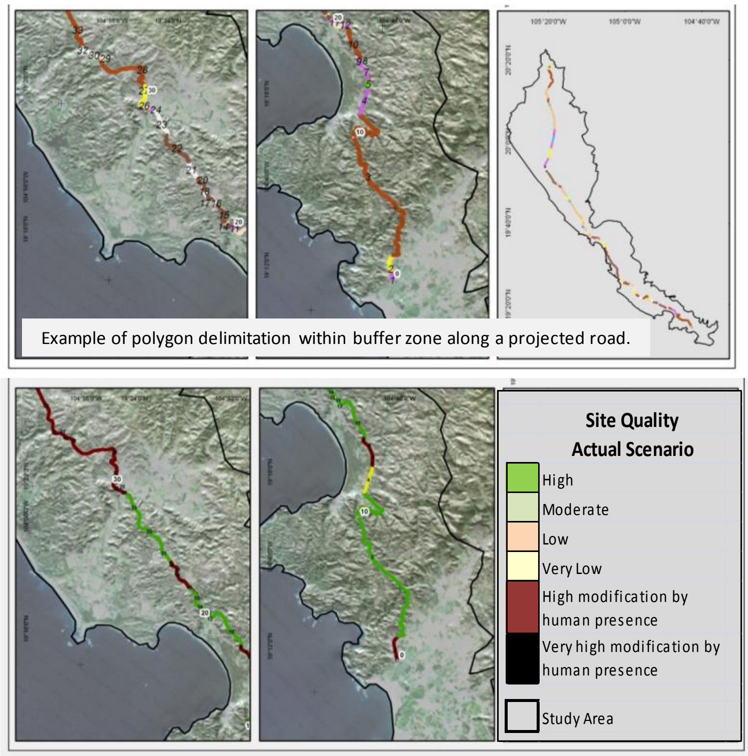

Figure 1 - Polygon delimitation and site quality distribution for present time scenario along buffer zone of projected road

2.2. Factors affecting site quality.

We considered human presence as the main element of site quality deterioration in a cause-effect relationship. Human presence at each site was evaluated through an index (Human Presence Index; HPI) for the year 2010, integrated by GIS and census obtained information, therefore the developed index was calculated considering actual population of all municipalities within the study area, percentage of polygon surface occupied by human activities and human infrastructure with a 20 m ratio or buffer zone such as irrigation channels, water tanks, fences, etcetera.

For population effect on landscape quality, we additionally considered the presence of other roads and the surface they occupied within each polygon, taking into account road width. Road type and access to human penetration constant factors within each polygon were estimated for this model according to the feasibility of each road type to promote human penetration to nearby terrain. From the experience in Mexican roads, trails and dust roads, even though vehicle speed is low, they trend to promote less human penetration within the immediate landscape, whereas state and federal roads trend to promote such access due to a combination of vehicle speed, TDPA (daily average transit within a year) and road design. On the other hand, highways are confined roads with high speed vehicles and high TDPA values; therefore, users cannot stop and exit their cars anywhere they please, reducing human penetration to the immediate landscape units.

Human penetration (access) derived from a road type was scaled in a constant factor with values from 0 to 1; where 1 would be the highest penetration rate considered for a state road (table 2), where users are allowed to get on and off the road at different spots, and services are offered immediately beside the right of way of the road or even inside it.

Table 2 - Estimated feasibility of each road type to promote human penetration to nearby terrain

Type of road	Road width	Access to human penetration constant factors *
Trail	5	0.25
Dust road	7	0.50
Streets	7	0.75
State road	10	1.00
Federal road	10	0.75
A2 Highway	12	0.50
A4 Highway	21	0.25

* Assigned constant values for this model purposes based on the experience in Mexico

In conjunction with actual population of all municipalities, polygon surface occupied by human activities and/or infrastructure and the presence of other roads, a human presence index (HPI) was estimated considering variants in table 3.

Table 3 - Human presence index estimated for each polygon after several criteria

	A	B	C	D	E	F	G	H	I	J	**K**
Polygon	Human presence for each site	% of polygon surface occupied by human activities (agriculture, grassland, urban,etc.)	Qualification of polygon surface occupied by human activities	% of polygon surface occupied by human infrastructure (irrigation channels, water tanks, fences,etc.)	Total population of municipalities within study area for 2010 E1: 57920 Population within study area (estimated 20% of total population) E2: 11584	human presence affected by population incidence	Effect of other roads within polygon	Additive effect of different road types	Total surface of roads within each polygon (considering road width on table 2 and road length within polygon)	Effect of actual project *	Human Presence Estimated Index (HPI) (2010)
	(C+(D*2))/2	(GIS obtained)	(B*10)	(GIS obtained)	A*(E2/E1)	(A+E)	(H+I)/2	(Table 2)	(GIS obtained)		(F+(G/3)+J)
1	5.00	1.00	10.00	0.00	1.00	6.00	0.00	0.00	0.00	0.00	6.00
2	4.73	0.94	9.45	0.00	1.00	5.73	5.28	10.50	0.06	0.00	7.49
3	0.45	0.09	0.86	0.02	0.09	0.54	1.51	3.00	0.01	0.00	1.04
4	3.38	0.67	6.73	0.01	0.67	4.05	1.43	2.75	0.11	0.00	4.53
5	5.03	1.00	10.00	0.03	1.00	6.03	0.00	0.00	0.00	0.00	6.03
6	5.49	1.00	10.00	0.49	1.00	6.49	0.00	0.00	0.00	0.00	6.49
7	5.02	1.00	10.00	0.02	1.00	6.02	0.00	0.00	0.00	0.00	6.02
8	5.02	1.00	10.00	0.02	1.00	6.02	0.00	0.00	0.00	0.00	6.02
9	5.00	1.00	10.00	0.00	1.00	6.00	1.14	2.25	0.04	0.00	6.38
10	0.73	0.14	1.43	0.02	0.14	0.88	0.38	0.75	0.01	0.00	1.00
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148	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.15	0.00	0.00	0.03

* For the present scenario, actual road is not considered as road is unexisting.

Once the human presence index (HPI) was estimated for each polygon, indicator variants of environmental factors were revised in relation to HPI, in order to define trend relationships and use those as prediction equations for human effect on each variant. General linear models were adjusted to the data in order to describe the trend in such relationships and the resulting equations were used to estimate (up to the determination coefficient, R^2 goodness of fit), the effect of the HPI on each environmental factor presented in previous table 1. For variable selection we considered only those with less data dispersion and highest R^2 values. The main consideration here is that HPI is not responsible of all of the observed deterioration on environmental factors, therefore, for modeling purposes, the amount of variance explained by each linear model was considered to be the amount of HPI participation in the observed response.

Total population within municipalities was modified in table 3 for projected population, considering census data (table 4) and a new HPI was estimated considering the previous 2010 index as initial human presence value for each site. New estimated human presence indexes were obtained for different time periods (2015, 2020 and 2030) using census estimated population increase.

Table 4 - Population growth within study area

Year	Estimated population *
2005	51607
2010	57920
2015	60841
2020	63762
2030	69604

*Y=584.2 (x) - 1E+06

Linear models between the quality of each environmental factor indicator variants and HPI were used to calculate new quality values of each variant for future tendencies scenario considering format in previous table 1. Site quality changes for 10, 15 and 20 years were modeled, without the presence of the projected road to identify local tendency to deterioration or recovery at each polygon. Three new site quality matrices were calculated for short (2015), medium (2020) and large (2030) term tendency projections, and site quality maps were done using PCA (considering 75 to 80% of cumulative variance explained by the first 3 components). Theoretical variables (components) considering estimated variables (with their corresponding component weights for each site; polygon) were used in a Cluster analysis to define site quality classes, as explained before (figure 2).

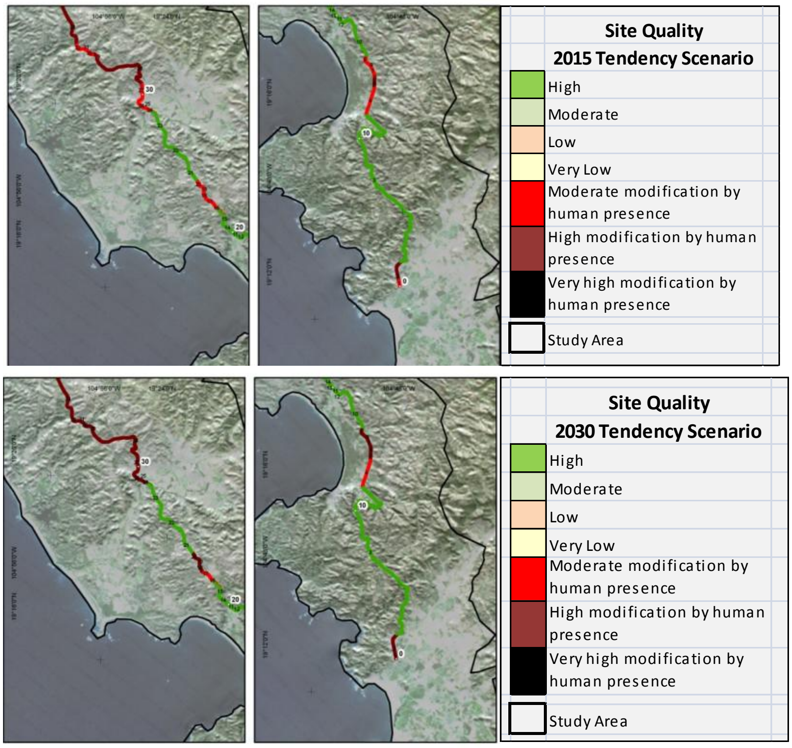

Figure 2 - Estimated site quality distribution for short and long term tendency scenario along projected road

2.3. Estimating project effect

The construction of projected roads considers different activities for each polygon to be occupied, depending on site topography, vegetation cover and project design. Such activities imply environmental impacts of different intensity, extend, persistence in time and cumulative effects; that would affect sites in distinctive ways, as they have different sensibility to construction actions. Therefore, an environmental impact index was estimated for each polygon following Bojorquez-Tapia *et al.* (1998), considering impact magnitude, extend, duration, synergy and cumulative effect, of project construction actions on the environment.

Such index was calculated for the worst possible scenario, considering the road would be built without any mitigation measures, and impact indexes were calculated for short (2015), medium (2020) and large (2030) term effects on each polygon. Following the same procedure, environmental impact indexes were calculated for the actual project, including the mitigation actions considered in the project to reduce the effect either on impact magnitude, occupied surface, duration of impact in the environment, or cumulative effects, as stated in the environmental impact statement (table 5).

Table 5 – Estimating environmental impact index without mitigation measures for short term modeling.

ROAD CONSTRUCTION ACTIONS TO BE DONE AT EACH SITE		IMPACT SENSITIVITY OF SITE		ENVIRONMENTAL IMPACT INDEX WITHOUT MITIGATION MEASURES *									
		% cover	human presence	TYPE	M	E	D	S	A	C	MED_{ij}	SAC_{ij}	I_{ij}
POLYGON		evaluation criteria				1+sup pol/sup tot (GIS obtained)	short term (constant)[1]	other roads present	summarized human presence	within natural protected areas			
1	Widening of actual road	0.00	0.00	-1	3	1.166	8	0.00	6.0	1	0.337	0.259	-0.447
2	Widening of actual road	0.55	6.00	-1	2	1.685	8	5.28	7.5	1	0.333	0.510	-0.583
3	Hill cut, leveling and filling	9.14	7.48	-1	7	8.152	8	1.51	1.0	1	0.856	0.130	-0.873
4	Widening of actual road	3.27	1.02	-1	4	1.828	8	1.43	4.5	1	0.431	0.257	-0.536
5	Widening of actual road	0.00	4.52	-1	6	1.278	8	0.00	6.0	1	0.438	0.259	-0.543
6	Hill cut, leveling and filling	0.00	6.00	-1	4	1.124	8	0.00	6.0	1	0.367	0.259	-0.476
7	Widening of actual road	0.00	6.00	-1	3	1.240	8	0.00	6.0	1	0.344	0.259	-0.454
8	Widening of actual road	0.00	6.00	-1	3	1.205	8	0.00	6.0	1	0.341	0.259	-0.451
9	Widening of actual road	0.00	6.00	-1	3	1.225	8	1.14	6.4	1	0.343	0.316	-0.481
10	Hill cut, leveling and filling	8.57	6.38	-1	7	2.212	8	0.38	1.0	1	0.554	0.087	-0.583
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148	Hill cut, leveling and filling	0.10	6.36	-1	3	1.267	8	1.07	6.4	5	0.347	0.460	-0.565

* After Bojorquez Tapia et al 1998.

$$MED_{ij}=\frac{1}{27}(M_{ij}+E_{ij}+D_{ij})$$

$$SAC_{ij}=\frac{1}{27}(S_{ij}+A_{ij}+C_{ij})$$

where $\varphi = 1\text{-}SAC_{ij}$.

[1] short term constant = 8

medium term constant = 6

large term constant = 4

Mitigation effects were included in the modeling algorithm as the effect of actual project (table 3) estimated for tendency scenario due to human presence presented before, and maps for estimated site quality considering the multivariate cluster defined index, were made (figure 3).

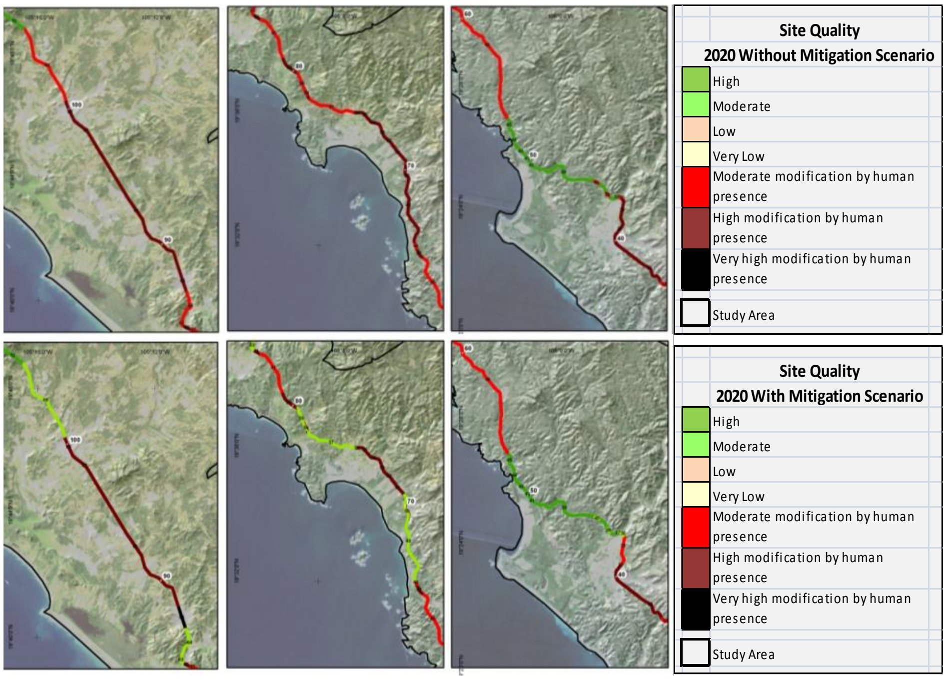

Figure 3 - Estimated site quality distribution for medium term scenario under two mitigation considerations

3. CONCLUSIONS

This method has proven to be useful for evaluating, in a graphic way, expected site quality variations attributed to the road project within a changing environment. Presence of people, human activities and infrastructure are considered to be the main changing force in site quality reduction, and new roads can promote the increase of actual trends of change.

Results that can be visualized for each of the landscape units under analysis (polygons) along the projected road up to a width according to the considered buffer zone; which makes this method very easy to adjust to any kind of road project.

Using this procedure to previously analyze the possible effect of mitigation measures, is useful for hot spots detection along the projected road, and identifying the need to increase such measures in order to reduce projected site quality negative effects.

Mitigation measures can be modified or increased in order to contain or even reverse expected deterioration tendencies.

REFERENCES

1. Bojorquez-Tapia, L. A., E. Ezcurra and O. Garcıa (1998). Appraisal of environmental impacts and mitigation measures through mathematical matrices. Journal of Environmental Management 53, 91–99.