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2019

The International Mathematical Modeling Challenge (IM²C) Summary Sheet
(Your team's summary should be included as the first page of your electronic submission.)

Summary:

The world is inevitably running out of resources at our current rate, and mankind does not have a choice. The Earth has a maximum carrying capacity for the amount of human beings it can sustain based on current conditions and circumstances. Our aim in this report was not only to determine the Earth's current carrying capacity based on our current distribution, but also to discuss the ways mankind can realistically elevate the carrying capacity of the Earth moving forward.

The first part of the task required us to identify the most crucial factors that limit the Earth's carrying capacity for human life under current conditions. Physiological needs were placed in paramount importance as humans physically need to be sustained before any of their psychological or mental needs are tended to. Thus, the requirements of food, shelter and water were selected to be analysed further as they were deemed the most essential to human survival. The world was split up into 13 different regions, to allow for greater differences in quantity of food, shelter and water around the Earth.

We are currently only using a percentage of our total resources available. Therefore, we had to identify what proportion of available resources we are using currently and keep these proportions constant. These factors were broken down and analysed further in depth to produce a model which determines the current carrying capacity of the Earth. Current conditions were defined as the current distribution of resources on the Earth. There were two resources identified in our analysis which influenced the requirements. These were land and water. For our first model, we realised to reach maximum carrying capacity, we must use up at least one of the resources completely, which will limit the population capacity. We modelled this off current conditions, by keeping the current distribution of resources the same as it is presently. The amount of land used for food and shelter was considered and the limit was found based on current conditions. The amount of water used for agricultural purposes and daily household water usage was also investigated and the limit was found based on current conditions. Thus, each region of the world ended up having a limiting requirement, whether it be food, land or shelter. Using this model, it was determined that the Earth, under current circumstances, could sustain approximately 9.9 billion human beings.

The second part of the task required us to identify what mankind can do to improve the carrying capacity of the world based on future conditions. To do so the two resources were considered separately and the limits for the populations were found for each resource individually. It was found that the world could sustain up to about 24 billion people.

Introduction

The world today is currently home to 7.53 billion people. However, with the current rapid increase in the world's population, the need to identify how many human beings can live on this Earth is more important than ever. The world has limited resources for unlimited needs and wants. Every extra person brings about a greater consumption of resources which further decreases the Earth's ability to sustain more life. Our goal through this investigation is to determine the Earth's carrying capacity for human life. The carrying capacity was defined as the maximum population size of a biological species in an environment that can sustain the species indefinitely, given the food, habitat, water, and other necessities available in the environment.

The majority of previous attempts at determining the earth's carrying capacity have been based solely on one human requirement, either food or water. Firstly, for greater accuracy, the world was split into regions. We identified several physiological requirements to sustain human life. These are food, shelter and water. Each requirement can be modelled using two resources, land and water. Using data from secondary sources, it is possible to determine the quantity of each resource available in the world and the amount of each that we currently use. To reach maximum carrying capacity, one of the resources must be utilised completely, which will limit the population capacity. Current conditions are the current distribution of resources around the world and this was kept constant to simulate the present-day carrying capacity. Thus, a spreadsheet was produced, using the latest data and distribution of resources to model the maximum carrying capacity for our existing conditions.

In addition to the current conditions, we have to identify the most efficient and suitable way to raise the carrying capacity of the Earth in perceived future condition. This was achieved by considering two resources separately and the limits for the populations were found for each resource individually. It was determined that the world could sustain up to about 24 billion people.

Overall, this problem requires us to complete four tasks:

1. Identify the major factors that are crucial to limiting the Earth's carrying capacity
2. Define and determine current conditions
3. Analyse the major factors and mathematically model the maximum carrying capacity of the Earth using the conditions.
4. Realistically optimise the carrying capacity using the described factors for future conditions.

Assumptions

Assume that sparsely vegetated land is habitable land and can be used either for agriculture or living

Assume that for food to sustain humans, the proportions of livestock products compared to crop products has to be present in everyone's diet.

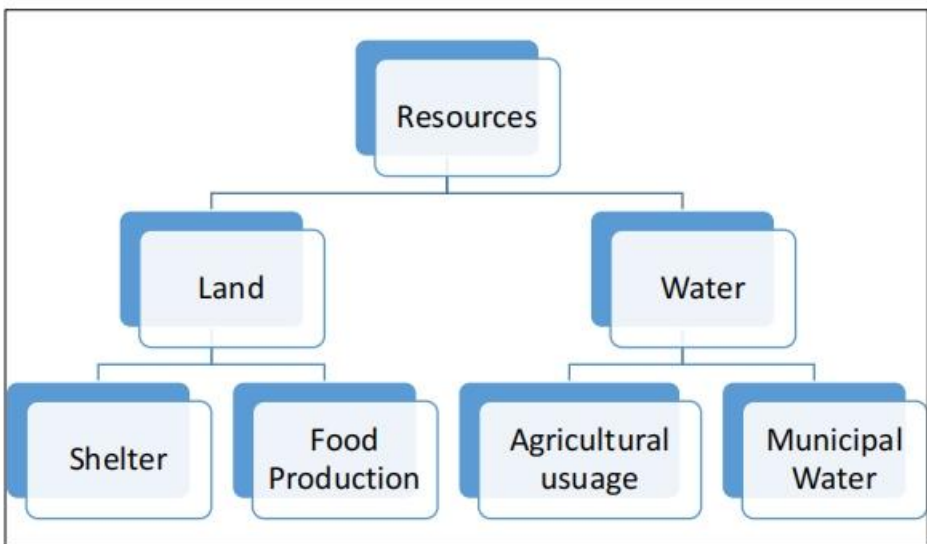
Assume that people can survive with the required amount of food, water and shelter.

Identification of Major Factors for Human Life:

Firstly, using Maslow's hierarchy of needs (McLeod, 2018), we identified how the needs were categorized: Physiological, safety, love and belongingness, esteem and self-actualization. The Earth's carrying capacity for human life depends on its ability to sustain human survival. Physiological needs were identified as the biological requirements for human survival, such as food, drink, shelter, clothing, warmth, sex and sleep. Thus, it was considered the most important and crucial category because without satisfying these basic requirements, human life is physically limited. The other categories were of less importance because they did not directly limit the growth of human life but rather addressed psychological and secondary needs of humans. Of the physiological examples, food, water and shelter are the most essential for human function and the other biological needs are dependent on the availability of these. Things like sleep and warmth were less tangible than food, and therefore were more difficult to model. Therefore, these are the three crucial parameters that will limit the carrying capacity of the Earth while the others were not considered highly influential in determining maximum capacity.

Within physiological needs, the two most important resources needed to satisfy the three biological requirements (food, water and shelter) were land and water.

Land, as a resource, is used for both living and agricultural purposes. These requirements are labelled as shelter and food production. Similarly, water, as a resource, is used for both food irrigation and daily human use. The flow chart below describes the split in resources into two categories, followed by the three requirements. The common factor across both resources is food. The maximum limit of food is dependent on which resource caps out first as food needs both water and land to be produced. If there isn't enough land suitable for agriculture, then land becomes the limiting resource and water is in excess. Likewise, if there isn't enough water to irrigate the available land or hydrate the livestock, then water becomes the limiting resource and land is in excess.



Model 1

Reasoning

This question requires us to determine the current carrying capacity of human beings on the earth, given today's conditions. Conditions were defined by how resources are currently distributed across the requirements. Carrying capacity is defined as the maximum number of people the Earth can hold based on the way we are currently distributing resources. The resources available have a fixed quantity. We are currently only utilising a percentage of our resources, which we classify as our resources in use. This means that the population has room for growth because the resources are what limit the factors which in turn limit the population. To reach carrying capacity, our resources in use will eventually equal the total available amount of resource in either category (land and water).

In this document a factor will refer to the requirements for life and a resource will refer to the available materials.

For this model the world was split into 13 regions namely: Africa, Brazil, Canada, China, Europe (excluding Russia), Greenland, India, Latin America and the Caribbean (excluding Brazil), Middle East, Oceania, Rest of Asia (excluding China and India), Russia and USA.

Land, as a resource, was divided into habitable and uninhabitable land. Uninhabitable land was classified as the addition of all barren land, snow and glaciers, inland water bodies and mangroves.

$$\text{Uninhabitable Land} = \text{Barren land} + \text{snow and glacier} + \text{mangroves} + \text{water bodies}$$

It was assumed that sparsely vegetated land could be inhabited and used for either agriculture or living. The amount of habitable land used was calculated by the sum of all grazing, crop and urban areas.

$$\text{Used Habitable Land} = \text{Agriculture Land} + \text{Urban Land}$$

$$\text{Used Habitable Land} = \text{Crop} + \text{grazing} + \text{Urban Land}$$

Remaining habitable land could be calculated by subtracting uninhabitable, used habitable land and forests from total land area.

$$\text{Remaining habitable Land} = \text{Total land} - \text{Uninhabitable land} - \text{Used Habitable land} - \text{forests}$$

Forests are defined as habitable land but are classified as used in some regions and unused in other regions. Based on the current conditions, some countries are cutting down their forests while some are preserving their forestry. By looking at trends over the past 30 years, it could be determined whether a region's forests will be cut down in the future. Because forests are defined as habitable, a region that cuts down its forests will have more unused land for agriculture or living. Thus, to calculate total unused habitable land, some regions will include all forest area while other will not include forest area.

$$\text{Total Unused habitable Land} = \text{Remaining habitable land} + \text{forests}^*$$

*when forest area is trending downwards

	Land (Million Hectares)								
Region	Total	Urban	Grazing	Crop	Forest	Uninhabitable	Remaining	Forest Trend	Total Unused Area
Africa	3037.00	3.87	889.15	273.62	620.46	930.73	319.18	Stable	319.18
Brazil	851.60	3.92	195.99	79.61	492.55	16.78	62.76	Down	555.31
Canada	998.50	0.84	14.60	50.74	347.02	183.70	401.59	Down	748.62
China	959.70	8.41	424.14	103.59	209.86	194.34	19.36	Stable	19.36
Europe Excluding Russia	1018.00	14.64	99.83	191.82	215.79	36.57	459.35	Stable	459.35
Greenland	216.60	0.00	0.00	0.00	0.00	38.12	178.48	Stable	178.48
India	328.70	3.11	10.30	169.00	70.86	34.41	41.02	Stable	41.02
Latin American and the Caribbean excluding brazil	1162.34	5.38	364.69	108.92	442.50	115.66	125.19	Down	567.70
Middle East	720.80	3.46	201.32	35.19	14.28	459.82	6.72	Stable	6.72
Oceania	852.60	1.05	349.51	48.71	264.79	46.22	142.33	Stable	142.33
Rest of Asia excluding India and China	2054.76	5.28	307.96	196.89	324.89	217.95	1001.80	Down	1326.68
Russia	1710.00	2.60	98.76	124.51	814.89	116.51	552.74	Stable	552.74
United States of America	983.40	11.97	251.00	159.72	310.37	97.03	153.31	Stable	153.31
World	14894.00	64.52	3289.47	1562.41	4128.26	2487.84	3361.49		5070.78

Table 1 Inhabitable and Uninhabitable Land split

	Land (Million Hectares)			
Region	Urban	Grazing	Crop	Forest
Africa	4.92	1132.41	348.48	620.46
Brazil	11.71	585.35	237.76	0.00
Canada	10.31	179.75	624.74	0.00
China	8.72	439.45	107.33	209.86
Europe Excluding Russia	36.59	249.54	479.51	215.79
Greenland	0.00	0.00	0.00	0.00
India	3.81	12.62	207.01	70.86
Latin American and the Caribbean excluding brazil	11.75	796.92	238.01	0.00
Middle East	3.56	206.96	36.18	14.28
Oceania	1.42	474.10	66.07	264.79
Rest of Asia excluding India and China	19.00	1108.86	708.95	0.00
Russia	8.96	340.44	429.20	814.89
United States of America	16.31	342.03	217.65	310.37
World	137.07	5868.43	3700.88	2521.30

Table 2 Total land available for each area

In order to determine the distribution of the unused habitable land, the land was split up in the same proportions as it is currently.

General Formula:

$$\text{Total Urban land} = \text{current urban land} + \frac{\text{current urban land}}{\text{crop} + \text{urban} + \text{grazing}} * \text{total unused area}$$

$$\text{Total Cropland} = \text{current cropland} + \frac{\text{current cropland}}{\text{crop} + \text{urban} + \text{grazing}} * \text{total unused area}$$

$$\text{Total grazing land} = \text{current grazing land} + \frac{\text{current grazing land}}{\text{crop} + \text{urban} + \text{grazing}} * \text{total unused area}$$

For example, African Croplands:

$$\text{Total Cropland} = 273.62 + \frac{273.62}{1166.64} * 319.18$$

$$\text{Total Cropland} = 348.48 \text{ million hectares}$$

Water, as a resource, was divided into municipal water and agricultural water. The type of water considered was “blue water,” which is renewable water. Rainwater was not considered as it varies greatly and is dependent on weather cycle. Additionally, rainwater is derived from renewable water so it is still being taken into account to an extent. Renewable water is used for municipal, agricultural and industrial water. Municipal water is defined as the water used by households for drinking and daily use (e.g. showering, cleaning and cooking). Agricultural water is used for crop irrigation and watering livestock. Industrial water is used in industry and was not considered as it does not limit any of the requirements directly. The total renewable fresh water resources were found per region in cubic kilometres. We determined water stress, the ratio of withdrawal to water supplies, should not exceed 40% to maintain a stable environmental function (Maddocks, 2013). We then determined total usage of water in each region per year, and found the usage of water in each category. The total usage was adjusted for water stress. To find the amount of water each category is assigned, the proportions of current water usage are kept the same.

$$\text{Possible Municipal water} = \frac{\text{current municipal water}}{\text{total used}} * \text{adjusted total water}$$

$$\text{Possible Industrial water} = \frac{\text{current industrial water}}{\text{total used}} * \text{adjusted total water}$$

$$\text{Possible Agricultural water} = \frac{\text{current agricultural water}}{\text{total used}} * \text{adjusted total water}$$

	Water (km ³ per year)					
Region	Renewable freshwater resources	Adjusted water resource	Agricultural	Industrial	Municipal	Total used
Africa	3931.00	1572.40	180.35	11.73	28.01	220.10
Brazil	5660.64	2264.25	44.90	12.72	17.16	74.78
Canada	3259.20	1303.68	4.75	33.12	0.93	38.80
China	2812.44	1124.98	385.20	133.50	75.50	594.20
Europe (ex Russia)	6576.00	2630.40	98.69	146.56	65.73	310.99
Greenland	603.00	241.20	0.00	0.00	0.00	0.00
India	1446.16	578.46	558.40	17.00	72.10	647.50
Latin America and the Caribbean (ex Brazil)	7798.36	3119.35	194.37	26.90	35.54	256.81
Middle East	484.00	193.60	218.67	16.95	14.45	250.07
Oceania	902.00	360.80	13.85	4.13	4.46	22.44
Rest of Asia (Ex India and China)	1328.40	531.36	771.40	77.97	49.68	899.06
Russia	6278.00	2511.20	13.20	39.60	8.20	61.00
US	2817.80	1127.12	175.10	248.40	55.10	478.60
World	43897.00	17558.80	2658.89	768.58	426.87	3854.34

Table 3 Water usage per region

	Water (km ³ per year)			
Region	Adjusted water resource	Possible agricultural	Possible industrial	Possible municipal
Africa	1572.40	1288.46	83.79	200.14
Brazil	2264.25	1359.52	385.15	519.59
Canada	1303.68	159.57	1112.83	31.28
China	1124.98	729.29	252.75	142.94
Europe (ex Russia)	2630.40	834.77	1239.65	555.98
Greenland	241.20	0.00	0.00	0.00
India	578.46	498.86	15.19	64.41
Latin America and the Caribbean (ex Brazil)	3119.35	2360.94	326.73	431.67
Middle East	193.60	169.29	13.12	11.19
Oceania	360.80	222.67	66.40	71.73
Rest of Asia (Ex India and China)	531.36	455.91	46.08	29.36
Russia	2511.20	543.41	1630.22	337.57
US	1127.12	412.37	584.99	129.76
World	17558.80	9035.07	5756.91	2525.63

Table 4 Possible future water supply per category