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2019

The International Mathematical Modeling Challenge (IM^{2}C) Summary Sheet

(Your team's summary should be included as the first page of your electronic submission.)

Summary:

The world is inevitability 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 needs to be sustain 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 the 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.

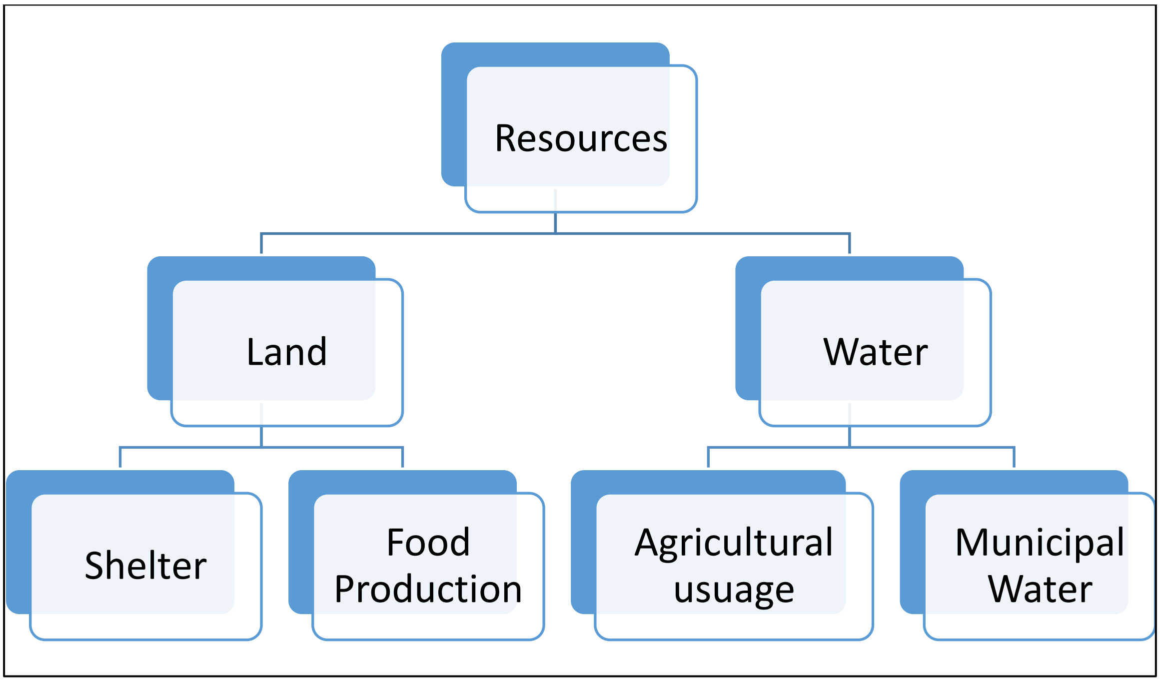
Assume that people can survive with the required amount of food, water and shelter.

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.

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

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.

$$Used\ Habitable\ Land = Agriculture\ Land + Urban\ Land$$

$$Used\ Habitable\ Land = Crop + grazing + Urban\ Land$$

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

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

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.

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

*when forest area is trending downwards

Region	Land (Million Hectares)								
	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:

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

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

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

For example, African Croplands:

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

$$Total\ Cropland = 348.48\ million\ hectares$$

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 in 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.

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

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

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

	Water (kmÂ³ 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 (kmÂ³ 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

The next population limiting factor was water available for consumption:

$$Population\ limiting\ factor_{water} = \frac{Water\ available\ for\ consumption}{consumption\ rate_{water}}$$

The water consumption was calculated using the formula:

$$Consumption\ rate_{water} = \frac{total\ municipal\ water\ used\ currently}{current\ population}$$

The final limiting factor was shelter:

$$Population\ limiting\ factor_{shelter} = Available\ urban\ land * urban\ density + Available\ rural\ land * rural\ density$$

Population density can be calculated:

$$Population\ density_{urban} = \frac{current\ urban\ population}{current\ urban\ land}$$

Rural population is defined as the people who live on agricultural land

$$Population\ density_{rural} = \frac{current\ rural\ population}{current\ agricultural\ land}$$

$$Population\ density_{rural} = \frac{current\ rural\ population}{grazing\ land + cropland}$$

Data was found for the percentage of people living in urban and rural areas in each regions. So, the total current population was multiplied by the respective percentages to find urban and rural population.

Region	Municipal Water (kmÂ³)	Population	Consumption Rate (kmÂ³/person)	Population possible due to municipal
Africa	2.80E+01	1.22E+09	2.30E-08	8.69E+09
Brazil	1.72E+01	2.09E+08	8.20E-08	6.34E+09
Canada	9.31E-01	3.71E+07	2.51E-08	1.25E+09
China	7.55E+01	1.39E+09	5.45E-08	2.62E+09
Europe (ex Russia)	6.57E+01	5.97E+08	1.10E-07	5.05E+09
Greenland	0.00E+00	5.62E+04	0.00E+00	5.62E+04
India	7.21E+01	1.34E+09	5.38E-08	1.20E+09
Latin America and the carribean (ex Brazil)	3.55E+01	4.47E+08	7.94E-08	5.43E+09
Middle East	1.45E+01	4.11E+08	3.52E-08	3.18E+08
Oceania	4.46E+00	3.88E+07	1.15E-07	6.24E+08
Rest of Asia (Ex India and China)	4.97E+01	1.59E+09	3.12E-08	9.42E+08
Russia	8.20E+00	1.45E+08	5.67E-08	5.95E+09
US	5.51E+01	3.27E+08	1.68E-07	7.71E+08
World	4.27E+02	7.75E+09	5.51E-08	3.92E+10

Table 5 Population limited by water

Region	Population	Rural	Urban	Rural Percentage	Urban Percentage
Africa	1216000000	717440000	498560000	59	41
Brazil	209300000	28655263	180644737	13.691	86.309
Canada	37060000	6911690	30148310	18.65	81.35
China	1386000000	582674400	803325600	42.04	57.96
Europe (ex Russia)	596900000	146550529.9	450349470.1	24.55	75.45
Greenland	56171	7541.51846	48629.48154	13.246	86.754
India	1339000000	889096000	449904000	66.4	33.6
Latin America and the carribean (ex Brazil)	447396700	100030365.6	347366334.4	19.59	80.41
Middle East	411000000	113970300	297029700	27.73	72.27
Oceania	38820000	11529540	27290460	29.7	70.3
Rest of Asia (Ex India and China)	1593500000	865417949.8	728082050.2	54.3092532	45.6907468
Russia	144500000	37148060	107351940	25.708	74.292
US	327200000	58706224	268493776	17.94	82.06
World	7746732871	3499431640	4247301231	45.17	54.83

Table 6 Rural and Urban population and percentages

	Land (million hectares)				Density (People/million hectares)		
Region	**Urban Land**	**Grazing**	**Crop**	**Agricultural**	**Urban Density**	**Rural Density**	**Population**
Africa	4.92338575	1132.411656	348.4812327	1480.892889	128968348.7	617009.0166	1548685195
Brazil	11.71229094	585.3539869	237.7573286	823.1113156	46065486.6	103977.1786	625117173.6
Canada	10.31261511	179.7463993	624.7384687	804.484868	35991604.59	105772.6579	456260068.1
China	8.715927279	439.4513492	107.3341273	546.7854764	95495020.64	1104108.327	1436038053
Europe (ex Russia)	36.58840368	249.5421988	479.5113332	729.053532	30768282.85	502487.2424	1492102452
Greenland	0	0	0	0	0	0	0
India	3.809798573	12.61646515	207.0056753	219.6221404	144645322.1	4958600.159	1640087922
Latin America and the Caribbean (ex Brazil)	11.75377979	796.9219808	238.0068235	1034.928804	64580600.54	211209.4205	977652870.3
Middle East	3.559230139	206.9557886	36.17831276	243.1341013	85788541.7	481871.5593	422500571.7
Oceania	1.423152851	474.0979786	66.07348735	540.1714659	26011696.39	28952.74254	52658065.26
Rest of Asia (Ex India and China)	19.00348411	1108.858133	708.9457619	1817.803894	137954212.4	1714220.731	5737727804
Russia	8.957113266	340.4397465	429.2018025	769.641549	41315838.93	166388.1442	498129878
US	16.31124516	342.0347359	217.6499204	559.6846563	22431034.83	142936.4358	445877438.2
World	137.0704266	5868.430419	3700.884274	9569.314693	65828814.58	721251.7188	15332837492

Table 7 Land densities and population limit for shelter

			Water (kmÂ³ per year)		Land (million hectares)		Water (kmÂ³ per year)		Land (million hectares)	
	Total Available Resource		Agricultural							
REGION	**Water (kmÂ³ per year)**	**Land (million hectares)**	**Grazing**	**Crops**	**Grazing**	**Crops**	**Grazing**	**Crops**	**Grazing**	**Crops**
Africa	1572.40	1485.82	0.27	0.55	0.76	0.23	429.06	859.40	1132.41	348.48
Brazil	2264.25	834.82	0.20	0.40	0.70	0.28	452.72	906.80	585.35	237.76
Canada	1303.68	814.80	0.04	0.08	0.22	0.77	53.14	106.43	179.75	624.74
China	1124.98	555.50	0.22	0.43	0.79	0.19	242.85	486.43	439.45	107.33
Europe (exc. Russia)	2630.40	765.64	0.11	0.21	0.33	0.63	277.98	556.79	249.54	479.51
Greenland	241.20	178.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
India	578.46	223.43	0.29	0.58	0.06	0.93	166.12	332.74	12.62	207.01
Latin America and the Caribbean (exc. Brazil)	3119.35	1046.68	0.25	0.50	0.76	0.23	786.19	1574.75	796.92	238.01
Middle East	193.60	246.69	0.29	0.58	0.84	0.15	56.37	112.92	206.96	36.18
Oceania	360.80	541.59	0.21	0.41	0.88	0.12	74.15	148.52	474.10	66.07
Rest of Asia (exc. India and China)	531.36	1836.81	0.29	0.57	0.60	0.39	151.82	304.09	1108.86	708.95

Russia	2511.20	778.60	0.07	0.14	0.44	0.55	180.95	362.45	340.44	429.20
US	1127.12	576.00	0.12	0.24	0.59	0.38	137.32	275.05	342.03	217.65
WORLD	17558.80	9884.86	2.35	4.71	6.97	4.84	3008.68	6026.39	5868.43	3700.88

The final factor to be considered is the food:

$$Population\ limiting\ factor_{food} = \frac{Food\ available\ for\ consumption}{consumption\ rate_{food}}$$

$$= \frac{food\ produced - food\ exported + food\ imported}{consumption\ rate_{food}}$$

$$= \frac{(usable\ agricultural\ land \times yield\ of\ land) - food\ exported + food\ imported}{consumption\ rate_{food}}$$

Usable agricultural land is dependent on water and land available for use and so the limiting of these two will define this variable. Water defines usable land in the following way:

$$Usable\ agricultural\ land_{water\ factor} = \frac{water\ for\ agriculture}{usage\ rate\ of\ water\ for\ agriculture}$$

Land defines usable land in the following way:

$$Usable\ agricultural\ land_{land\ factor} = total\ agricultural\ land$$

If:

$$Usable\ agricultural\ land_{water\ factor} < Usable\ agricultural\ land_{land\ factor}$$

Then:

$$Usable\ agricultural\ land = Usable\ agricultural\ land_{water\ factor}$$

Else:

$$Usable\ agricultural\ land = Usable\ agricultural\ land_{land\ factor}$$

The food consumption was calculated using the formula:

$$Consumption\ rate_{food} = \frac{total\ food\ currently\ consumed}{current\ population}$$

NOTE: Food consumption and the following calculations were done for both livestock and crops

The possible amount of food produced is:

$$Possible\ food\ produced = \frac{usable\ agricultural\ land}{tonnes\ produced\ per\ million\ hectares}$$

However, although this is the possible food produce in a region, food is also imported and exported. This would affect the amount of food each region has for consumption. Values for food exported and imported were determined through research.

Each regions exports and imports were determined as a proportion of the world's imports and exports.

$$Resulting\ total\ food = possible\ food\ produced - food\ exported + food\ imported$$

$$Food\ imported = \frac{Regions\ percentage\ imports}{total\ exports}$$

$$Total\ exports = \sum Food\ produce\ \times percentage\ export$$

Since there are two values for resulting total food, one for livestock produce and one for crops produced the lower value is taken as it is assumed that a human should have a balance of both types of food.

i.e If:

$$Livestock\ food\ produced < Crop\ food\ produced$$

Then:

$$Resulting\ total\ food = Livestock\ food\ produced$$

Else:

$$Resulting\ total\ food = Crop\ food\ produced$$

To calculate the possible number of people:

$$Possible\ population_{food} = \frac{Resulting\ total\ food}{current\ consumption\ rate}$$

	Production ratios					
	Land (tonnes per million hectares)		Water (kmÂ³ per million hectares)		Limiting	
REGION	**Grazing**	**Crops**	**Grazing**	**Crops**	**Grazing**	**Crops**
Africa	79042.6399	2720222.384	0.06754431	0.21948947	Land	Land
Brazil	323159.2976	3308694.854	0.0762894	0.18782304	Land	Land
Canada	898103.6314	1842994.843	0.10831616	0.03116414	Land	Land
China	378181.282	16088328.99	0.3024283	1.23821312	Land	Land
Europe (exc. Russia)	2560226.813	3717700.944	0.3292244	0.17133147	Land	Land
Greenland	0	0	0	0	Unknown	Unknown
India	17193277.11	3659125.178	18.0525478	1.1002565	Water	Land
Latin America and the Caribbean (exc. Brazil)	210897.0675	3661665.742	0.17748426	0.59427333	Land	Land
Middle East	230208.6305	5540031.449	0.36168857	2.06901698	Water	Land
Oceania	108050.4296	1265194.21	0.01319388	0.09467023	Land	Land
Rest of Asia (exc. India and China)	438823.5188	5407756.889	0.83413701	1.30466906	Water	Water
Russia	436381.2555	1502086.005	0.04450949	0.03530461	Land	Land
US	585875.1211	4350695.81	0.23230704	0.36506825	Land	Land
WORLD	23442226.8	53064497.3	20.5996706	7.4112802	0	0

	Produces		Ratio			
			Export (of produce)		Import (of world export)	
REGION	**Grazing**	**Crops**	**Grazing**	**Crops**	**Grazing**	**Crops**
Africa	89508806.76	947946449.6	0.00860202	0.02663916	0.058086	0.125710736
Brazil	189162583.3	786666449.7	0.11025693	0.35479724	0.003722	0.016668183
Canada	161430893.9	1151389776	0.14393248	0.58273224	0.011639	0.011734652
China	166192274.6	1726826752	0.01144347	0.01224592	0.106539	0.165719763
Europe (exc. Russia)	638884628.4	1782679736	0.18590315	0.34960743	0.505005	0.299383939
Greenland	0	0	0	0	0	0
India	158214229.2	757459678.4	0.00764721	0.04679913	0.000182	0.01171657
Latin America and the carribean (exc. Brazil)	168068508.8	871501431.9	0.03882403	0.3591426	0.073786	0.093935214
Middle East	35880773.85	200428990.5	0.04269319	0.09834079	0.078594	0.103947607
Oceania	51226490.24	83595793.61	0.17856547	0.49441925	0.010731	0.007303605
Rest of Asia (exc. India and China)	79869259.39	1260449778	0.01534066	0.0794822	0.143782	0.20623813
Russia	148561524	644698020.7	0.0080482	0.21048336	0.027351	0.013032966
US	200389642.3	946928596.8	0.05908832	0.25457232	0.030876	0.048078532
WORLD	2087389615	11160571453	0.81034514	2.86926164	1.050292	1.103469898

	Resulting Food		Consumption Rate		Possible Population		
REGION	**Grazing**	**Crops**	**Grazing**	**Crops**	**Grazing**	**Crops**	**Minimum**
Africa	100251970.7	1237740519	0.05779664	0.61209757	1.73E+09	2022129434	1.73E+09
Brazil	169043760.7	549331876.8	0.3026034	1.25843039	5.59E+08	436521463.9	4.37E+08
Canada	140502749.4	509846319.5	0.35381333	2.52353834	3.97E+08	202036288	2.02E+08
China	185407440.4	2120994280	0.11572972	1.20249373	1.6E+09	1763829807	1.6E+09
Europe (exc. Russia)	620210898.7	1909734617	0.42817745	1.19474352	1.45E+09	1598447353	1.45E+09
Greenland	0	0	0	1	0	0	0
India	157040426.7	751374388.4	0.13226022	0.4618409	1.19E+09	1626911762	1.19E+09
Latin America and the carribean (exc. Brazil)	176168437.4	793921340.9	0.17191021	0.89142216	1.02E+09	890623296	8.91E+08
Middle East	49926976.58	441224133.3	0.11276436	0.4743875	4.43E+08	930092239.4	4.43E+08
Oceania	44206161.49	60568155.59	0.97281376	1.58752117	45441546	38152659.98	38152660
Rest of Asia (exc. India and China)	107143080.9	1677124576	0.08480588	0.66817501	1.26E+09	2510007937	1.26E+09
Russia	152787146.1	541662032.8	0.29823853	1.2942368	5.12E+08	418518490.3	4.19E+08
US	194668939.4	826357501.1	0.44942763	2.1237419	4.33E+08	389104486.7	3.89E+08
WORLD	2097357988	11419879742	3.48034113	15.292629	1.07E+10	12826375218	1.01E+10

	Population			Final Population	Limiting Factor
REGION	**Food**	**Water**	**Shelter**		
Africa	1643342732	8687320447	1548685195	1548685195	Shelter
Brazil	622162053.9	6337368827	625117174	622162053.9	Food
Canada	381828250.2	1245215701	456260068	381828250.2	Food
China	1540336600	2624063543	1436038053	1436038053	Shelter
Europe (exc. Russia)	1497344131	5048651746	1492102452	1492102452	Shelter
Greenland	0	0	0	0	
India	1196413318	1196234477	1640087922	1196234477	Water
Latin America and the carribean (exc. Brazil)	989547564.6	5434239342	977652870	977652870.3	Shelter
Middle East	406624958.5	318192488	422500572	318192488	Water
Oceania	53874105.68	624220340.5	52658065.3	52658065.26	Shelter
Rest of Asia (exc. India and China)	1183845862	941789224.9	5737727804	941789224.9	Water
Russia	491424026.7	5948662295	498129878	491424026.7	Food
US	452516623.2	770567836	445877438	445877438.2	Shelter
WORLD	**10459260226**	**39176526267**	**1.5333E+10**	**9904644595**	

After the maximum possible population was determined for each requirement (water, food, shelter) for each region, the smallest, maximum population was considered from each of the three requirements and this requirement was the limiting condition. For example, Africa's limiting factor was shelter and so the carrying capacity of Africa was limited by the area required for shelter.

Adding all the minimum maximum populations from each region the world's carrying capacity using current conditions was approximately 9.9 billion people.

Strengths and Limitations:

- Our first model takes into account the instantaneous distribution of resources throughout the world rather than considering trends. As our population grows in the future, the way in which we divide our resources will change, however, our model does not take this into account as it is modelling current conditions
- Our model considers livestock and crop products separately, so one category is limiting, then food becomes limiting as a whole. In reality, this is not always the case as humans can be sustained on different foods and proportions.

Model 2

The aim of the second model was to optimise the conditions to fine the highest realistic carrying capacity of the earth. This carrying capacity was defined by the same factors, the only difference being the ratios into which the resources are split. That is, lowering and raising the amounts of land for urban versus the land for crops, or the municipal water and grazing water, ect. The other factors were treated in two ways:

1. For consumption rates, the values were standardised between regions to ensure an equal living standard. These rates were the consumption of crop, the consumption of livestock/products, the consumption of water, and the densities of urban and rural land.
2. For yields it was decided that they would be kept the same as today's data, as they are dependent on the conditions of the region. These yields were the productivity of land for both livestock and crops, and the water required per land, to produce either livestock or crops.

To determine the maximum carrying capacity, and the change of conditions to optimise this, the maximum amount of each resource must be in use, and the possible 'population' due to the factors must be equal. That is, land is a defining resource, in both the necessities of food and shelter, so the land used for the production of food should result in a population equal to the population as a result of the land used for shelter.

However, it is unlikely that there will be a balance in a region's water and land such that they both result in an equivalent population. Instead, these resources were considered separately, and distributed in their optimum way, to find an equivalent maximum population across that resources defined factors, and then the lower maximum population is the carrying capacity of the region.

To determine the maximum population as a result of land the following equations were considered:

$$P_{Shelter} = Density_{Urban} \times Land_{Urban} + Density_{Rural} \times Land_{Agricultural}$$

$$P_{Grazing} = \frac{Yield_{Grazing} \times Land_{Grazing}}{Consumption_{Grazing}}$$

$$P_{Crop} = \frac{Yield_{Crop} \times Land_{Crop}}{Consumption_{Crop}}$$

$$Land_{Total} = Land_{Urban} + Land_{Grazing} + Land_{Crop}$$

As all the populations (P) are to be equal this is a 4-way simultaneous equation where the unknowns are:

- Population (P)
- $Land_{Urban}$
- $Land_{Grazing}$
- $Land_{Crop}$

All other variables are constants.

To determine the maximum population as a result of water the following equations were considered:

$$P_{Living} = \frac{Water_{Municipal}}{Consumption_{Water}}$$

$$P_{Grazing} = \frac{Yield_{Grazing} \times Water_{Grazing}}{Water\ Useage_{Grazing} \times Consumption_{Grazing}}$$

$$P_{Crop} = \frac{Yield_{Crop} \times Water_{Crop}}{Water\ Useage_{Crop} \times Consumption_{Crop}}$$

$$Water_{Total} = Water_{Muincipal} + Water_{Grazing} + Water_{Crop}$$

As all the populations (P) are to be equal this is a 4-way simultaneous equation where the unknowns are:

- Population (P)
- $Water_{Municipal}$
- $Water_{Grazing}$
- $Water_{Crop}$

All other variables are constants.

When each of these simultaneous equations are solved for the two resources and 13 regions the following data is obtained:

			Useage							Food				Water			
			Water (kmÂ³ per year)				Land (million hectares)			Population							
	Total Available Resource		Agricultural		Industrial	Municipal	Agricultural		Urban					Population			
REGION	Water (kmÂ³ per year)	Land (million hectares)	Grazing	Crops			Grazing	Crops		Grazing	Crops		Minimum		Population		Population
Africa	1572.4	1485.816275	556.6518	414.5876	83.79478	517.3658	1231.773	251.5966	2.447188	1.6E+09	1.6E+09	Crops	1595979020	11247083282	1595979020		1595979020
Brazil	2264.254376	834.8236065	307.551	422.1187	385.1473	1149.437	556.4512	267.4251	10.94729	2.95E+09	2.95E+09	Crops	2947670641	24987767509	2947670641		2947670641
Canada	1303.679687	814.7974831	53.1356	106.4308	1112.832	31.28159	235.8378	565.4979	13.46171	3.47E+09	3.47E+09	Crops	3471963597	680034619.5	3471963597		680034619.5
China	1124.977314	555.5014037	310.4004	203.3893	252.7507	358.4369	486.9578	56.32428	12.21929	3.02E+09	3.02E+09	Crops	3018746294	7792106025	3018746294		3018746294
Europe (ex	2630.4	765.6419357	140.8509	34.73972	1239.648	1215.161	167.5701	567.8267	30.24515	7.03E+09	2.51E+09	Crops	2511213643	26416544900	7032508317		2511213643
Greenland	241.2	178.4758617	0	0	0	0	0	0	0	0	0	Crops	0	0	0		0
India	578.4629005	223.431939	175.6298	258.2061	15.18744	129.4395	8.813701	203.7769	10.84134	2.48E+09	2.48E+09	Crops	2484003607	2813901699	2484003607		2484003607
Latin Amer	3119.345624	1046.682584	898.4006	1004.938	326.7333	889.2739	808.1369	229.0298	9.515826	2.79E+09	2.79E+09	Grazing	2793770538	19332040327	2793770538		2793770538
Middle Eas	193.6	246.6933315	64.08659	83.54977	13.12176	32.84187	202.543	41.41349	2.736831	6.69E+08	7.45E+08	Grazing	668635184.1	713953739.1	764318004.1		668635184.1
Oceania	360.8	541.5946188	25.25525	84.49307	66.39698	184.6547	380.413	159.86	1.321544	6.74E+08	6.74E+08	Crops	673778457.9	4014232541	673778457.9		673778457.9
Rest of Asi	531.3597857	1836.807379	222.6051	166.7083	46.08384	95.96251	1286.23	513.5782	36.99907	1.92E+09	2.3E+09	Grazing	1919653588	2086141559	9252173909		1919653588
Russia	2511.2	778.5986623	180.9546	362.4526	1630.222	337.5711	317.1959	453.4339	7.968892	2.27E+09	2.27E+09	Crops	2268970348	7338503207	2268970348		2268970348
US	1127.120313	575.9959015	123.8864	60.37622	584.991	357.8667	338.4806	224.2825	13.23279	3.25E+09	2.4E+09	Crops	2397014286	7779710040	3250679111		2397014286
																	23959470226

It can be seen from the table above that the overall carrying capacity of the world is 24 billion under the given requirements for living.

Conclusion:

In conclusion, our modelling has been successful in achieving two values for the maximum carrying capacity of the Earth. Firstly, it was determined that under our current conditions, the Earth could hold approximately 9.9 billion people. Secondly, it was found that when optimised to ensure every human being had a healthy standard of living, the maximum carrying capacity was found to be 24 billion. Further investigation into other secondary factors influencing carrying capacity would be interesting in the future.

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