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Estimation and Prediction of Population Using Mathematical Models in Tanzania

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Abstract: *The purpose of this study focused on exploring and determining an effective and plausible mathematical growth model for prediction of future Population size of United Republic of Tanzania for the next two censuses of 2022 and 2032.Tanzania's Population is growing faster as science and Technology growing which become a burden to Government budget in allocation of the limited resources available. The Exponential, Logistic growth model and Method of Least square (MLS) were employed by using previous census data from 1980 to 2016 inclusive and analyzed by using MATLAB (R2017a) software. The study determined that Logistic model is more effective and reliable with Average relative error of 0.72%, carrying Capacity (K) of 728133426 and vital coefficients of* $\mathrm{r} = 0.032$ *and* $\frac{r}{K} = 4.39479892796461 \times 10^{-11}$*.These plausible parameters used to predict Tanzania's Population to be 667853660 and 88896969 in 2022 and 2032 respectively.*

Keywords: *modeling, estimation, model fitting, parameters, prediction, mathematical models.*

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I. Introduction

We can not have sustainable development of a nation without stabilizing the population growth, as human Population increase the demands of resources increase as well [Venkatesha,2017]. Chidumayo N. 2018 indicates that population studies are well addressed qualitatively neither quantitatively. However little has been done including [Blossfeld. H. P. et al ,2014] exemplify that population studies are a better fit for social sciences as opposed to natural sciences where as mathematical models are used to transform different data sets into reality. The use of systematic and reliable examples from developed and developing countries portrays that chance of uncertainty demarcates the expected outputs from either sides. Developed countries are able to control the birth and mortality rate due to a stable economy and database established as described in [Hayami, Y., & Godo, Y. (2005) and Gertler, P. J., & Molyneaux, J. W. (1994)]. This is contrary from developing countries become a burden due to the limited budget and unstable economy which lead to failure in control of birth and mortality rates [Smith, L. C., & Haddad, L. J, 2000].In any country there is a need to have a desirable, monitored and known population that help the decision and policy makers to advise the government to reserve and allocate its resources accordingly [Wali.A.2011]. In the same view Richard P and Robert E 1997 argued that population growth runs contrary to food supply in the entire population relying on a theory that developed to justify the necessity of population studies. Population grows exponentially that means it increases as the birth rate rises due to the dynamic population we have in the world. There are countries that have managed to reduce the birth rate in order to manage the resources they have for the future generation[Nargund G. ,2009.], to mention a few: Switzerland, Greece, Italy and Lithuania.

Studies are being done upon population growth in order to reflect on economic growth, employment, savings and environment, conservation of assets, investments and environmental impacts [Richard and Robert, 1997; Ehrlin and Lui, 1997; Walker,2016]. Recent studies about population foster for solving problems that are presumed to be happening in future that will lead to some difficulties in resource allocation especially in developing countries [Guria, 2015; Gao, 2015]. In order to obtain good and reliable estimates we need to employ mathematical models for the sake of ob- taining precise and accurate estimations of parameters and predictions as stated in [Kapur and Khan, 1979; Vankatesha, 2017].

Rapid population growth in developing countries especially African countries directly influence the poverty in economy, policy, culture, education and environment of that country this lead to unsuitable exploring and cost of natural resources.

Like other country in Africa, United Republic of Tanzania is a developing country in East Africa situated just south of the Equator. It has an area of 945, 087km^2. Bounded by Uganda, Lake Victoria, and Kenya to the north, by the Indian Ocean to the east, by Mozambique, Lake Nyasa, Malawi, and Zambia to the south and southwest, and by Lake Tanganyika, Burundi, and Rwanda to the west. Tanzania as a country its population is growing as fast as the way technology grows [Larsen, P. O., & von Ins, M. 2010]. Tanzania has a high population among the East African Community (EAC) Countries. This continuous and constant increase has great impact to the national resources and demand especially land utility, settlements and basic needs.

According to http://www.worldometers.info(2019) Tanzania's share of the World population is 0.79% with approximately 60 million population size. Population is the vital element of the nation rendering its projection has become one of the most serious problems in third world countries because when not well addressed it significantly affects planning, decision making for the socio-economic and demographic development[Wali.A. et al , 2011]. Basing on these evidences, there is a need to have mathematical model that estimate and predict the population growth and allocation of resources. As [Kapur and Khan, 1979; Vankatesha, 2017] argued that In order to obtain good and reliable estimates we need to employ mathematical models for the sake of obtaining precise and accurate estimations of parameters and prediction of population growth. Therefore, in this study Exponential model, Logistic model and Method of Least the square were used to estimate the model parameters and predict the future population size of the Tanzania

II. Material and Methods

The study used previous data obtained from the National bureau of Statistics in Tanzania from 1980 to 2016.The study simulated and used the real data to estimate and fit them in two models namely exponential and Logistic growth model and Method of Least Square. The results obtained in the previous step were used to predict the future population of the united republic of Tanzania. The experimental processes were done in a windows machine installed with MatLab version (R2017a) and results were presented in terms of numerals, tables and graphs.

2.1. Exponential Model.

Thomas R.Malthus (1798), proposed a mathematical model of population growth. The exponential model is the model that relies on the assumption that population grows at a constant rate proportional to the original population size. This assumption is reasonable for the ideal condition that unlimited environment, adequate nutrition, absence of predators and immunity from diseases are excluded in the model and the model is expressed in simple differential equation as follows;

$$\frac{dP}{dt} = \beta P$$

Where P is the total population size and β is the constant growth rate defined as the difference between the birth rate and death rate for a certain population size. We determine the solution of the first order differential equation as shown here below

$$\frac{dP}{dt} = \beta P$$

$$\int_{P_o}^{P(t)} \frac{dp}{p} = \int_{t_O=0}^{t} \beta dt$$

$$lnP(t) - lnP_o = \beta t$$

$$ln\frac{P(t)}{P_o} = \beta t$$

$$P(t) = P_o Exp(\beta t) = P_o e^{\beta t} \tag{1}$$

The model is referred as an exponential law,

The parameter β can be estimated from equation (2);

$$\beta = \frac{lnP(t) - lnP_o}{t} \tag{2}$$

In equation (1) as $t \to \infty$, $P(t) \to \infty$

2.2. Logistic growth model

A Belgium Mathematician Verhulst, described that the population growth does not depends on the population size but also on how far this size is from its upper boundary which known as carrying capacity. The logistic model is an extension of exponential model that includes the ideal conditions that some were excluded in the model as follows

$$\frac{dP}{dt} = rP\left(1 - \frac{P}{K}\right) \quad where\ r, K > 0$$

Where K is the maximum sustainable population(carrying capacity) and r is the growth rate, r and r/K are vital constants. For small population $P \ll K$ then $P^2 \to 0$ and the logistic model reduces to exponential growth signifying that as P is greater K then the rate of growth becomes negative and population decreases.

We can find the solution of the non-linear differential equation as follows;

$$\frac{dP}{P\left(\frac{K-P}{K}\right)} = rdt$$

$$\int_{P_o}^{P(t)} \frac{K}{P(K-P)} dP = \int_0^t rdt$$

$$\int_{P_o}^{P(t)} \left[\frac{1}{P} + \frac{1}{K-P}\right] dP = \int_0^t rdt$$

It follows,

$$\frac{P(t)(K-P)}{P_o(K-P(t))} = e^{rt}$$

By rearrangement gives

$$P(t) = \frac{K}{1 + \left(\frac{K}{P_o} - 1\right)e^{-rt}} \qquad (3)$$

Taking a limit of the equation (3) gives;

$$P\max = \lim_{t\to\infty} P(t) = \lim_{t\to\infty}\left(\frac{K}{1+\left(\frac{K}{P_o}-1\right)e^{-rt}}\right) = K(carrying\ capacity)$$

Determination of the parameters r and K by estimation by using equation (3)

Let P_O : Population at $t = t_O = 0$,

P_T : Population at $t = T$ and

P_{2T}: Population at $t = 2T$, then

$$\frac{1}{K}[1 - e^{-rT}] = \frac{1}{P_T} - \frac{e^{-rT}}{P_o} \qquad (4)$$

$$\frac{1}{K}[1 - e^{-2rT}] = \frac{1}{P_{2T}} - \frac{e^{-2rT}}{P_o} \qquad (5)$$

By dividing equation (5)to (4) gives

$$\frac{[1 - e^{-rT}]}{[1 - e^{-2rT}]} = \frac{\frac{1}{P_T} - \frac{e^{-rT}}{P_o}}{\frac{1}{P_{2T}} - \frac{e^{-2rT}}{P_o}}$$

$$\to 1 + e^{-rT} = \frac{\frac{1}{P_T} - \frac{e^{-rT}}{P_o}}{\frac{1}{P_{2T}} - \frac{e^{-2rT}}{P_o}}$$

So that $e^{-rT} = \frac{P_o(P_{2T} - P_T)}{P_{2T}(P_T - P_o)}$

This implies that, If $0 < \frac{P_o(P_{2T}-P_T)}{P_{2T}(P_T-P_o)} < 1$ then

$$r = \frac{1}{T} ln\left(\frac{P_o(P_{2T}-P_T)}{P_{2T}(P_T-P_o)}\right)$$

By direct substitution into equation (4) yields;

$$K = \frac{P_T(P_oP_T - 2P_oP_{2T} + P_TP_{2T})}{(P_T)^2 - P_oP_{2T}} \qquad (6)$$

Both exponential and logistic models originated from observations of biological re- production process. However, human population is believed to be dynamic, and then the growth rate cannot be constant as stipulated in the two models and one method by the constants. As per our study, we must show the implementation of this model based on constant growth rate and explain in mathematical terms however, the reality remains in controversy.

2.3. Method of least square

A French mathematician Adrien-Marie Legendre(1805),The method of least squares is an ideal algorithm in regression analysis that has most important application in data fitting. This algorithm involves minimization of sum of squared residuals for the sake of maximizing objective function of the model. In various areas of experimental sciences, maximization theory is associated with accuracy and precision of the predicted output is attained by error reduction. The essence and necessity of using this method is to fit the exponential function that has similar properties with the previous models.

$$P = Ae^{\alpha t}$$

Where A and α are constants which are required to be evaluated.
For many observed data point, the method of least square is reasonably most systematic procedure to fit the unique curve. Suppose we have set of observation, ((t_0, P_0), (t_1, P_1), ...(t_{n-1}, P_{n-1})) we transform the exponential $P(t) = Ae^{\alpha t}$ into linear as follows

$$lnP = lnAe^{\alpha t} = lnA + \alpha t$$

Let $lnP = y$ and $lnA = \gamma$, Generally we have

$$y_i = \alpha t_i + \gamma \qquad (7)$$

We define the error associated in the set of data with the equation (7) by

$$E(\alpha,\gamma) = \sum_{i=0}^{n-1}(y_i - (\alpha t_i + \gamma))^2$$

For n − 1 times the variance of the data set $\{(y_0 - (\alpha t_0 + \gamma), ..., (y_{n-1} - (\alpha t_{n-1} + \gamma)\}$
The main target to determine the value of α and γ is to minimize the error.
By using the concept of Calculus,

$$\frac{\partial E}{\partial \alpha} = \frac{\partial E}{\partial \gamma} = 0$$

By using this condition there is no need to about boundary even if $|\alpha|$ and $|\gamma|$ become very large.
Differentiating $E(\alpha,\gamma)$ yields,

$$\frac{\partial E}{\partial \alpha} = 2\sum_{i=0}^{n-1}\left(y_i - (\alpha t_i + \gamma)\right)(-t_i)$$

$$\frac{\partial E}{\partial \gamma} = 2\sum_{i=0}^{n-1}\left(y_i - (\alpha t_i + \gamma)\right)$$

Since $\frac{\partial E}{\partial \alpha} = \frac{\partial E}{\partial \gamma} = 0$, then

$$\sum_{i=0}^{n-1}\left(y_i - (\alpha t_i + \gamma)\right)t_i = 0$$

$$\sum_{i=0}^{n-1}\left(y_i - (\alpha t_i + \gamma)\right) = 0$$

By rearrangement it gives

$$\begin{cases} \left(\sum_{i=0}^{n-1}(t_i)^2\right)\gamma + \left(\sum_{i=0}^{n-1} t_i\right)\alpha = \sum_{i=0}^{n-1} y_i t_i \\ \left(\sum_{i=0}^{n-1} t_i\right)\gamma + \left(\sum_{i=0}^{n-1} 1\right)\alpha = \sum_{i=0}^{n-1} y_i \end{cases} \tag{8}$$

It is invertible matrix; therefore it is easy to determine the value of γ and α

III. Results

To estimate the population of United Republic of Tanzania,

(a) We need to determine the parameter (growth rate) using exponential growth model in equation (1).By using the actual population of united republic of Tanzania with $(t_o, P_o) = (0, 18683157)$ and $(t_1, P_1) = (1, 19277108)$

$$\beta = \frac{\ln(19277108) - \ln(18683157)}{1} = 0.0312$$

Hence, the general solution for exponential model is given by;

$$P(t) = 18683157e^{0.0312t}$$
$$0 \le t \le 36$$

(b)By using equation (6) we estimate the Carrying Capacity of United republic of Tanzania at $(P_o, P_T, P_{2T}) = (18683157, 32451713, 55572201)$

The better choice of P_T, and P_{2T} lead to better approximation of K.

$$K = \frac{P_T(P_oP_T - 2P_oP_{2T} + P_TP_{2T})}{(P_T)^2 - P_oP_{2T}}$$

$$K = \frac{32451713(18683157 \times 32451713 - 2 \times 18683157 \times 55572201 + 32451713 \times 55572201)}{32451713^2 - 18683157 \times 55572201}$$

$$\lim_{t\to\infty} P(t) = \lim_{t\to\infty}\left(\frac{K}{1+\left(\frac{K}{P_o}-1\right)e^{-rt}}\right) = K = 728133426\ (carrying\ capacity)$$

The estimated value of K can be used to estimate r in the equation (3)

We have $K = 728133426$, $(t_o, P_o) = (0, 18683157)$ and $(t_1, P_1) = (1, 19277108)$ then;

$$P(t) = \frac{K}{1+\left(\frac{K}{P_o}-1\right)e^{-rt}}$$

Direct substitution of values gives

$$19277108 = \frac{728133426}{1+\left(\frac{728133426}{18683157}-1\right)e^{-r}}$$
$$\to r = 0.032$$

And $\frac{r}{K} = \frac{0.032}{728133426} = 4.39479892796461 \times 10^{-11}$

The general solution for Logistic growth model with constant growth rate of $r = 3.2\%$ is given by $P(t) = \frac{728133426}{1+37.97e^{-0.032t}}$

(c)From equation (8) we have to determine α and γ

$$\begin{cases} \left(\sum_{i=0}^{n-1}(t_i)^2\right)\gamma + \left(\sum_{i=0}^{n-1} t_i\right)\alpha = \sum_{i=0}^{n-1} y_i t_i \\ \left(\sum_{i=0}^{n-1} t_i\right)\gamma + \left(\sum_{i=0}^{n-1} 1\right)\alpha = \sum_{i=0}^{n-1} y_i \end{cases}$$

$$\begin{cases} 666\gamma + 16206\alpha = 11644 \\ 36\gamma + 666\alpha = 623 \end{cases}$$

$\gamma = 16.7$ and $\alpha = 0.03$ but $\ln A = \gamma$, $A = e^{\gamma} = e^{16.7} = 17983283$
The general solution is given by $P(t) = Ae^{\alpha t} = 17983283e^{0.03t}$

The results shown in the Table 1, 2 and 3 by using all models as Attached in Appendices

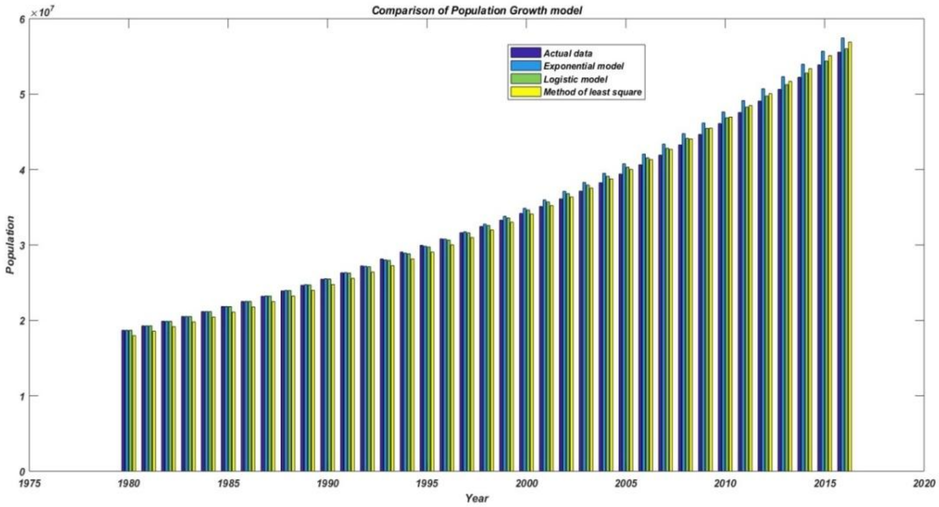
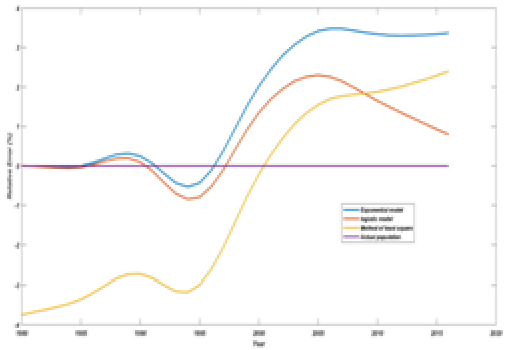


Figure 1.
The figure 1. Shows the Comparison of growth models



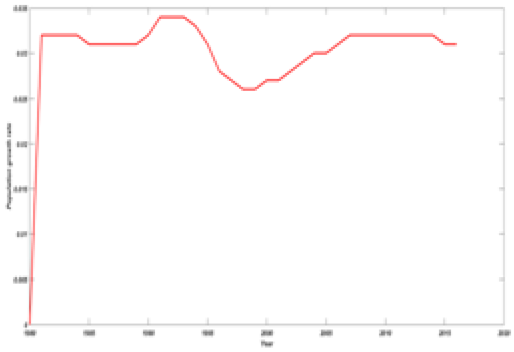


Figure 2. **Figure 3**
Figure 2. Shows the Comparison of Relative error in each model from 1980 to 2016 and Figure 3. Shows the actual population growth rate from 1980 to 2016

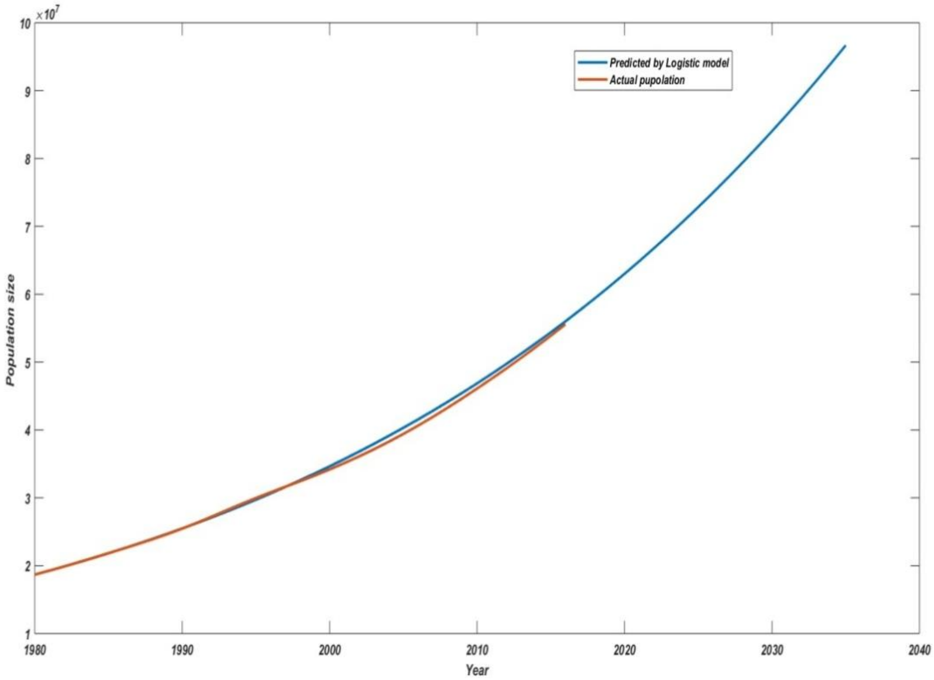


Figure 4.

Figure 4. Shows the graph of predicted Tanzania's human population from 1980 to 2035

IV. Discussion

Figure 1. Shows that from 1980 to 2016, Tanzania has a monotonic increase of population. But from 1980 to 1995, actual populations, predicted population size by exponential and logistic model are very closer to each other. This indicates that the variation is very small. By using the fitting least the square method from the base year show a great deviation by lowering the initial population, as time increases also the population increases faster than the actual population size. Method of least the square is not reliable method to use in estimation as assumed in this study, but is reliable in fitting experimental data and stochastic process .As time (t) increases the absolute error increases in Exponential growth model become more bigger which is not good in measurement and prediction. This model is not reliable when time (t) is large.

Figure 2.Shows that the Logistic growth model is more reliable and effective model in Human population estimation with mean relative error of 0.72% this is results also supported by many different previous related works such as [Wali.A 2011]. Figure 3.shows the actual growth rate of United Republic of Tanzania which used is a point of reference in Figure 2 to test which model is reliable and useful to Tanzania population. All models show the great deviation from the actual population from 1995 to 2005. This can be observed from figure3. This is due to low growth rate of the actual population can be seen in figure 3.

To determine what model is better and acceptable is not easy, but in this study we proposed and applied a logistic growth model which also is deterministic model by using same data to predict future population. This study help us also to predict the next two census of 2022 and 2032.which expected to be conducted by Tanzania Government to be 66785360 and 88896969 respectively

V. Conclusion

We have discussed and implemented the procedures of fitting, estimating and predicting population growth of the United Republic of Tanzania. We used Exponential, Logistic and the method of Least Squares to determine the parameters of the model that triggered the best prediction of the future population in more than 20 years. Finally, it was observed that the population parameters from the two models have a slightly significant difference that leads to a better selection of which model to use. We predicted the population size of Tanzania for the next two censuses of 2022 and 2032. Therefore, we conclude that a logistic model is the best fit for deterministic trend of the model leading a precise, plausible and accurate prediction

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Year	Actual population	exponential model	Logistic model	Method of least square
1980	18683157	18683157	18684460	17983283
1981	19277108	19275260	19275948	18568054
1982	19891548	19886128	19885635	19171841
1983	20524666	20516356	20514049	19795261
1984	21173603	21166556	21161727	20438954
1985	21836999	21837363	21829224	21103578
1986	22511243	22529429	22517105	21789813
1987	23198533	23243427	23225949	22498364
1988	23909954	23980054	23956351	23229954
1989	24660575	24740026	24708916	23985335
1990	25459604	25524082	25484268	24765278
1991	26315013	26332987	26283040	25570583
1992	27219619	27167527	27105883	26402074
1993	28149328	28028516	27953461	27260604
1994	29070615	28916790	28826451	28147051
1995	29960776	29833216	29725548	29062323
1996	30811854	30778685	30651459	30007357
1997	31635251	31754118	31604906	30983121
1998	32451713	32760464	32586624	31990615
1999	33291540	33798702	33597367	33030870
2000	34178042	34869845	34637898	34104952
2001	35117019	35974934	35708998	35213960
2002	36105808	37115045	36811462	36359030
2003	37149072	38291287	37946097	37541335
2004	38249984	39504809	39113727	38762086
2005	39410545	40756788	40315186	40022532
2006	40634948	42048445	41551326	41323965
2007	41923715	43381037	42823007	42667717
2008	43270144	44755861	44131108	44055165
2009	44664231	46174256	45476514	45487729
2010	46098591	47637602	46860128	46966876
2011	47570902	49147325	48282860	48494122
2012	49082992	50704893	49745634	50071030
2013	50636595	52311823	51249384	51699215
2014	52234869	53969680	52795052	53380344
2015	53879957	55680078	54383592	55116140
2016	55572201	57444684	56015965	56908379

Table1.

Year	RE Exponential%	RE Logistic %	RE Method LS %	Rate of growth	Pop. density
1980	0.00	0.01	-3.75	0.000	19.77
1981	-0.01	-0.01	-3.68	0.032	20.40
1982	-0.03	-0.03	-3.62	0.032	21.05
1983	-0.04	-0.05	-3.55	0.032	21.72
1984	-0.03	-0.06	-3.47	0.032	22.40
1985	0.00	-0.04	-3.36	0.031	23.10
1986	0.08	0.03	-3.20	0.031	23.82
1987	0.19	0.12	-3.02	0.031	24.54
1988	0.29	0.19	-2.84	0.031	25.30
1989	0.32	0.20	-2.74	0.031	26.09
1990	0.25	0.10	-2.73	0.032	26.94
1991	0.07	-0.12	-2.83	0.034	27.84
1992	-0.19	-0.42	-3.00	0.034	28.80
1993	-0.43	-0.70	-3.16	0.034	29.78
1994	-0.53	-0.84	-3.18	0.033	30.76
1995	-0.43	-0.79	-3.00	0.031	31.70
1996	-0.11	-0.52	-2.61	0.028	32.60
1997	0.38	-0.10	-2.06	0.027	33.47
1998	0.95	0.42	-1.42	0.026	34.33
1999	1.52	0.92	-0.78	0.026	35.22
2000	2.02	1.35	-0.21	0.027	36.16
2001	2.44	1.69	0.28	0.027	37.15
2002	2.80	1.95	0.70	0.028	38.20
2003	3.07	2.15	1.06	0.029	39.30
2004	3.28	2.26	1.34	0.030	40.47
2005	3.42	2.30	1.55	0.030	41.70
2006	3.48	2.26	1.70	0.031	42.99
2007	3.48	2.15	1.77	0.032	44.36
2008	3.43	1.99	1.81	0.032	45.78
2009	3.38	1.82	1.84	0.032	47.25
2010	3.34	1.65	1.88	0.032	48.77
2011	3.31	1.50	1.94	0.032	50.33
2012	3.30	1.35	2.01	0.032	51.93
2013	3.31	1.21	2.10	0.032	53.57
2014	3.32	1.07	2.19	0.032	55.26
2015	3.34	0.93	2.29	0.031	57.00
2016	3.37	0.80	2.40	0.031	58.80

Table2

Year	Actual	Projected by Logistic	Year	Actual	Projected by Logistic
1980	18683157	18684460	2009	44664231	45476514
1981	19277108	19275948	2010	46098591	46860128
1982	19891548	19885635	2011	47570902	48282860
1983	20524666	20514049	2012	49082992	49745634
1984	21173603	21161727	2013	50636595	51249384
1985	21836999	21829224	2014	52234869	52795052
1986	22511243	22517105	2015	53879957	54383592

1987	23198533	23225949	2016	55572201	56015965
1988	23909954	23956351	2017		57693139
1989	24660575	24708916	2018		59416090
1990	25459604	25484268	2019		61185800
1991	26315013	26283040	2020		63003255
1992	27219619	27105883	2021		64869444
1993	28149328	27953461	2022		66785360
1994	29070615	28826451	2023		68751997
1995	29960776	29725548	2024		70770349
1996	30811854	30651459	2025		72841408
1997	31635251	31604906	2026		74966164
1998	32451713	32586624	2027		77145601
1999	33291540	33597367	2028		79380699
2000	34178042	34637898	2029		81672430
2001	35117019	35708998	2030		84021753
2002	36105808	36811462	2031		86429621
2003	37149072	37946097	2032		88896969
2004	38249984	39113727	2033		91424718
2005	39410545	40315186	2034		94013772
2006	40634948	41551326	2035		96665014
2007	41923715	42823007			
2008	43270144	44131108			

Table.3

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