Sustaining Aquifers and their Water Economies

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Sustaining Aquifers and their Water Economies

1. Abstract

A long-established practice of managing aquifers relies on pumping restrictions to curtail drawdowns, in spite of their high economic impacts and the serious disputes that can follow such decisions. This paper applies an empirical, quantitative hydro-economic model that helps aquifer managers reverse aquifer drawdowns while minimizing the economic losses from pumping restrictions. We develop and present an innovative optimization framework for identifying pumping restrictions that minimize economic losses from current economic activities while eliminating the unsustainable threats from falling aquifers. We investigate several alternative measures to reduce economic costs of pumping limitations, including a proportional sharing of reductions across uses, several priority allocation methods, and permitted pumping caps augmented by permit trading. Results show that the largest reduction in costs of aquifer protection occurs when permitted pumping caps are combined with trading. The model is applied to improve management of two heavily-pumped aquifers in Kenya, but are generalizable to many aquifers worldwide experiencing unsustainable pumping.

2. Background

Debates over policies to control hydrologic stress from heavy groundwater pumping, elevated by growing water scarcity in arid regions, continue unabated as population growth increases water demand for industrial, agricultural, and domestic purposes. Meanwhile climate change and variability reduce water availability and reliability^{1,2}. Climate variability and related drought stress heighten the importance of groundwater as an essential source of water to serve expanding populations and as a mechanism to balance future supplies and demands. The need to find economically and hydrologically viable approaches to sustain groundwater aquifers has been recognized for some time. For decades aquifer management plans have attempted to control drawdown of aquifers through pumping restrictions regardless of economic disputes and sometimes violent behaviors associated with those use restrictions^{3,4}.

Numerous works have analyzed policies for protecting the sustainability of aquifers from climate stress and unsustainable pumping^{5,6,7}. Some policy proposals for groundwater use and protection include water-saving crop subsidies^{8,9,10}, installation of modern sensors^{11,12}, implementation of managed aquifer recharge, water importation, as well as recycling, reuse and improved water accounting^{13,14,15,16}.

Despite the achievements of the works described above, significant gaps remain in the search for groundwater use and sustainability programs. This is especially true for arid and semi-arid regions world-wide where there are ongoing needs for policies to discover, measure, and control the economic cost of adapting to pumping restrictions. Aquifer protection policies that limit pumping can be an economically expensive proposition for the reason that water uses that rely on current aquifer pumping may produce a considerable economic value that would be lost if such protection plans are implemented. Therefore, it is important to seek out and discover policies that can protect high-valued economic activity relying on continued access to aquifer pumping while also assuring protection of stressed aquifers for future supplies and use. Despite some related recent works⁷ we were able to identify no analysis that integrate hydrogeologic and economic principles to discover and implement economically workable policies that minimize the economic cost of protecting economically important aquifers.

The original contribution of this paper is to formulate and apply a hydro-economic optimization model to inform a wide range of policy proposals for sustaining aquifers to better adapt to forces of

climate change and ongoing population growth. This work addresses the challenge of protecting groundwater-dependent economic activities, such as residential water use, commercial use, as well as crop and livestock uses, with the goal of achieving affordable aquifer sustainability with application to two heavily pumped aquifers in Kenya. The more general objective is to formulate an approach that permits discovery of policies and programs that minimize the economic cost of protecting stressed aquifers in various locations for future generations.

3. Results

3.1. Overview

Table 1 shows the most significant hydrogeologic data, while Table 2 displays important water use and economic data used for our model. Figure 1 presents our study area. These are described in more detail in the Methods of Analysis.

Results presented in tables 3-4 carry several messages: The economic cost required to bring an aquifer back to a sustainable future level is the additional cost of bringing back an aquifer to its starting storage level by the last period. That cost is measured as the reduction in discounted net present value (DNPV) of total economic benefits summed over sectors and uses needed to sustain an aquifer. These two tables emphasize the wide variability of DNPV and pumping outcomes according to which policy measure in place would govern an aquifer's pumping patterns over our 11 year time horizon. Table 3 shows a considerable amount of detail that allows us to conclude that the economic costs (DNPV displaced) of protecting aquifer sustainability increase with:

- Reduced aquifer recharge,
- Higher substitute water costs, such as costs of surface water importation or desalination,
- Less flexible rules for allocating pumping reductions compared to a pumping cap and trade arrangement,
- Longer term opportunities for adjustment to pumping restrictions,
- Higher economic value of water in existing uses, reflecting the well-known difficulty of protecting aquifers in regions that support much high-valued commerce and industry,
- Greater population growth for which domestic water use demands must be met,
- Lower price elasticity of demand for domestic or commercial water use,
- Greater excess of historical over sustainable pumping.

While not all these results are shown in table 3 because of space limitations, the model data and code attached to the appendix can be re-run with new values of the base model parameters to produce the results described above.

3.2. Economic Outcomes

The results in Table 3 illustrate several findings. The table shows several indicators of total economic benefit from alternative pumping restriction measures needed to support aquifer protection. The alternative economic indicators include DNPV (top block), DNPV losses compared to unrestricted pumping (second block) proportion of DNPV losses compared to cap and trade pumping (third block), and marginal economic loss in DNPV per unit pumping restricted (bottom block).

Total economic benefits from water use under the various pumping restrictions (top block) vary widely by aquifer, economic sector, and by measures to promote sustainable pumping. This point is brought out vividly in the second block, and shows economic losses compared to the DNPV achieved under the base policy of unrestricted pumping.

DNPV losses (second block) vary widely by sector from a low of zero, with unrestricted pumping, to a high of about US \$31.1 million suffered by domestic users when a crop irrigation priority system is practiced. The lowest cost pumping control policy is “cap and trade,” with a loss summed over both aquifers and all sectors of about US \$4.6 million. The next smallest pumping control policy is just under twice that high, US \$8.0 million summed over both aquifers, which occurs when a commercial priority system is established, because its priority protects a high-valued use of water. For other aquifers not studied here, the highest valued current use would normally come at the lowest cost when prioritized over the others. A common water shortage sharing method in aquifer dependent regions is a proportional sharing of those shortages¹⁷ when restrictions are necessary to protect an aquifer, labelled as “cap and share.” For our two aquifers, proportional shortage sharing is the second worst method to practice in terms of economic damages incurred from aquifer protection.

The third block of table 3 shows proportional comparisons among the various shortage sharing measures, for which “cap and trade” takes a baseline value of 1.00 by each and aquifer. Compared to cap and trade, a commercial priority for handling shortages has only a slightly higher loss of 1.73 averaged over both aquifers.

This finding is remarkable, since that policy measure allows no permit trading arrangements, often desirable in cultures where market trading of pumping permits is not widely practiced or acceptable¹⁸. Economic losses from the crop irrigation priority allocation system appears at 8.35 times the minimum

loss produced under the most efficient policy, mostly because irrigated agriculture typically carries a much lower economic value per unit of pumped water than livestock, commercial, or domestic uses in our two aquifers. This finding is likely to be similar to future findings in many of the drier parts of the world where irrigation produces a comparatively low value of farm income per unit of water pumped. So assigning a top priority to irrigated agriculture imposes considerable losses on the other sectors, even if those other sectors' pumping is allowed to adjust optimally among themselves as done in our model.

The bottom block of table 3 summarizes the "marginal economic loss per unit reduced pumping," for which results are consistent with the other three economic indicators of pumping restriction costs. Marginal economic losses per unit of reduced pumping for both aquifers is lowest under the cap and trade system and highest for the crop irrigation priority system. The lowest marginal cost per unit water use restriction is US \$44 per 1000 cubic meters for the case of cap and trade for the Merti Aquifer, consistent with a number of other works investigating the economic value of water for irrigation ¹⁹.

3.3. Hydrologic Outcomes

Table 4 shows various measures of water use and the distribution of their reductions by policy sector, and aquifer summed over the years 2009-2019. Notice for each aquifer that the six alternative policies to the base policy of unrestricted pumping produces an identical level of total water use over our eleven year time horizon. The Nairobi aquifer always shows 656.02 million cubic meters of pumping as required by the model, a check on model consistency, while the more lightly used Merti shows an identical pumping level of 50.5 million cubic meters for all pumping restriction policies for those years.

As expected, the pumping reductions (middle block) are an equal 53.29 million cubic meters for the five alternatives (Nairobi) and 5.78 million cubic meter reductions for the Merti. As required, all five alternatives to cap and trade show an identical proportion of pumping reductions, since all require identical pumping reductions to return the aquifers to historical (2009) starting conditions. The proportion of reductions compared to the most efficient alternative to the base, cap and trade, is identical for all six alternative policies at 1.0 (bottom block) since all reduce pumping by the same amount.

4. Discussion

Groundwater aquifers are an important water source worldwide. In the face of climate change and predicted increases in population, groundwater use and development must meet both future and current beneficial purposes with no negative repercussions. Certain attributes of groundwater systems

such as their comparative drought-resistance compared to surface supplies, reduced risk of pollution because of natural filtration of soils, cheap water provision on-demand, smaller storage and transmission losses, make groundwater systems cheaper and an attractive source than surface water systems^{20, 21}.

Supply and demand for groundwater use determine the sustainable use of aquifers. If aquifer water pumping demand exceeds recharge continuously, eventually, the groundwater level will be lower than its starting level with potential irreversible impacts on recovery²². Economically and hydrologically sustainable groundwater management requires average use to be equal to or less than average renewable recharge²³. One method of protecting aquifers is pumping restrictions. However, pumping reduction measures can be an economically expensive proposition as current aquifer water-dependent activities may produce a considerable economic value that would be lost with reduced pumping needed to protect sustainability. This work has formulated an approach that enables discovery of policies and programs that minimize the economic cost of protecting aquifers via permitted pumping caps combined with an allowance for trading the permits, a program that would require little to no government financing.

The important insight provided by our model results is that pumping permits issued to control unsustainable pumping without tradability can protect aquifers, but at a high current economic cost with considerable controversy generated among water users. Proportional sharing of shortages of permitted pumping can also reduce aquifer pumping stress but may also come at a high economic cost if most or all of the low-valued uses stay in production after the shortage sharing is implemented. In contrast, the establishment and enforcement of pumping permits that are tradable by which permittees can transfer their permit to higher valued users through a market system administered by relevant authorities can potentially reduce the economic cost of limiting current groundwater pumping by moving existing low valued pumping permitted rights to pumping by higher valued uses.

A cap and trade pumping policy is flexible, as has been shown for carbon trading²⁴, and can accommodate growth in water demand from future high-valued uses such as commerce and industry that uses small amounts of pumped water. In our study region in Kenya and in many other parts of the world, new high-valued use sectors if given the chance, could simply enter the market and buy pumping permits from existing lower-valued permittees, typically irrigated agriculture, who are the likely sellers under a pumping cap and trade system.

A limitation of our analysis is the lack of research-grade data showing high quality and detailed analysis of declines in average depth to pumping for either the Merti or Nairobi Aquifers. We used the

best data we could secure, but better data are needed to raise the rigor and certainty of our results. Lack of a complete inventory of groundwater use and users in our two aquifer regions also limits the scope of our analysis. Several extensions of our model such as the inclusion of surface water sources and analysis of conjunctive use, and combinations of aquifer protection policies such as the installation of meters, managed aquifer storage and recharge interventions, water use subsidies, along with tradable surface and groundwater water permits can be analyzed for our study regions and other arid regions in the world's aquifer dependent economies.

Despite accounting for a large number of hydrologic and economic indicators of needs for reduced aquifer pumping, several important elements of aquifer protection policy analysis are beyond the scope of this work for which we hope to see attention in future work:

- Economic analysis of alternative sustainability policy measures for confined aquifers of various levels of hydrogeological complexity.
- Preservation value of protecting aquifers, including value of groundwater-dependent ecosystems.
- Economic cost of water quality protection by limiting pollutants such as toxic metals and nitrates.
- Economic cost of policy measures from protecting aquifer lands from subsidence from reduced pumping.

5. Conclusions

For years aquifer management internationally has favored managing aquifer drawdowns through pumping restrictions regardless of economic controversy and sometimes violent behavior associated with water use limitations, especially for the case where pumping occurs on private property. We have analyzed several alternatives to classical pumping restrictions by examining integrated measures that sustain aquifers while maintaining economic activities to the greatest extent possible. Our paper has developed and applied an integrated quantitative optimization empirical model for informing sustainable and affordable management of aquifers that face stress.

Our approach presents a state-of-the arts optimization framework discovering how to protect current economic activity while eliminating sustainability threats from falling aquifer levels for which pumping has historically exceeded recharge. We investigate several alternative policy measures to reduce economic costs of pumping limitations needed to protect an aquifer's sustainability for future generations. These measures include a proportional sharing of reductions among all uses, domestic use

243 priority, irrigation use priority, urban use priority, and permitted pumping caps augmented by permit
244 trading. Our results show outcomes of all these measures if implemented. It finds that the largest
245 reduction in costs of aquifer protection with considerable capacity to contribute to dispute resolution,
246 when permitted pumping caps are combined with permit trading. While our analysis is applied to
247 management of two heavily pumped aquifers in Kenya, the methods are generalizable to many aquifers
248 worldwide currently experiencing unsustainable water pumping to protect local economic activity. This
249 paper has presented an approach that reduces both hydrologic, economic, and future impacts of aquifer
250 pumping compared to conventional approaches to protect aquifers through pumping restrictions.

253 6. Tables

254 6.1. Table 1: Selected Hydrogeologic Data for Aquifer Protection Model, Kenya

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Aquifer Characteristics	Units	Nairobi Aquifer	Merti Aquifer	Data Sources
Starting storage	million m ³	648,375	270,000	25, 26, 27
Starting Average Depth	meters	100.00	100.00	
Pumping Area	1000 km ²	6.50	5.50	
Aquifer Porosity (Storage Coefficient)	unitless	0.420	0.150	
Ave Change in Depth to Pumping from Previous Year	meters	1.95	0.70	
Marginal Cost Per Unit Depth Per Volume Pumped	US \$/1000 m ³ /meter	1.20	1.20	28, 29
Pumping Cost Per Unit at Start Depth	US \$/1000 m ³	450.00	450.00	
Areas abstracting water from the Aquifers		City of Nairobi	Habaswein	25, 27, 30, 31
		Kikuyu-Kiambu Area	Wajir	
		Kajiado East Area	Dadaab Area	

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6.2. Table 2: Selected Water Use and Economic Data Aquifer Protection Model, Kenya

Data	Units	Data Sources
Water Uses/Sectors (Irrigated Crop Production, Livestock Production, Residential and Commercial)	million m ³	27, 32
Irrigated Land	1000 hectares	33, 34, 35
Crop Water ET	meters/cropping season	
Crop Yield	metric ton/hectare	
Crop Prices	US \$/metric ton	
Livestock Population	1000 head	34, 36, 37, 38
Livestock Water Use Requirements	1000 m ³ /head/year	
Livestock Productivity	metric ton/head	
Livestock Output Prices	US \$/metric ton	
Population of Residents and Commercial Enterprises	1000	28, 36, 38, 39, 40, 41, 42
Population Growth Rates	proportion/year	
Groundwater Pumping Rate by Residential and Commercial Users	1000 m ³ /capita/year	
Average Cost of Water Supply	US \$/1000 m ³	
Price Elasticity of Demand	Unitless	

261 6.3. Table 3: Economic Performance Indicators, by Indicator, Pumping Management Policy, Sector, and Aquifer, Northern Kenya, 2009-2020

Table 3: Economic Performance Indicators, by Indicator, Pumping Management Policy, Sector, and Aquifer, Kenya, 2009-2019												
Economic Indicator	Policy	Sector								Aquifer		
		Agriculture				Domestic		Commercial		Nairobi Total	Merti Total	All Total
		Crop Water Use		Livestock Water Use		Household Water Use		Businesses				
		Nairobi Aquifer	Merti Aquifer	Nairobi Aquifer	Merti Aquifer	Nairobi Aquifer	Merti Aquifer	Nairobi Aquifer	Merti Aquifer			
Discounted Net Present Economic Value (DNPV), All Years (US\$ 1000)	01_unrestricted_pumping	43,220	239	942	7,531	3,377,059	259,986	983,109	23,692	4,404,329	291,449	4,695,778
	02_cap_and_trade	39,980	236	792	7,296	3,376,252	259,972	982,939	23,691	4,399,963	291,195	4,691,158
	03_cap_and_share	43,148	238	939	7,510	3,352,534	256,891	976,014	23,414	4,372,634	288,052	4,660,687
	04_domestic_priority	34,593	235	649	7,239	3,377,059	259,986	979,125	23,691	4,391,427	291,150	4,682,577
	05_commercial_priority	38,421	236	714	7,270	3,374,365	259,970	983,109	23,692	4,396,609	291,168	4,687,777
	06_livestock_priority	38,478	87	942	7,531	3,374,604	254,598	982,596	23,342	4,396,620	285,559	4,682,179
	07_crop_irrigation_priority	43,220	239	327	7,266	3,345,912	259,969	976,599	23,691	4,366,058	291,165	4,657,223
DNPV Losses Compared to Unrestricted Pumping (\$US 1000)	01_unrestricted_pumping	0	0	0	0	0	0	0	0	0	0	0
	02_cap_and_trade	3,240	3	150	235	807	14	169	1	4,366	254	4,620
	03_cap_and_share	72	2	3	21	24,525	3,095	7,095	278	31,695	3,397	35,092
	04_domestic_priority	8,627	5	292	293	0	0	3,983	1	12,903	299	13,201
	05_commercial_priority	4,798	4	227	261	2,695	16	0	0	7,720	281	8,001
	06_livestock_priority	4,742	152	0	0	2,456	5,388	512	350	7,710	5,890	13,600
	07_crop_irrigation_priority	0	0	615	266	31,147	17	6,509	1	38,271	284	38,555
Proportion DNPV Loss Compared to Cap and Trade Pumping Restrictions (0-1.00)	01_unrestricted_pumping	-	-	-	-	-	-			-	-	-
	02_cap_and_trade	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	03_cap_and_share	0.02	0.52	0.02	0.09	30.38	215.80	41.89	296.72	7.26	13.39	7.60
	04_domestic_priority	2.66	1.49	1.95	1.24	0.00	0.00	23.52	1.53	2.95	1.18	2.86
	05_commercial_priority	1.48	1.15	1.52	1.11	3.34	1.15	0.00	0.00	1.77	1.11	1.73
	06_livestock_priority	1.46	48.87	0.00	0.00	3.04	375.60	3.03	373.01	1.77	23.22	2.94
	07_crop_irrigation_priority	0.00	0.00	4.10	1.13	38.58	1.18	38.44	1.17	8.76	1.12	8.35
Marginal Economic Loss in DNPV Per Unit Reduced Pumping (\$US per 1000 m³)	01_unrestricted_pumping	-	-	-	-	-	-			-	-	-
	02_cap_and_trade	76	52	85	43	108	52	108	52	82	44	78
	03_cap_and_share	11	41	11	14	659	795	774	933	595	588	594
	04_domestic_priority	187	69	148	51	0	0	766	70	242	52	224
	05_commercial_priority	118	59	128	48	249	60	0	0	145	49	135
	06_livestock_priority	117	462	0	0	234	1,054	234	1,051	145	1,020	230
	07_crop_irrigation_priority	0	0	214	49	747	60	746	60	718	49	653

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6.4. Table 4: Water Use Indicator, by Indicator, Pumping Management Policy, Sector, and Aquifer, 2009-2019

Table 4: Water Use Indicator, by Indicator, Pumping Management Policy, Sector, and Aquifer, Kenya, 2009-2019												
Water Use Indicator	Policy	Sector								Aquifer		
		Agriculture				Domestic		Commercial		Nairobi Total	Merti Total	All Total
		Crop Water Use		Livestock Water Use		Household Water Use		All Business Activity				
		Nairobi Aquifer	Merti Aquifer	Nairobi Aquifer	Merti Aquifer	Nairobi Aquifer	Merti Aquifer	Nairobi Aquifer	Merti Aquifer			
Total water use, 2009-2019 (million m³)	01_unrestricted_pumping	92.05	0.40	3.70	15.12	491.95	37.84	121.61	2.92	709.31	56.28	765.59
	02_cap_and_trade	49.55	0.34	1.93	9.70	484.50	37.56	120.05	2.91	656.02	50.50	706.53
	03_cap_and_share	85.42	0.36	3.42	13.57	454.73	33.94	112.45	2.63	656.02	50.50	706.53
	04_domestic_priority	45.94	0.33	1.73	9.43	491.95	37.84	116.41	2.90	656.02	50.50	706.53
	05_commercial_priority	51.37	0.34	1.92	9.68	481.11	37.56	121.61	2.92	656.02	50.50	706.53
	06_livestock_priority	51.44	0.07	3.70	15.12	481.46	32.73	119.42	2.59	656.02	50.50	706.53
	07_crop_irrigation_priority	92.05	0.40	0.82	9.64	450.26	37.56	112.89	2.91	656.02	50.50	706.53
Total Water Use Losses Compared to Unrestricted Pumping, 2009-2019 (million m³)	01_unrestricted_pumping	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	02_cap_and_trade	42.50	0.06	1.77	5.42	7.45	0.28	1.56	0.02	53.29	5.78	59.06
	03_cap_and_share	6.64	0.04	0.27	1.54	37.22	3.89	9.16	0.30	53.29	5.78	59.06
	04_domestic_priority	46.11	0.07	1.97	5.69	0.00	0.00	5.20	0.02	53.29	5.78	59.06
	05_commercial_priority	40.68	0.06	1.77	5.44	10.84	0.28	0.00	0.00	53.29	5.78	59.06
	06_livestock_priority	40.61	0.33	0.00	0.00	10.49	5.11	2.19	0.33	53.29	5.78	59.06
	07_crop_irrigation_priority	0.00	0.00	2.87	5.48	41.69	0.28	8.72	0.02	53.29	5.78	59.06
Proportion Water Use Loss Compared to Cap and Trade Pumping Restrictions, 2009-2019 Averaged (0 to 1.00)	01_unrestricted_pumping	-	-	-	-	-	-	-	-	-	-	-
	02_cap_and_trade	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	03_cap_and_share	0.16	0.67	0.15	0.28	4.99	14.14	5.86	16.58	1.00	1.00	1.00
	04_domestic_priority	1.08	1.13	1.11	1.05	0.00	0.00	3.33	1.14	1.00	1.00	1.00
	05_commercial_priority	0.96	1.01	1.00	1.00	1.45	1.00	0.00	0.00	1.00	1.00	1.00
	06_livestock_priority	0.96	5.52	0.00	0.00	1.41	18.57	1.40	18.49	1.00	1.00	1.00
	07_crop_irrigation_priority	0.00	0.00	1.63	1.01	5.59	1.01	5.58	1.01	1.00	1.00	1.00

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265 7. Figures
266 7.1. Nairobi and Merti Aquifer Study Regions in Kenya
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8. Methods of Analysis

8.1. Study Area

Figure 1 shows the location of the two aquifer systems examined for this work – the Nairobi and Merti aquifer systems in Kenya. The Nairobi aquifer region continues to witness increases in population from rapid urbanization, while the Merti aquifer region continues to face local and refugee population growth due to its location to neighboring Somalia. Cities and rural communities in the aquifer regions typically access groundwater from boreholes equipped with hand pumps or via piped supplies from wellfields⁴³.

The Nairobi aquifer region covers an area of 6,500 km², underlining much of the Nairobi County and surrounding counties of Kiambu and Kajado east making up the Nairobi metropolitan area. It is a complex multilayered volcanic aquifer system, recharged along the eastern edge of the Rift Valley with groundwater moving toward the east²⁷. It accounts for between 34 and 44 percent of baseflow for streamflow across the aquifer region⁴⁴. An effort to control water abstraction from the Nairobi aquifer system was established in 1953 with the institution of the Nairobi Groundwater Conservation Area^{45, 46}. Despite these efforts, the policy has failed to hold back pumping as the number of boreholes has increased from 10 in 1940 to 4,856 in 2009^{45, 46} with volume of water pumped per year increasing by 388 percent from 1980 - 2009^{27, 46}. Though there are no research grade data for verification, estimated groundwater tables have declined; one well indicated an increased pumping depth of 40 meters over the 40-year period from 1958 – 1996⁴⁵.

The Merti aquifer is a transboundary resource and covers an area of 61,000 km² within northeastern Kenya. It comprises intercalated clays, semi-cemented to cemented sands, and intercalated limestone beds. Water withdrawal comes from fossil water with no significant recharge⁴⁷. However, the volume of water pumping has increased significantly from 0.0289 million m³ in 1970 to about 4.6 million m³ in 2009²⁷. One important work from 2015 analyzed the impact of managed aquifer recharge (MAR) interventions on shallow and deep aquifers in northeastern Kenya. The work concluded that MAR interventions such as direct aquifer infiltration, localized land surface infiltration, diffuse land surface infiltration for shallow aquifers, and injection wells for deep confined aquifers could contribute to intergenerational sustainability of the aquifers⁴⁸. However, despite the potential capacity of MAR interventions to balance some effects of climatic variations and secure water supply, they are typically expensive to implement⁴⁹ and are not an economically viable substitute for groundwater management through abstraction control to protect longer term sustainability⁵⁰.

8.1.1. Groundwater Use Patterns

The dominant water uses in our two aquifer regions are domestic household use, commercial and industrial use, livestock use, as well as water used for crop irrigation^{27, 32, 35}. Groundwater use for livestock include livestock drinking, servicing, and processing of primary livestock products. Household water use for villages and cities is calculated as domestic water use per capita multiplied by the number of residents who use water in each of the two aquifer regions. Irrigated crop water use is calculated as crop ET per unit land multiplied by cropland under production. Commercial and Industrial use data sources is found by multiplying per unit use by the historical number of units over our eleven-year study period of 2009-2019. For each aquifer, total water use is the summation of water use by all four sectors.

8.1.2. Water Use Permitting

A permitting system is currently used by the Kenyan Water Resources Authority (WRA) to regulate the use of groundwater resources, legally vested in the Government of Kenya⁴⁴. Water user response to the permitting system has historically been characterized by a low level of compliance²⁷. However, permitting authorization and issuance for groundwater, which comprises about 80 percent of all the permits issued, has been steadily increasing (from 2,100 in 2006 to 14,000 in 2016) with more water users registering their pumping with the WRA⁵¹. The Nairobi aquifer region has the highest number of groundwater permits issued to water pumpers and the highest proportion of the pumped water volume with valid permits compared to all other aquifer regions in Kenya^{44, 51}.

8.2. Data

Table 1 shows the most significant hydrogeologic data, while Table 2 displays important water use and economic data used for our model. Table 2 shows the regions pumping water from the study aquifers. The Kenyan government has classified our two study aquifers, the Nairobi and Merti, as strategic for groundwater permitting purposes^{26, 27}. A strategic aquifer is an aquifer that is used to supply a significant amount of water in a given area for which there are no available alternative water sources^{26, 44}. Both the Nairobi and Merti aquifers are large scale non-renewable resources which sources supply much water in the Nairobi and Merti regions for which there are few reliable alternative water sources in the area^{26, 27}.

Beginning in the early to mid-1990's, considerable population growth in both aquifer regions occurred due urbanization in the Nairobi area and emigration of large numbers of refugees from

Somalia to northeastern Kenya area, resulting in elevated drinking water demands. More than 25 percent of the water supply in the Nairobi metro area comes from groundwater⁴⁵. For drinking water use in the Merti area, both local populations and refugees depend entirely on groundwater³². While the Nairobi and Merti aquifers are an important source of fresh water in their respective areas, comparatively little is known about their size, shape, and net recharge⁵².

Despite the two aquifers' apparently large storage capacity, they have a low current rate of average recharge. The aquifers have been classified as largely non-renewable under current conditions based on current information available^{27, 53}; therefore, sustainable policies for their maximum long term sustainability makes for a compelling policy challenge.

8.3. Conceptual Framework

8.3.1. Economic Value of Water

The incremental economic value of water is what the user is willing to forgo to obtain the water with respect to changes from baseline in any of its dimensions of location, timing, quantity, quality, costs, and price⁵⁴. For aquifer systems, the economic value of water is the total value generated by all its using sectors, economic activities, and time periods – the sum of all benefits net of costs to all users. Information on water's economic value enables informed choices on water development, conservation, allocation, purification, and protection when climate variability and growing demands for all uses occur with increased scarcity⁵⁵. For example, the economic value of changing the current pattern of water use between farms and domestic used when aquifer protection is needed is the gain or loss in farm income added to the gain or loss in domestic economic benefits made possible by the altered shortage sharing system. When considering the future as different from the past there are an infinite number of altered use patterns from the history that actually occurred. Therefore, an optimized counter-factual history is what is sought with an optimization model, in the sense of seeking a minimized overall cost of reducing total community pumping needed to secure long term aquifer protection. Valuing changes in location, timing, quantity, quality, costs, and price of water use requires an economic model grounded in a physical reality⁷.

8.3.2. Safe Minimum Standard

The present work attempts to increase the extent of knowledge and optimizable use of aquifers with known storage capacities and a known rate of average recharge, supplying a significant amount of

water to dry areas with few to no alternative water sources. Economically sustainable groundwater use requires average use to be no larger than average renewable recharge^{56, 57, 58}.

A celebrated natural resource economist of the mid-20th century coined the ‘safe minimum standard’ to identify principles to avoid crossing the threshold of irreversible damage^{59, 60}. As the only perennial source of water for humans and livestock economic activities²⁷ in our two study regions in Kenya, the scale of groundwater use in the Nairobi and Merti aquifer systems continues to increase with economic growth in the area, with demands for pumping exceeding recharge for renewable storage and attendant depletion of the savings account of non-renewable storage²⁷. Aquifers risk depletion beyond economic recovery, where a threshold at which the ‘safe minimum standard’ is compromised if water abstraction consistently exceeds recharge for an extended period of time. To guard against this irreversible aquifer status, several potential policy options are available, seven of which we analyze in detail.

8.4. Policy Choices

Several policy choices for addressing aquifer depletion and restoration were investigated for this work. They include:

- Unrestricted historical pumping: This replicates observed pumping for each of the two aquifers, as well as observed average drawdown per year for each of our four sectors. Our method uses positive mathematical programming⁶¹ implemented with quadratic programming⁶² so that the base optimization exactly replicates historical data for which small changes in the data produces small changes in the results. It is desirable for the base optimization to replicate history so that deviations from history needed to sustain the aquifer have a measured starting point grounded in reality, before investigating a counter-factual history that could have happened with those observed hydrologic and economic conditions.
- Cap and trade: This policy, would have returned both aquifers to observed 2009 starting levels by 2019 through the mechanism of reducing over time and economic sectors, a level of permitted pumping sufficiently protecting of each aquifer’s sustainability while also allowing a trading of pumping permits. This program would assure pumping is no larger than the limited permitted amount. Its implementation, requires measurement, monitoring, and enforcement. Under such a program, a sustainable level of pumping is permitted, but permit holders are

allowed to trade their permit for cash or other assets. This trade would occur if the permit buyer has a higher valued use of water than the existing holder, permitting both parties to the trade to gain, while protecting the aquifer .

A cap and trade policy would implement an aggregate level of pumping reductions needed to secure aquifer sustainability. Allowing permit trading would move use reductions out of low valued uses and limit shortages from high valued economic uses displaced that would otherwise occur in high valued uses, especially high valued crops and high valued commercial and domestic uses. Several works have studied tradable permits as a measure to minimize the economic costs of protecting environmental assets, such as high seas fisheries^{63, 64, 65, 66, 67}, and climate change adaptation^{24, 68, 69, 70}. However, with few exceptions little has been published for addressing aquifer protection policy design^{71, 72}

- Cap and Share, also described by some as a proportional sharing of shortages: This policy would reduce permitted pumping in each aquifer by a sufficient amount to promote aquifer sustainability defined above. It would be implemented through a plan to share required reductions in pumping among sectors in proportion to each's observed pumping levels seen for the years 2009-2019. If, for example, pumping must fall by X percent per year for an aquifer to secure sustainability, then all groundwater-using economic sectors would see their permitted pumping allowances reduced by an equal X percent, implemented through suitable monitoring and enforcement. A proportional sharing of use reductions, for which all water users bear the same proportion reductions in current uses, has been described in several works^{17, 18, 73, 74, 75}.
- Domestic Priority: In most water shortage scenarios, domestic and other non-agricultural sectors get priority in times of shortage because of the typically much higher economic value of water for domestic use, typically measured as total benefits per unit of water or as a marginal economic benefit per additional unit of water. For our analysis, we implemented a domestic priority by assigning 100 percent of historical domestic use to domestic users even when overall water pumping reductions were needed to protect each aquifer. All non-domestic users allocated the remaining pumping rights among themselves efficiently. A celebrated 2009 work⁷⁶ found that for water shortages faced by commercial, industry, and tourism the Eastern Seaboard region near Bangkok Thailand, were quickly restored by implementation of several

interbasin transfers combined with the development of numerous wells to secure short term supplies.

- Commercial / Industrial Priority: Commercial and industrial users of pumped water are typically among the highest valued uses when measured as the income generated per unit of water pumped or the incremental income produced per additional unit pumped. Especially in industrialized areas that rely heavily on pumped water, such as Denver, Phoenix, Albuquerque, and much of southern California (USA)⁷⁷ or in many dry heavily populated communities in Asia, Africa, and South America⁷⁸, there is ongoing interest in investigating economic impacts of a commercial/industrial priority allocation system.
- Livestock Priority: In a livestock-dependent economy where much income is generated from various kinds of ranching activities⁷⁹, political leaders and other policymakers often wish information on economic impacts of a policy that would protect this sector's right to protect historical its pumped water even if the other sectors must cut back to protect the community aquifer.
- Crop Irrigation Priority: Crop irrigation is a dominant use of pumped water in many of the world's highly-stressed aquifers, such as the High Plains^{23,80} and Edwards⁸¹ aquifers of the USA. In places like those, numerous policy debates pose questions about the economic payoff from protecting irrigation economic values by assigning top priority to crop irrigation⁸² while assuring long term aquifer sustainability.

8.5. Optimization Framework

Our model is implemented by discovering water use pumping patterns by sector, year period, and aquifer that optimize the discounted net present value (DNPV) of economic benefits summed over uses, sectors, and years that can be achieved from pumping from each of our two aquifers. The software used is the celebrated General Algebraic Modeling System (GAMS) language⁸³, which has impressive up-scalability properties. The model accounts for proposals that would sustain both aquifers to return to starting (2009) level by the last year (2019). The impact of aquifer protection targets is addressed by specifying and enforcing terminal level aquifer levels to match beginning levels as lower bounds that

must be respected. A complete copy of the GAMS code, including data read, parameters, variables, equations, bounds, and the objective for each of our policies is attached as an appendix to this paper.

Economic benefits from groundwater use come from income from irrigated farming, livestock production, domestic, and commercial/industrial pumping. Irrigated crop farm income is measured as crop output prices multiplied by yields minus production cost multiplied by cropland in production. Livestock income is measured as livestock prices multiplied by livestock productivity minus production cost multiplied by livestock in production. Domestic and commercial/industrial water use economic benefits are measured as the sum of consumer surplus added to profitability.

The model accounts for recharge, storage, and pumping for the uses described above. The model reads known hydrologic and economic data as well optimizing to discover values of unknown variables recovered as part of the optimization exercise (math appendix). For each of the unknown variables, numerical values of each is discovered to produce a single overall economic optimum⁸⁴. Using elasticity matrices⁷ impacts on the results from changes in the data can be easily estimated.

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742 10. Supplementary Materials: GAMS Code and Data

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749 * double forward slash for end of line comments for your eyes: GAMS ignores

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751 * October 7 2020

752 * Prepared by Frank Ward and Bernard Baah-Kumi

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754 * -----

755 * GAMS demo model for generic aquifer protection based on Kenya work Fall 2020

756 * After a '*' you can enter comments that GAMS ignores but you can see

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759 Option limrow = 0; option limcol = 0;

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761 * -----*

762 * columns are variables to be optimized. Rows are equations (expressed as constraints)*

763 * put in larger numbers for limrow if you want GAMS to display more equations *

764 * A good idea until model is working right *

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766

767 * Think of sets as indices in regular algebra

768 * Sets are the foundation of GAMS models

769

770 * Competition for scarce water by n sectors for m years - dynamic optimization

771 * residential domestic, livestock, irrigated agriculture, and commercial/industrial

772 * Aquifer has fixed capacity but storage can be increased with recharge and reduced by pumping

773 * Pump costs increase with increased depth to pumping

774

775 \$ontext

776

777

778 Model has these characteristics

779

780 4 sectors (farming, domestic, livestock, and commercial/industrial

781 5 urban areas- 2 pump from Nairobi Aquifer Ssystem (NAS) and 3 pump from Merti Aquifer System (MAS)
 782 11 time periods 2009-2019
 783 7 Aquifer pumping policy options (base, cap and trade, cap and share, domestic priority, commercial
 784 priority, irrigation priority, livestock pumping priority)
 785
 786 * Positive Math Programming: optimized base pumping historical results match historical exactly
 787 * It is a quadratic programming model with nice smooth pasting properties
 788
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790 AQUIFER SYSTEMS ANALYZED

791
 792 The Nairobi aquifer region covers an area of 6,500 km², underlining much of the Nairobi
 793 County and surrounding counties of Kiambu and Kajiado east making up the Nairobi
 794 metropolitan area. It is a complex multilayered volcanic aquifer system, recharged along
 795 the eastern edge of the Rift Valley with groundwater moving toward the east (Mumma et
 796 al. 2011). It accounts for between 34 and 44 percent of baseflow for streamflow across
 797 the aquifer region (WRA 2010). An effort to control water abstraction from the Nairobi
 798 aquifer system was established in 1953 with the institution of the Nairobi Groundwater
 799 Conservation Area (Foster and Tuinhof 2005; Water Resources Authority (WRA) 2010),
 800 however, the policy has failed to hold back pumping as the number of boreholes has
 801 increased from 10 in 1940 to 4,856 in 2009 (Foster and Tuinhof 2005; Water Resources
 802 Authority (WRA) 2010) with volume of water pumped per year increasing by 388 percent
 803 from 1980 - 2009 (Mumma et al. 2011; Water Resources Authority (WRA) 2010). Though there
 804 are no research grade data for verification, estimated groundwater table has declined;
 805 one well indicated an increased pumping depth of 40 meters over the 40-year period from
 806 1958 - 1996 (Foster and Tuinhof 2005).
 807

808 The Merti aquifer is a transboundary resource and covers an area of 61,000 km² within
 809 northeastern Kenya. It comprises intercalated clays, semi-cemented to cemented sands,
 810 and intercalated limestone beds. Water withdrawal comes from fossil water with no
 811 significant recharge (International Groundwater Resources Assessment Centre 2020).
 812 However, the volume of water pumping has increased significantly from 0.0289 million
 813 m³ in 1970 to about 4.6 million m³ in 2009 (Mumma et al. 2011). One important work
 814 from 2015 analyzed the impact of managed aquifer recharge (MAR) interventions on
 815 shallow and deep aquifers in northeastern Kenya. The work concluded that MAR
 816 interventions such as direct aquifer infiltration, localized land surface infiltration,
 817 diffuse land surface infiltration for shallow aquifers, and injection wells for deep
 818 confined aquifers could contribute to intergenerational sustainability of the aquifers
 819 (Ansems et al. 2015). However, despite the capacity of MAR interventions to balance
 820 out some effects of climatic variations and secure water supply, they are typically
 821 expensive to implement (Khan et al. 2008) and are not a substitute for groundwater

822 management through abstraction control to protect longer term sustainability
 823 (Casanova, Devau, and Pettenati 2016).
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 828 sets
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 830 i farming areas /1_Nairobi__farm, 2_KiamArea_farm, 3_Wajir_farm, 4_Habaswein_farm/
 831
 832 k residential areas /1_Nairobi_resid, 2_KiamArea_resid, 3_Wajir_resid, 4_Habaswein_resid,
 833 5_Mert_Ddab_resid/
 834
 835 *Residential area include all households use in rural and urban areas
 836
 837 l livestock areas /1_Nairobi_lvstk, 2_KiamArea_lvstk, 3_Wajir_lvstk, 4_Habaswein_lvstk/
 838
 839 n commercial areas /1_Nairobi_indus, 2_KiamArea_indus, 3_Wajir_indus, 4_Mert_Ddab_indus/
 840
 841 *Commercial areas contain industrial enterprises, and commercial enterprises such as hotels,
 842 * and shops (excludes ag)
 843
 844 z aquifer system /1_NAS_Aqf, 2_MAS_Aqf/
 845
 846 c agr crop type /1_maize, 2_potatoes, 3_tomatoes, 4_kale, 5_onion, 6_watmelon/
 847
 848 u domestic wat use /all_residential/
 849
 850 *Household water use include water use in schools, churches, mosques, hospitals and
 851 * all other dwellings except hotels
 852
 853 v livestock species /1_Cattle, 2_Camel, 3_Goat, 4_Sheep/
 854
 855 j indus & hotel use /1_all_comml, 2_all_indus/
 856
 857 *NOTE: 1_all_comml is all commercial enterprises including hotels and shops
 858 *NOTE: 2_all_indus is all industrial enterprises
 859
 860 r agr resource /ag_water, land/
 861
 862 q lvstk resource /lv_water, head/


```

863
864 t   Year           /2009*2019/
865
866
867 p   Policy   /01_unrestricted_pumping   no pumping limitations
868              02_cap_and_trade           cap and trade
869              03_cap_and_share           proportional sharing of pumping reductions
870              04_domestic_priority        domestic historical use protected
871              05_commercial_priority      commercial historical use protected
872              06_livestock_priority       livestock historical use protected
873              07_crop_irrigation_priority irrigated ag historical use protected
874              /
875
876 tfirst(t)      first Year
877 tlater(t)      later Years
878 tlast (t)      last year
879
880 ;
881 tfirst(t) = yes $ (ord(t) eq 1);
882 tlater(t) = yes $ (ord(t) gt 1);
883 tlast(t)   = yes $ (ord(t) eq card(t));
884
885
886 set  zi(z,i)   mapping set assigns aquifers to farming areas
887
888 /    1_NAS_Aqf . (1_Nairobi_farm)
889      1_NAS_Aqf . (2_KiamArea_farm)
890      2_MAS_Aqf . (3_Wajir_farm)
891      2_MAS_Aqf . (4_Habaswein_farm)
892 /
893
894 set  zk(z,k)   mapping set assigns aquifers to residential areas
895
896 /    1_NAS_Aqf. (1_Nairobi_resid)
897      1_NAS_Aqf. (2_KiamArea_resid)
898      2_MAS_Aqf. (3_Wajir_resid)
899      2_MAS_Aqf. (4_Habaswein_resid)
900      2_MAS_Aqf. (5_Mert_Ddab_resid)
901 /
902
903 set  zl(z,l)   mapping set assigns aquifers to livestock areas

```

```

904
905 /    1_NAS_Aqf.  (1_Nairobi_lvstk)
906    1_NAS_Aqf.  (2_KiamArea_lvstk)
907    2_MAS_Aqf.  (3_Wajir_lvstk)
908    2_MAS_Aqf.  (4_Habaswein_lvstk)
909 /
910
911 set zn(z,n)  mapping set assigns aquifers to industrial and commercial uses
912
913 /    1_NAS_Aqf.  (1_Nairobi_indus)
914    1_NAS_Aqf.  (2_KiamArea_indus)
915    2_MAS_Aqf.  (3_Wajir_indus)
916    2_MAS_Aqf.  (4_Mert_Ddab_indus)
917 /
918
919
920 alias (t,tp);
921
922
923 display zi, zk, zl, zn;
924
925 * ----- Begin with data directly read by GAMS -----
926
927 parameters
928 *AQUIFER PARAMETERS
929
930 aq_area_p(z)    aquifer land area          (1000 ha)          /1_NAS_Aqf        6.50
931                                                         2_MAS_Aqf        10.00/
932
933
934 porosity_p(z)    aquifer porosity           (unitless)           /1_NAS_Aqf        0.4200
935                                                         2_MAS_Aqf        0.1500/
936
937
938 storage0_p(z)    aquifer starting storage (million M3)        /1_NAS_Aqf        648375
939                                                         2_MAS_Aqf        270000/
940
941 *Initial storage Calculation
942
943 * Total Pore Volume or Storage
944
945 * NAS volume m3 = Area (6500 000 000 m2)* Average Saturated Thickness(237.5 m)* Average
946 * Total Porosity (0.4200 unitless)

```

```

945
946 *MAS volume m3 = Area (10000 000 000 m2)* Average Saturated Thickness(180.0 m)* Average
947 * Total Porosity (0.1500 unitless)
948
949
950 * Calculation Reference
951 * https://albertawater.com/groundwater/balance-and-inventory/how-much-groundwater-is-there
952
953
954 depth0_p(z)          initial aquifer depth      (M)                /1_NAS_Aqf      100
955                                                              2_MAS_Aqf      100/
956
957 change_depth0_p(z)    observed change in depth  (M per Year)    /1_NAS_Aqf      1.952
958                                                              2_MAS_Aqf      0.700/
959
960 *Citations aquifer parameters (read data):
961
962 *Mumma et al., Kenya groundwater governance case study.World Bank,(2011). (page 41)
963
964 *Oord and de Leeuw, Hydrogeology of the Merti Aquifer: Impact of abstractions on drawdown of water
965 *level and salinity. Acacia Water - Solutions in Groundwater (2015).
966
967 *Oord et al., Hydrogeological Assessment of the Merti Aquifer, Kenya.Technical report no 1 of ARIGA
968 *Assessing Risks of Investment in Groundwater Development in Sub-Saharan Africa.Acacia Water.(2014)
969
970 *Barasa et al., Africa Groundwater Atlas: Hydrogeology of Kenya. British Geological Survey. (2018).
971
972 *Foster and Tuinhof, Kenya: The Role of Groundwater in the Water Supply of Greater Nairobi.
973 *GW, MATE Case Profile Collection The World Bank, Washington DC, 6 (2005). (page 4)
974 * -----
975
976
977 *ECONOMIC PARAMETERS
978
979 rho_p                discount rate          (unitless)                /0.05/
980
981
982 pc_af_p(z)          pump cost per unit at start depth  (US$ \ 1000 M3)    /1_NAS_Aqf      450
983                                                              2_MAS_Aqf      450/
984
985

```

```

986 pc_af_f_p(z) added pump cost per unit per unit depth (US$\1000 M3\M) /1_NAS_Aqf 1.2
987                                     2_MAS_Aqf 1.2/
988
989
990 ag_crop_cost_prop_p(c) proportion of ag revenue = costs (unitless)
991
992 /1_maize 0.90
993 2_potatoes 0.90
994 3_tomatoes 0.90
995 4_kale 0.90
996 5_onion 0.90
997 6_watmelon 0.90/
998
999
1000 ag_lvstk_cost_prop_p(v) prop of livestock revenue=costs (unitless) /1_Cattle 0.95
1001                                     2_Camel 0.90
1002                                     3_Goat 0.90
1003                                     4_Sheep 0.90/
1004
1005 cost_export_p cost per unit exported ($ per 1000 M3) /0.01/
1006 ;
1007
1008 *Citations economic parameters (read data):
1009 *Pavelic et al., Groundwater availability and use in Sub-Saharan Africa: a review of 15 countries.
1010 *International Water Management Institute (IWMI) (2012). (page 73)
1011 *Winrock International. Winrock International's USAID-funded Kenya Smallholder Solar Irrigation
1012 *(KSSI) project ) (2017).
1013
1014 *USD 450 = KSh 48780 US$ borehole eqiuped with hand pumps
1015 *Wind pumps, diesel, electric and solar pumps are relatively higher than hand pumps in
1016 *the range of USD 600 (KSh 65,040) - USD 7,000 (KSh 758,800)
1017 *Hand pump is used by over 80% since it is relatively cheaper
1018 * -----
1019
1020
1021 *adjustement of aquifer area to pumped area
1022
1023 aq_area_p('1_NAS_Aqf') = 1.00 * aq_area_p('1_NAS_Aqf');
1024
1025
1026 aq_area_p('2_MAS_Aqf') = 0.55 * aq_area_p('2_MAS_Aqf');

```

```

1027
1028
1029 display aq_area_p, storage0_p, pc_af_p, pc_af_f_p, depth0_p;
1030
1031 *Citation:
1032 *Mumma et al., Kenya groundwater governance case study.World Bank,(2011). (page 41)
1033 *Oord and de Leeuw, Hydrogeology of the Merti Aquifer: Impact of abstractions on drawdown of water
1034 *level and salinity. Acacia Water - Solutions in Groundwater (2015).
1035
1036
1037
1038
1039 * ----- Read Agricultural Data -----
1040
1041 table yield_agr_p(c,i,t)          observed crop yield          (metric tons per HA)
1042
1043          1_Nairobi_farm.2009  2_KiamArea_farm.2009  3_Wajir_farm.2009  4_Habaswein_farm.2009
1044 1_maize          1.29          1.29          1.29          1.29
1045 2_potatoes       19.12       19.12       19.12       19.12
1046 3_tomatoes       30.58       30.58       30.58       30.58
1047 4_kale           21.90       21.90       21.90       21.90
1048 5_onion          10.45       10.45       10.45       10.45
1049 6_watmelon       19.12       19.12       19.12       19.12
1050
1051 +
1052          1_Nairobi_farm.2010  2_KiamArea_farm.2010  3_Wajir_farm.2010  4_Habaswein_farm.2010
1053 1_maize          1.73          1.73          1.73          1.73
1054 2_potatoes       22.43       22.43       22.43       22.43
1055 3_tomatoes       29.18       29.18       29.18       29.18
1056 4_kale           17.90       17.90       17.90       17.90
1057 5_onion          11.01       11.01       11.01       11.01
1058 6_watmelon       24.37       24.37       24.37       24.37
1059
1060 +
1061          1_Nairobi_farm.2011  2_KiamArea_farm.2011  3_Wajir_farm.2011  4_Habaswein_farm.2011
1062 1_maize          1.58          1.58          1.58          1.58
1063 2_potatoes       19.17       19.17       19.17       19.17
1064 3_tomatoes       19.26       19.26       19.26       19.26
1065 4_kale           10.40       10.40       10.40       10.40
1066 5_onion          10.45       10.45       10.45       10.45
1067 6_watmelon       20.21       20.21       20.21       20.21

```

1068					
1069	+				
1070		1_Nairobi__farm.2012	2_KiamArea_farm.2012	3_Wajir_farm.2012	4_Habaswein_farm.2012
1071	1_maize	1.74	1.74	1.74	1.74
1072	2_potatoes	14.07	14.07	14.07	14.07
1073	3_tomatoes	20.34	20.34	20.34	20.34
1074	4_kale	10.06	10.06	10.06	10.06
1075	5_onion	15.32	15.32	15.32	15.32
1076	6_watmelon	22.49	22.49	22.49	22.49
1077					
1078	+				
1079		1_Nairobi__farm.2013	2_KiamArea_farm.2013	3_Wajir_farm.2013	4_Habaswein_farm.2013
1080	1_maize	1.69	1.69	1.69	1.69
1081	2_potatoes	14.43	14.43	14.43	14.43
1082	3_tomatoes	20.70	20.70	20.70	20.70
1083	4_kale	15.63	15.63	15.63	15.63
1084	5_onion	16.76	16.76	16.76	16.76
1085	6_watmelon	20.35	20.35	20.35	20.35
1086					
1087	+				
1088		1_Nairobi__farm.2014	2_KiamArea_farm.2014	3_Wajir_farm.2014	4_Habaswein_farm.2014
1089	1_maize	1.66	1.66	1.66	1.66
1090	2_potatoes	14.07	14.07	14.07	14.07
1091	3_tomatoes	18.07	18.07	18.07	18.07
1092	4_kale	9.56	9.56	9.56	9.56
1093	5_onion	16.32	16.32	16.32	16.32
1094	6_watmelon	24.56	24.56	24.56	24.56
1095					
1096	+				
1097		1_Nairobi__farm.2015	2_KiamArea_farm.2015	3_Wajir_farm.2015	4_Habaswein_farm.2015
1098	1_maize	1.82	1.82	1.82	1.82
1099	2_potatoes	14.70	14.70	14.70	14.70
1100	3_tomatoes	21.15	21.15	21.15	21.15
1101	4_kale	14.44	14.44	14.44	14.44
1102	5_onion	14.85	14.85	14.85	14.85
1103	6_watmelon	35.70	35.70	35.70	35.70
1104					
1105	+				
1106		1_Nairobi__farm.2016	2_KiamArea_farm.2016	3_Wajir_farm.2016	4_Habaswein_farm.2016
1107	1_maize	1.43	1.43	1.43	1.43
1108	2_potatoes	9.15	9.15	9.15	9.15

```

1109 3_tomatoes          18.71          18.71          18.71          18.71
1110 4_kale               13.46          13.46          13.46          13.46
1111 5_onion              14.82          14.82          14.82          14.82
1112 6_watmelon           21.83          21.83          21.83          21.83
1113
1114 +
1115      1_Nairobi_farm.2017  2_KiamArea_farm.2017  3_Wajir_farm.2017  4_Habaswein_farm.2017
1116 1_maize              1.76          1.76          1.76          1.76
1117 2_potatoes           7.91          7.91          7.91          7.91
1118 3_tomatoes           18.35          18.35          18.35          18.35
1119 4_kale               17.75          17.75          17.75          17.75
1120 5_onion              14.92          14.92          14.92          14.92
1121 6_watmelon           17.67          17.67          17.67          17.67
1122
1123 +
1124      1_Nairobi_farm.2018  2_KiamArea_farm.2018  3_Wajir_farm.2018  4_Habaswein_farm.2018
1125 1_maize              1.87          1.87          1.87          1.87
1126 2_potatoes           8.61          8.61          8.61          8.61
1127 3_tomatoes           21.21          21.21          21.21          21.21
1128 4_kale               18.48          18.48          18.48          18.48
1129 5_onion              15.02          15.02          15.02          15.02
1130 6_watmelon           24.16          24.16          24.16          24.16
1131
1132 +
1133      1_Nairobi_farm.2019  2_KiamArea_farm.2019  3_Wajir_farm.2019  4_Habaswein_farm.2019
1134 1_maize              1.87          1.87          1.87          1.87
1135 2_potatoes           8.61          8.61          8.61          8.61
1136 3_tomatoes           21.21          21.21          21.21          21.21
1137 4_kale               18.48          18.48          18.48          18.48
1138 5_onion              15.02          15.02          15.02          15.02
1139 6_watmelon           24.16          24.16          24.16          24.16
1140 ;
1141
1142
1143 display yield_agr_p;
1144
1145 table  price_agr_p(c,t)      crop price      (US $ per metric ton)  national average prices
1146      2009      2010      2011      2012      2013      2014      2015
1147 1_maize      309.1      217.2      281.5      401.8      363.8      377.4      292.3
1148 2_potatoes   241.6      285.1      324.7      334.7      311.8      349.9      349.2
1149 3_tomatoes   412.9      505.9      480.0      545.7      647.1      721.1      627.1

```

```

1150 4_kale          139.1    139.1    139.1    139.1    139.1    139.1    139.1
1151 5_onion         696.8    740.7    552.2    765.7    732.4    520.9    418.5
1152 6_watmelon     215.1    215.1    215.1    215.1    215.1    215.1    215.1
1153
1154 +
1155           2016      2017      2018      2019
1156 1_maize       292.5    292.5    292.5    309.1
1157 2_potatoes    349.2    349.2    349.2    349.2
1158 3_tomatoes    605.0    605.0    605.0    605.0
1159 4_kale        139.1    139.1    139.1    139.1
1160 5_onion       441.1    441.1    441.1    696.8
1161 6_watmelon    226.9    226.9    226.9    226.9
1162 ;
1163
1164
1165 display price_agr_p;
1166
1167
1168 table res_use_agr_p(c,r,i)    resource use requirements    (ET Meter depth per year)
1169
1170           ag_water.1_Nairobi__farm    ag_water.2_KiamArea_farm
1171 1_maize                0.80                0.80
1172 2_potatoes            0.75                0.75
1173 3_tomatoes            0.85                0.85
1174 4_kale                0.85                0.85
1175 5_onion               0.65                0.65
1176 6_watmelon           0.68                0.68
1177
1178 +
1179
1180           ag_water.3_Wajir_farm    ag_water.4_Habaswein_farm
1181 1_maize                0.80                0.80
1182 2_potatoes            0.75                0.75
1183 3_tomatoes            0.85                0.85
1184 4_kale                0.85                0.85
1185 5_onion               0.65                0.65
1186 6_watmelon           0.68                0.68
1187 ;
1188
1189
1190 res_use_agr_p(c,'land',i) = 1;    // ha per ha = 1

```



```

1191
1192
1193 display res_use_agr_p;
1194
1195 table land_agr_p(z,c,i,t) observed land in production by crop (1000 HA)
1196
1197          1_Nairobi__farm.2009      2_KiamArea_farm.2009
1198 1_NAS_Aqf.1_maize          1.0549          1.523
1199 1_NAS_Aqf.2_potatoes      1.0219          1.725
1200 1_NAS_Aqf.3_tomatoes      1.0225          1.525
1201 1_NAS_Aqf.4_kale          1.0225          1.425
1202 1_NAS_Aqf.5_onion         eps            eps
1203 1_NAS_Aqf.6_watmelon     eps            eps
1204
1205 2_MAS_Aqf.1_maize         eps            eps
1206 2_MAS_Aqf.2_potatoes     eps            eps
1207 2_MAS_Aqf.3_tomatoes     eps            eps
1208 2_MAS_Aqf.4_kale         eps            eps
1209 2_MAS_Aqf.5_onion        eps            eps
1210 2_MAS_Aqf.6_watmelon     eps            eps
1211
1212 +
1213          3_Wajir_farm.2009  4_Habaswein_farm.2009
1214 1_NAS_Aqf.1_maize         eps            eps
1215 1_NAS_Aqf.2_potatoes     eps            eps
1216 1_NAS_Aqf.3_tomatoes     eps            eps
1217 1_NAS_Aqf.4_kale         eps            eps
1218 1_NAS_Aqf.5_onion        eps            eps
1219 1_NAS_Aqf.6_watmelon     eps            eps
1220
1221 2_MAS_Aqf.1_maize         eps            eps
1222 2_MAS_Aqf.2_potatoes     eps            eps
1223 2_MAS_Aqf.3_tomatoes     0.006          0.004
1224 2_MAS_Aqf.4_kale         0.003          0.014
1225 2_MAS_Aqf.5_onion        0.002          0.003
1226 2_MAS_Aqf.6_watmelon     0.007          0.008
1227 ;
1228
1229 land_agr_p(z,c,i,t)= land_agr_p(z,c,i,'2009')+ eps;
1230
1231 Parameter growth_land_p(i) // Assume no growth in irrigated land since 2009

```

```

1232 /1_Nairobi_farm      .00
1233 2_KiamArea_farm      .00
1234 3_Wajir_farm         .00
1235 4_Habaswein_farm     .00
1236 /
1237 ;
1238
1239 land_agr_p(z,c,i,t) = [(1 + growth_land_p(i)) ** ord(t)] * land_agr_p(z,c,i,'2009');
1240
1241 option land_agr_p:4; display land_agr_p;
1242
1243
1244 land_agr_p(z,c,i,t) = 1.0 * land_agr_p(z,c,i,t) + eps;
1245
1246 parameter tot_land_agr_p(z,t) total land in crop prod by county and Year;
1247
1248 tot_land_agr_p(z,t) = sum((c,i), land_agr_p(z,c,i,t)) + eps;
1249
1250 display land_agr_p, tot_land_agr_p;
1251
1252 *Citations for irrigated agriculture parameters (read data):
1253
1254 *Koei N. The Project on the Development of the National Water Master Plan 2030; Final Report;
1255 *Volume V Sectoral Report (E)-Agriculture and Irrigation; The Republic of Kenya. Water Resources
1256 * Management Authority: Nairobi, Kenya, (2013).
1257
1258 *FAO. Irrigation water requirement and water withdrawal by country. 2012).
1259
1260 *FAO. Food Price Monitoring and Analysis Database:
1261 *A web-based tool for analysis and dissemination of price data. (2020).
1262 * ----- end of irrg ag read paramaters -----
1263 * ----- Read livestock Data -----
1264
1265
1266 table yield_lvstk_p(v,l,t) observed livestock productivity (metric ton per animal\yr)
1267
1268 1_Nairobi_lvstk.2009 2_KiamArea_lvstk.2009 3_Wajir_lvstk.2009 4_Habaswein_lvstk.2009
1269 1_Cattle 0.2348 0.2348 0.2348 0.2348
1270 2_Camel 0.3000 0.3000 0.3000 0.3000
1271 3_Goat 0.0120 0.0120 0.0120 0.0120
1272 4_Sheep 0.0140 0.0140 0.0140 0.0140

```

1273					
1274	+				
1275		1_Nairobi_lvstk.2010	2_KiamArea_lvstk.2010	3_Wajir_lvstk.2010	4_Habaswein_lvstk.2010
1276	1_Cattle	0.2402	0.2402	0.2402	0.2402
1277	2_Camel	0.3000	0.3000	0.3000	0.3000
1278	3_Goat	0.0120	0.0120	0.0120	0.0120
1279	4_Sheep	0.0140	0.0140	0.0140	0.0140
1280					
1281	+				
1282		1_Nairobi_lvstk.2011	2_KiamArea_lvstk.2011	3_Wajir_lvstk.2011	4_Habaswein_lvstk.2011
1283	1_Cattle	0.2177	0.2177	0.2177	0.2177
1284	2_Camel	0.3000	0.3000	0.3000	0.3000
1285	3_Goat	0.0146	0.0146	0.0146	0.0146
1286	4_Sheep	0.0131	0.0131	0.0131	0.0131
1287					
1288	+				
1289		1_Nairobi_lvstk.2012	2_KiamArea_lvstk.2012	3_Wajir_lvstk.2012	4_Habaswein_lvstk.2012
1290	1_Cattle	0.1871	0.1871	0.1871	0.1871
1291	2_Camel	0.3000	0.3000	0.3000	0.3000
1292	3_Goat	0.0167	0.0167	0.0167	0.0167
1293	4_Sheep	0.0140	0.0140	0.0140	0.0140
1294					
1295	+				
1296		1_Nairobi_lvstk.2013	2_KiamArea_lvstk.2013	3_Wajir_lvstk.2013	4_Habaswein_lvstk.2013
1297	1_Cattle	0.1979	0.1979	0.1979	0.1979
1298	2_Camel	0.3000	0.3000	0.3000	0.3000
1299	3_Goat	0.0176	0.0176	0.0176	0.0176
1300	4_Sheep	0.0150	0.0150	0.0150	0.0150
1301					
1302	+				
1303					
1304		1_Nairobi_lvstk.2014	2_KiamArea_lvstk.2014	3_Wajir_lvstk.2014	4_Habaswein_lvstk.2014
1305	1_Cattle	0.2131	0.2131	0.2131	0.2131
1306	2_Camel	0.2994	0.2994	0.2994	0.2994
1307	3_Goat	0.0171	0.0171	0.0171	0.0171
1308	4_Sheep	0.0131	0.0131	0.0131	0.0131
1309					
1310	+				
1311		1_Nairobi_lvstk.2015	2_KiamArea_lvstk.2015	3_Wajir_lvstk.2015	4_Habaswein_lvstk.2015
1312	1_Cattle	0.2142	0.2142	0.2142	0.2142
1313	2_Camel	0.2996	0.2996	0.2996	0.2996

```

1314 3_Goat          0.0159          0.0159          0.0159          0.0159
1315 4_Sheep         0.0116          0.0116          0.0116          0.0116
1316
1317 +
1318      1_Nairobi_lvstk.2016  2_KiamArea_lvstk.2016  3_Wajir_lvstk.2016  4_Habaswein_lvstk.2016
1319 1_Cattle         0.2150          0.2150          0.2150          0.2150
1320 2_Camel          0.3001          0.3001          0.3001          0.3001
1321 3_Goat           0.0094          0.0094          0.0094          0.0094
1322 4_Sheep         0.0097          0.0097          0.0097          0.0097
1323
1324 +
1325      1_Nairobi_lvstk.2017  2_KiamArea_lvstk.2017  3_Wajir_lvstk.2017  4_Habaswein_lvstk.2017
1326 1_Cattle         0.2274          0.2274          0.2274          0.2274
1327 2_Camel          0.3000          0.3000          0.3000          0.3000
1328 3_Goat           0.0076          0.0076          0.0076          0.0076
1329 4_Sheep         0.0062          0.0062          0.0062          0.0062
1330
1331 +
1332      1_Nairobi_lvstk.2018  2_KiamArea_lvstk.2018  3_Wajir_lvstk.2018  4_Habaswein_lvstk.2018
1333 1_Cattle         0.2344          0.2344          0.2344          0.2344
1334 2_Camel          0.3000          0.3000          0.3000          0.3000
1335 3_Goat           0.0077          0.0077          0.0077          0.0077
1336 4_Sheep         0.0088          0.0088          0.0088          0.0088
1337
1338 +
1339      1_Nairobi_lvstk.2019  2_KiamArea_lvstk.2019  3_Wajir_lvstk.2019  4_Habaswein_lvstk.2019
1340 1_Cattle         0.2344          0.2344          0.2344          0.2344
1341 2_Camel          0.3000          0.3000          0.3000          0.3000
1342 3_Goat           0.0077          0.0077          0.0077          0.0077
1343 4_Sheep         0.0088          0.0088          0.0088          0.0088
1344 ;
1345
1346 option yield_lvstk_p:4;      display yield_lvstk_p;
1347
1348 *-----
1349
1350 table price_lvstk_p(v,t)      output price      (US$ per metric ton)
1351      2009      2010      2011      2012      2013      2014
1352 1_Cattle      1009.0      1077.9      1011.6      1311.3      1414.7      1530.4
1353 2_Camel      1429.8      1706.1      1245.3      1308.4      1418.0      1572.4
1354 3_Goat      1621.1      1386.7      1332.9      1433.0      1312.6      1349.8

```

```

1355 4_Sheep          2227.1      2227.1      2227.1      2210.3      1903.8      1695.1
1356
1357 +
1358          2015      2016      2017      2018      2019
1359 1_Cattle          905.4      905.4      905.4      905.4      1009.0
1360 2_Camel          1544.3      1544.3      1544.3      1544.3      1429.8
1361 3_Goat           905.4      905.4      905.4      905.4      1621.1
1362 4_Sheep          763.9      763.9      763.9      763.9      2227.1
1363 ;
1364
1365 display price_lvstk_p;
1366
1367
1368
1369 table    res_use_lvstk_p(v,q,l)    livestock water use requirements (1000 M3 per head per year)
1370 * data limits require constant for all Years
1371
1372          lv_water.1_Nairobi_lvstk  lv_water.2_KiamArea_lvstk
1373 1_Cattle          .028              .028
1374 2_Camel          .021              .021
1375 3_Goat           .012              .012
1376 4_Sheep          .013              .013
1377
1378 +
1379
1380          lv_water.3_Wajir_lvstk  lv_water.4_Habaswein_lvstk
1381 1_Cattle          .028              .028
1382 2_Camel          .021              .021
1383 3_Goat           .012              .012
1384 4_Sheep          .013              .013
1385 ;
1386
1387
1388 res_use_lvstk_p(v,'head',l) = 1;    // head per head = 1
1389
1390 display res_use_agr_p;
1391
1392 table  head_lvstk_p(z,v,l,t)  livestock population water demand served by groundwater  (1000 head)
1393
1394          1_Nairobi_lvstk.2009      2_KiamArea_lvstk.2009
1395 1_NAS_Aqf.1_Cattle          0.872              6.557

```

```

1396 1_NAS_Aqf.2_Camel          eps          eps
1397 1_NAS_Aqf.3_Goat          0.699        1.667
1398 1_NAS_Aqf.4_Sheep         0.641        5.516
1399
1400 2_MAS_Aqf.1_Cattle          eps          eps
1401 2_MAS_Aqf.2_Camel          eps          eps
1402 2_MAS_Aqf.3_Goat          eps          eps
1403 2_MAS_Aqf.4_Sheep          eps          eps
1404
1405 +
1406
1407          3_Wajir_lvstk.2009      4_Habaswein_lvstk.2009
1408 1_NAS_Aqf.1_Cattle          eps          eps
1409 1_NAS_Aqf.2_Camel          eps          eps
1410 1_NAS_Aqf.3_Goat          eps          eps
1411 1_NAS_Aqf.4_Sheep          eps          eps
1412
1413 2_MAS_Aqf.1_Cattle          0.213        10.217
1414 2_MAS_Aqf.2_Camel          0.338        12.569
1415 2_MAS_Aqf.3_Goat          1.105        28.084
1416 2_MAS_Aqf.4_Sheep          1.850        24.471
1417 ;
1418
1419
1420 Parameter growth_lvstk_p(1)    // Assume growth rate of 1% in NAS and 1.5% in MAS
1421 /1_Nairobi_lvstk      0.010
1422 2_KiamArea_lvstk      0.010
1423 3_Wajir_lvstk         0.015
1424 4_Habaswein_lvstk     0.015
1425 /
1426 ;
1427
1428 head_lvstk_p(z,v,l,t) = [(1 + growth_lvstk_p(1)) ** ord(t)] * head_lvstk_p(z,v,l,'2009') + eps;
1429
1430 * formula forecasts livestock numbers based on historical growth rates
1431 option head_lvstk_p:3; display head_lvstk_p;
1432
1433 *Citations for livestock agriculture parameters (read data):
1434
1435 *FAO. Food Price Monitoring and Analysis Database:
1436 *A web-based tool for analysis and dissemination of price data.) (2020).

```

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1437
1438 *Kenya National Bureau of Statistics. 2019 Kenya Population and Housing Census - Volume IV:
1439 *Distribution of Population by Socio-Economic Characteristics.). Released on December 2019,
1440 *Kenya National Bureau of Statistics (2019).
1441
1442 *FAO. Water use of livestock production systems and supply chains - Guidelines for assessment
1443 *(Draft for public review). Livestock Environmental Assessment and Performance (LEAP) Partnership.
1444 * Food and Agriculture Organization of the United Nations (2018).
1445
1446 *Kenya National Bureau of Statistics. 2009 Kenya Population and Housing Census - Volume II:
1447 *Population and Household Distribution by Socio-Economic Characteristics). Released on August 2010,
1448 *Kenya National Bureau of Statistics (2010).
1449
1450 * ----- end of livestock ag read parameter -----
1451
1452 * ----- begin residential use parameters -----
1453
1454 *Observed pumping per a household based on an average household size of 5 in NAS MAS areas
1455 *(each person consume 40 m3/yr)
1456
1457 table pumping_urb_cap_p (u,k) observed average resid pumping per unit per year(1000 M3 per Year)
1458
1459         1_Nairobi_resid      2_KiamArea_resid      3_Wajir_resid
1460 all_residential      .20      .20      .20
1461
1462 +
1463
1464         4_Habaswein_resid      5_Mert_Ddab_resid
1465 all_residential      .20      0.20
1466 ;
1467
1468 *DATA from Guyalni et al 2005 World Bank study      USD$ 3.5/m3 which is 3500 per 1000 m3
1469 table price_urb_p      (u,k)      observed price charged      (US $ per 1000 M3)
1470
1471         1_Nairobi_resid      2_KiamArea_resid      3_Wajir_resid
1472 all_residential      3500.00      3500.00      3500.00
1473
1474 +
1475         4_Habaswein_resid      5_Mert_Ddab_resid
1476 all_residential      3500.00      3500.00
1477

```

```

1478 ;
1479
1480
1481 *DATA from Guyalni et al 2005 World Bank study    USD$ 3.5/m3 which is 3500 per 1000 m3
1482 table    ave_cost_urb_p    (u,k)    average cost of residential supply    (US $ per 1000 M3)
1483
1484         1_Nairobi_resid    2_KiamArea_resid    3_Wajir_resid
1485 all_residential    3500.00    3500.00    3500.00
1486
1487 +
1488
1489         4_Habaswein_resid    5_Mert_Ddab_resid
1490 all_residential    3500.00    3500.00
1491
1492 ;
1493
1494 * -----
1495
1496 table    eta_urb_p    (u,k)    urban price elasticity of demand    (unitless)
1497
1498 * ---- typical shortrun price elasticity of demand - taken from the water economics literature
1499
1500         1_Nairobi_resid    2_KiamArea_resid    3_Wajir_resid
1501 all_residential    -0.20    -0.20    -0.20
1502
1503 +
1504         4_Habaswein_resid    5_Mert_Ddab_resid
1505 all_residential    -0.20    -0.20
1506 ;
1507
1508 display    eta_urb_p;
1509
1510
1511 table    pop_urb_p    (z,u,k,t)    population (scale) of users    (1000)
1512
1513         1_Nairobi_resid.2009    2_KiamArea_resid.2009    3_Wajir_resid.2009
1514 1_NAS_Aqf.all_residential    120.729    75.049    eps
1515 2_MAS_Aqf.all_residential    eps    eps    0.802
1516
1517 +
1518         4_Habaswein_resid.2009    5_Mert_Ddab_resid.2009

```



```

1519 1_NAS_Aqf.all_residential      eps      eps
1520 2_MAS_Aqf.all_residential      2.205    12.235
1521
1522 ;
1523
1524
1525 Parameter growth_urb_p(k)      // Assume 2.2% in NAS and 2% in NAS
1526
1527 /1_Nairobi_resid      0.022
1528 2_KiamArea_resid      0.022
1529 3_Wajir_resid      0.020
1530 4_Habaswein_resid      0.020
1531 5_Mert_Ddab_resid      0.020
1532 /
1533 ;
1534
1535 pop_urb_p (z,u,k,t)= [(1 + growth_urb_p(k)) ** ord(t)] * pop_urb_p(z,u,k,'2009') + eps;
1536
1537 * this formula forecasts population growth based on historical growth rates
1538 display pop_urb_p;
1539
1540 *Citations for residential use parameters:
1541
1542 *Pavelic P, Giordano M, Keraita BN, Ramesh V, Rao T. Groundwater availability and use in Sub-Sahara
1543 *Africa: a review of 15 countries.). International Water Management Institute (IWMI) (2012).
1544
1545 *Kenya National Bureau of Statistics. 2009 Kenya Population and Housing Census - Volume II:
1546 *Population and Household Distribution by Socio-Economic Characteristics). Released on August 2010,
1547 *Kenya National Bureau of Statistics (2010).
1548
1549 *Kenya National Bureau of Statistics. 2019 Kenya Population and Housing Census - Volume IV:
1550 *Distribution of Population by Socio-Economic Characteristics.). Released on December 2019,
1551 *Kenya National Bureau of Statistics (2019).
1552
1553 *Gulyani S, Talukdar D, Kariuki RM. Water for the urban poor: Water markets, household demand,
1554 *and service preferences in Kenya. (2005).
1555
1556 *Wagner J, Cook J, Kimuyu P. Household demand for water in rural Kenya.
1557 *Environmental and Resource Economics 74, 1563-1584 (2019).
1558
1559

```

```

1560 * -----end of urban read paramters -----
1561
1562
1563 * ----- begin industry read parameters -----
1564
1565 table  pumping_ind_unit_p      (j,n)      observed indus pumping per unit per year      (1000 M3 per yr)
1566
1567           1_Nairobi_indus      2_KiamArea_indus      3_Wajir_indus      4_Mert_Ddab_indus
1568 1_all_comml      0.128      0.128      0.128      0.128
1569 2_all_indus      0.098      0.098      0.098      0.098
1570 ;
1571
1572 table  price_ind_p      (j,n)      observed price charged      (US$ per 1000 M3)
1573
1574           1_Nairobi_indus      2_KiamArea_indus      3_Wajir_indus      4_Mert_Ddab_indus
1575 1_all_comml      3500.00      3500.00      3500.00      3500.00
1576 2_all_indus      3500.00      3500.00      3500.00      3500.00
1577 ;
1578
1579
1580 table  ave_cost_ind_p      (j,n)      average cost of industrial supply      (US$ per 1000 M3)
1581
1582           1_Nairobi_indus      2_KiamArea_indus      3_Wajir_indus      4_Mert_Ddab_indus
1583 1_all_comml      3500.00      3500.00      3500.00      3500.00
1584 2_all_indus      3500.00      3500.00      3500.00      3500.00
1585 ;
1586
1587
1588 table  eta_ind_p      (j,n)      industrial price elasticity of demand      (unitless)
1589
1590           1_Nairobi_indus      2_KiamArea_indus      3_Wajir_indus      4_Mert_Ddab_indus
1591 1_all_comml      -0.17      -0.17      -0.17      -0.17
1592 2_all_indus      -0.17      -0.17      -0.17      -0.17
1593
1594 ;
1595
1596 table  pop_ind_p      (z,j,n,t)      population (scale) of users - enterprises      (1000)
1597 * -----
1598           1_Nairobi_indus.2009      2_KiamArea_indus.2009
1599 1_NAS_Aqf.1_all_comml      50.417      5.210
1600 1_NAS_Aqf.2_all_indus      23.015      4.310

```

```

1601
1602 2_MAS_Aqf.1_all_comml      eps      eps
1603 2_MAS_Aqf.2_all_indus      eps      eps
1604
1605 +
1606
1607          3_Wajir_indus.2009      4_Mert_Ddab_indus.2009
1608 1_NAS_Aqf.1_all_comml      eps      eps
1609 1_NAS_Aqf.2_all_indus      eps      eps
1610
1611 2_MAS_Aqf.1_all_comml      0.577      1.320
1612 2_MAS_Aqf.2_all_indus      eps      eps
1613
1614 ;
1615
1616
1617 Parameter growth_ind_p(n)      // Assume 2% in NAS and 1.5% in MAS
1618
1619 /1_Nairobi_indus      .020
1620 2_KiamArea_indus      .020
1621 3_Wajir_indus      .015
1622 4_Mert_Ddab_indus      .015
1623 /
1624
1625 ;
1626
1627 pop_ind_p(z,j,n,t)= [(1 + growth_ind_p(n)) ** ord(t)] * pop_ind_p(z,j,n,'2009') + eps;
1628 * formula forecasts enterprises based on historical growth rates
1629
1630 option pop_ind_p:3; display      pop_ind_p;
1631
1632 *Citations for commercial and industrial use parameters (read data):
1633 *Gulyani S, Talukdar D, Kariuki RM. Water for the urban poor: Water markets, household demand,
1634 *and service preferences in Kenya. (2005).
1635
1636 *Kenya National Bureau of Statistics. Report on the 2017 Census of Establishments (CoE).
1637 *Kenya National Bureau of Statistics (2017).
1638
1639 *Wagner J, Cook J, Kimuyu P. Household demand for water in rural Kenya.
1640 *Environmental and Resource Economics 74, 1563-1584 (2019).
1641

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1642 *Kenya National Bureau of Statistics. Micro, Small and Medium Establishments, Basic Report.
1643 *Kenya National Bureau of Statistics (2016).
1644
1645
1646 * ----- end industry read parameters -----
1647 parameter
1648
1649 *hydrology overall and by sector
1650
1651 depth_p          (z, t)    aquifer depth by Year          (M)
1652 change_depth_p   (z, t)    change in aquifer depth by Year  (M per Year)
1653 disc_fact_p      ( t)     discount factor by Year          (unitless)
1654
1655 pumping_agr_p     (z,c,i,t) observed ag pumping          (million M3 per Year)
1656 tot_pump_agr_p    (z, t)    total observed ag pumping        (million M3 per Year)
1657
1658 pumping_lvstk_p   (z,v,l,t) observed livestock pumping    (million M3 per Year)
1659 tot_pump_lvstk_p  (z, t)    total observed ag pumping        (million M3 per Year)
1660
1661 pumping_urb_p     (z,u,k,t) observed urban pumping urban  (million M3 per Year)
1662 tot_pump_urb_p    (z, t)    total observed urban pumping      (million M3 per Year)
1663
1664 pumping_ind_p     (z,j,n,t) observed commercial pumping    (million M3 per Year)
1665 tot_pump_ind_p    (z, t)    total observed commercial pumping  (million M3 per Year)
1666
1667
1668 *----- economics ag -----
1669 * irrigated crop
1670 B0_agr_p          (z,c,i,t) intcpt crop wat prod fn - max yield  (m tons per HA)
1671 B1_agr_p          (z,c,i,t) slope crop wat prod fn - ch yield ch land (m tons per HA)
1672
1673 gross_rev_agr_p   ( c,i,t) gross revenue per unit land ag  (US$ per HA)
1674 cost_agr_p        ( c,i,t) crop variable cost incl base pump costs ost (US$ per HA)
1675 pump_cost_ac_agr_depth_p(z,c,i,t) ag pumping cost per acre per add depth (US$ per HA per M)
1676
1677 net_rev_agr_p     (z,c,i,t) observed net ag revenue per unit land  (US$ per HA)
1678 net_welfare_yr_agr_p (z,c,i,t) observed net welfare per Year  (US$ 1000 per yr)
1679 net_welfare_agr_p (z,c,i,t) observed net welfare agr  (US$ 1000)
1680
1681 *livestock
1682 B0_lvstk_p        (z,v,l,t) intcpt lvstk wat prod fn - max yield  (m tons per head)

```

1683	B1_lvstk_p	(z,v,l,t)	slope lvstk wat prod fn - ch yield ch land (m tons per head)	
1684				
1685	gross_rev_lvstk_p	(v,l,t)	gross revenue per unit land ag	(US\$ per head)
1686	cost_lvstk_p	(v,l,t)	head variable cost incl base pump costs	(US\$ per head)
1687	pump_cost_h_lvstk_depth_p	(z,v,l,t)	ag pumping cost per head per add depth	(US\$ per head per M)
1688				
1689	net_rev_lvstk_p	(z,v,l,t)	observed net livestock revenue per head	(US\$ per head)
1690	net_welfare_yr_lvstk_p	(z,v,l,t)	observed net welfare per Year	(US\$ 1000 per yr)
1691	net_welfare_lvstk_p		observed net welfare agr	(US\$ 1000)
1692				
1693	*-----			
1694				
1695	*economics residential water use			
1696				
1697	B0_urb_p	(z,u,k,t)	max price in price dependent urb demand	(US\$ per 1000 M3)
1698	B1_urb_p	(z,u,k,t)	slope in price dependent urb demand fn	(US\$ per 1000 M3 sq)
1699				
1700	c_sur_urb_p	(z,u,k,t)	total consumer surplus urb observed	(US\$ 1000 per Year)
1701	G_rev_urb_p	(z,u,k,t)	total gross revenue urb observed	(US\$ 1000 per Year)
1702	T_cost_urb_p	(z,u,k,t)	total cost urb observed	(US\$ 1000 per Year)
1703	welfare_urb_p	(z,u,k,t)	total urban welfare observed	(US\$ 1000 per Year)
1704	T_welfare_urb_p	(t)	total urban welfare over uses	(US\$ 1000 per Year)
1705				
1706	price_check_urb_p	(z,u,k,t)	cross check on predicted-obs price	(US\$ per 1000 M3)
1707				
1708	*economics commercial water use			
1709				
1710	B0_ind_p	(z,j,n,t)	max price in price dependent ind demand	(\$US per 1000 M3)
1711	B1_ind_p	(z,j,n,t)	slope in price dependent ind demand fn	(\$US per 1000 M3 sq)
1712				
1713	c_sur_ind_p	(z,j,n,t)	total consumer surplus urb observed	(\$US 1000 per Year)
1714	G_rev_ind_p	(z,j,n,t)	total gross revenue urb observed	(\$US 1000 per Year)
1715	T_cost_ind_p	(z,j,n,t)	total cost urb observed	(\$US 1000 per Year)
1716	welfare_ind_p	(z,j,n,t)	total urban welfare observed	(\$US 1000 per Year)
1717	T_welfare_ind_p	(t)	total urban welfare over uses	(\$US 1000 per Year)
1718				
1719	price_check_ind_p	(z,j,n,t)	cross check on predicted-obs price	(\$US per 1000 M3)
1720				
1721	*-----			
1722				
1723	* hydrology totals over sectors			

```

1724
1725 tot_pumping_p      (z,    t) tot obs pumping summed over sect uses      (million M3 per Year)
1726 tot_recharge_p     (z,    t) tot inferred rech based on pump + depth ch  (million M3 per Year)
1727 net_recharge_p     (z,    t) tot change in depth cross check             (M per Year      )
1728 change_depth_check_p (z,    t) ch depth check for consis                 (M              )
1729 rechrg_flux_p      (z,    t) recharge rate  calc below                  (million M3 per Year)
1730 change_storage_p   (z,    t) change in storage by Year                  (million M3 per Year)
1731 storage_p          (z,    t) aquifer storage over time                  (million M3 by  Year)
1732
1733
1734 * economics summed over sectors
1735
1736 tot_econ_welfare_p      total economic welfare in parameters      (US$)
1737 ;
1738
1739 * actual calculations for parameters
1740
1741 disc_fact_p    ( t) = 1/[(1+rho_p) ** (ord(t) - 1)];
1742
1743 display disc_fact_p;
1744
1745 * calculates depth over Years based on starting depth and observed change in depth by Year
1746
1747 change_depth_p(z,t) $ (ord(t) gt 1)  = change_depth0_p(z) + eps; // obs ave change depth to pump
1748
1749 depth_p(z,t) $ (ord(t) eq 1)  = depth0_p(z); // first Year's (starting) ave depth
1750
1751
1752 * loops below to track depth in all future Years after 1st
1753
1754 loop (t, depth_p(z,t) $ (ord(t) gt 1)  = depth_p(z,t-1) + change_depth_p(z,t));
1755
1756 display depth0_p, change_depth_p, depth_p;
1757
1758
1759 * ----- ag parameters calculated -----
1760 *irrigated crop
1761
1762 gross_rev_agr_p(c,i,t) = price_agr_p(c,t) * yield_agr_p(c,i,t) + eps;
1763
1764

```

```

1765 cost_agr_p(c,i,t) = ag_crop_cost_prop_p(c) * gross_rev_agr_p(c,i,t) + eps;
1766
1767 display gross_rev_agr_p, cost_agr_p;
1768
1769
1770 pumping_agr_p(z,c,i,t)      =      land_agr_p(z,c,i,t) * res_use_agr_p(c,'ag_water',i) + eps;
1771
1772 pumping_agr_p(z,c,i,t)      =      pumping_agr_p(z,c,i,t) + eps;
1773
1774 tot_pump_agr_p(z,t)          = sum((c,i), pumping_agr_p(z,c,i,t)) + eps;
1775
1776 display pumping_agr_p, tot_pump_agr_p;
1777
1778
1779 ;
1780 pump_cost_ac_agr_depth_p(z,c,i,t)  =  pc_af_f_p(z) *      (depth_p(z,t) - depth0_p(z))
1781                                     *      res_use_agr_p(c,'ag_water',i) + eps;
1782
1783 display pump_cost_ac_agr_depth_p;
1784
1785 net_rev_agr_p(z,c,i,t)            = price_agr_p(c,t) * yield_agr_p(c,i,t) - cost_agr_p(c,i,t)
1786                                   - pump_cost_ac_agr_depth_p(z,c,i,t) + eps;
1787
1788 net_welfare_yr_agr_p(z,c,i,t)     = net_rev_agr_p(z,c,i,t) * land_agr_p(z,c,i,t) + eps;
1789
1790 net_welfare_agr_p                  = sum((z,c,i,t), net_rev_agr_p(z,c,i,t) * land_agr_p(z,c,i,t))
1791                                   + eps;
1792
1793 display net_rev_agr_p, net_welfare_yr_agr_p;
1794
1795 option net_welfare_agr_p:0; display net_welfare_agr_p;
1796
1797 ;
1798 *-----begin livestock pumping -----
1799 *livestock
1800
1801 gross_rev_lvstk_p(v,l,t) = price_lvstk_p(v,t) * yield_lvstk_p(v,l,t) + eps;
1802 ;
1803
1804 cost_lvstk_p(v,l,t) = ag_lvstk_cost_prop_p(v) * gross_rev_lvstk_p(v,l,t) + eps;
1805

```

```

1806 display gross_rev_lvstk_p, cost_lvstk_p;
1807 ;
1808
1809 pumping_lvstk_p(z,v,l,t)      =      head_lvstk_p(z,v,l,t) * res_use_lvstk_p(v,'lv_water',l) + eps;
1810
1811 pumping_lvstk_p(z,v,l,t)      =      pumping_lvstk_p(z,v,l,t) + eps;
1812
1813 tot_pump_lvstk_p(z,t)         = sum((v,l), pumping_lvstk_p(z,v,l,t)) + eps;
1814
1815 display pumping_lvstk_p, tot_pump_lvstk_p;
1816
1817
1818 ;
1819 pump_cost_h_lvstk_depth_p(z,v,l,t)  =      pc_af_f_p(z) *      (depth_p(z,t) - depth0_p(z))
1820                                     *      res_use_lvstk_p(v,'lv_water',l)
1821                                     + eps;
1822
1823 display pump_cost_h_lvstk_depth_p;
1824
1825 net_rev_lvstk_p(z,v,l,t)          = price_lvstk_p(v,t) * yield_lvstk_p(v,l,t) - cost_lvstk_p(v,l,t)
1826                                   - pump_cost_h_lvstk_depth_p(z,v,l,t) + eps;
1827
1828 net_welfare_yr_lvstk_p(z,v,l,t) = net_rev_lvstk_p(z,v,l,t) * head_lvstk_p(z,v,l,t) + eps;
1829
1830 net_welfare_lvstk_p              = sum((z,v,l,t), net_rev_lvstk_p(z,v,l,t) * head_lvstk_p(z,v,l,t))+ eps;
1831
1832
1833 display net_rev_lvstk_p, net_welfare_yr_lvstk_p;
1834
1835 option net_welfare_lvstk_p:0; display net_welfare_lvstk_p;
1836
1837 ;
1838 * -----
1839 * Positive Mathematical Programming (pmp) parameters for agr derived below.
1840 * Derived are 2 parameters that force (calibrate) optimized acreage and yields to match
1841 * historical base conditions.
1842
1843 * This calibration sets the foundation for an unconstrained quadratic programming model
1844 * in which all constraints are removed to the crop mix.
1845 * model is driven only by these requirements
1846 *

```



```

1847 * 1. price of land/water equals declining value of marginal product under assumed profit max
1848 * 2. base land and water constraints are respected
1849 * 3. Hist data on average profitability, land in production, crop mix, and yield are reproduced
1850 *
1851 * PMP guarantees smooth adjustments to future water supply or Policy changes
1852
1853 * Cite:
1854 * Economics of Agricultural Water Conservation: Empirical Analysis and Policy Implications
1855 * Macarena Dagnino & Frank A. Ward
1856 * International Journal of Water Resources Development
1857 * Pages 577-600 Published 18 Apr 2012
1858 * ----- PMP for irrigated crop production parameters -----
1859
1860
1861 B1_agr_p(z,c,i,t) $(land_agr_p(z,c,i,t) > 0) = -Net_rev_agr_p(z,c,i,t)/[.0001 + Price_agr_p(c,t)
1862 * Land_agr_p(z,c,i,t)] + eps;
1863 * // see article above for derivation
1864
1865 B0_agr_p(z,c,i,t) $(land_agr_p(z,c,i,t) > 0) = Yield_agr_p( c,i,t) -
1866 B1_agr_p(z,c,i,t) * Land_agr_p(z,c,i,t) + eps;
1867 * // ditto
1868
1869
1870 display net_rev_agr_p, B0_agr_p, B1_agr_p;
1871
1872 * ----- end of irrigated crop calculated parameters -----
1873 * ----- PMP for livestock calculated parameters -----
1874
1875
1876 B1_lvstk_p(z,v,l,t)$(head_lvstk_p(z,v,l,t)> 0)= -Net_rev_lvstk_p(z,v,l,t)/[.0001+Price_lvstk_p(v,t)
1877 * head_lvstk_p(z,v,l,t)] + eps;
1878 * // see article above for derivation
1879
1880 B0_lvstk_p(z,v,l,t) $( head_lvstk_p(z,v,l,t) > 0) = Yield_lvstk_p( v,l,t) -
1881 B1_lvstk_p(z,v,l,t) * head_lvstk_p(z,v,l,t) + eps;
1882 * // ditto
1883
1884 display net_rev_lvstk_p, B0_lvstk_p, B1_lvstk_p;
1885
1886 * ----- begin urban calculated parameters -----
1887

```

```

1888
1889 * total pumping_urb use is pumping_urb per household times number of households
1890
1891 pumping_urb_p(z,u,k,t) = pumping_urb_cap_p(u,k) * pop_urb_p(z,u,k,t) + eps;
1892
1893 tot_pump_urb_p(z, t) = sum((u,k), pumping_urb_p(z,u,k,t)) + eps; //total observed urban pumping
1894
1895 // Slope and intercept terms for the linear price_urb-dependent equation are found below
1896 // They come by solving 2 equations and 2 unknowns for the unobserved B1_urb_p and B0_urb_p:
1897 // pumping_urb_p is observed total urban pumping (use)
1898 // price_urb_p is observed urban price charged per unit use
1899
1900 // 1. urban price elasticity, eta_urb_p, defined as: eta_urb_p = (dq/dp) * (p/q) = (1/B1_urb_p)
1901 // * (price_urb_p / pumping_urb_p);
1902 // 2. observed price, price_urb, is fn of quantity: price_urb0 = B0_urb_p + B1_urb_p * pumping_urb_p
1903
1904 // After messy algebra, we solve for B0_urb_p and B1_urb_p, giving intercept and slope on(inferred)
1905 // linear demand
1906 // Those 2 parameters can be used to forecast linear demand at forecast pumping, cost, population,
1907 // and elasticity
1908 // Urban price is a linear fn of use, price elasticity of demand
1909
1910 B1_urb_p(z,u,k,t) $ (pumping_urb_p(z,u,k,t) > 0) = price_urb_p(u,k) /
1911 (pumping_urb_p(z,u,k,t) * eta_urb_p(u,k)) + eps;
1912
1913 B0_urb_p(z,u,k,t) $ (pumping_urb_p(z,u,k,t) > 0) = price_urb_p(u,k) - B1_urb_p(z,u,k,t)
1914 * pumping_urb_p(z,u,k,t) + eps;
1915
1916 // Above finds B0_urb_p and B1_urb_p. It lets us calculate cons surplus and then optimized welfare:
1917
1918 price_check_urb_p(z,u,k,t) = B0_urb_p(z,u,k,t) + B1_urb_p(z,u,k,t)
1919 * pumping_urb_p(z,u,k,t) + eps;
1920
1921 C_sur_urb_p(z,u,k,t) = 0.5 * (B0_urb_p(z,u,k,t) - price_urb_p(u,k))
1922 * pumping_urb_p(z,u,k,t) + eps;
1923 * // note B0_urb depends on B1_urb
1924
1925
1926 G_rev_urb_p(z,u,k,t) = price_urb_p(u,k) * pumping_urb_p(z,u,k,t) + eps;
1927
1928 T_cost_urb_p(z,u,k,t) = ave_cost_urb_p(u,k) * pumping_urb_p(z,u,k,t) + eps;

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```

1929
1930 // Next is total observed urban welfare = urban consumer surplus + urb rev - urban production cost
1931
1932 welfare_urb_p(z,u,k,t) = C_sur_urb_p(z,u,k,t) + G_rev_urb_p(z,u,k,t) - T_cost_urb_p(z,u,k,t) + eps;
1933
1934 T_welfare_urb_p(    t) = sum((z,u,k), welfare_urb_p(z,u,k,t)) + eps;
1935
1936 display
1937
1938 pop_urb_p,  pumping_urb_cap_p, pumping_urb_p,  B1_urb_p, B0_urb_p, price_urb_p, price_check_urb_p,
1939 C_sur_urb_p, G_rev_urb_p, T_cost_urb_p, ave_cost_urb_p, tot_pump_urb_p,
1940 welfare_urb_p, T_welfare_urb_p
1941 ;
1942
1943 * ----- end urban parameters -----
1944
1945 * ----- begin industry calculated parameter eqs -----
1946
1947 * total pumping_ind use is pumping_ind per business unit times number of business units
1948
1949 pumping_ind_p(z,j,n,t) =    pumping_ind_unit_p(j,n) * pop_ind_p(z,j,n,t) + eps;
1950
1951 tot_pump_ind_p(z,    t) =    sum((j,n), pumping_ind_p(z,j,n,t)) + eps; // total obs industry pumping
1952
1953
1954 // Slope and intercept terms for the linear price_urb-dependent equation are found below
1955 // They come by solving 2 equations and 2 unknowns for the unobserved B1_urb_p and B0_urb_p:
1956 // pumping_urb_p is observed total urban pumping (use)
1957 // price_urb_p is observed urban price charged per unit use
1958
1959 // 1. industrial price elasticity, eta_urb_p, defined as: eta_urb_p= (dq/dp) * (p/q) = (1/B1_urb_p)
1960 //                                     * (price_urb_p / pumping_urb_p);
1961 // 2. observed price, price_urb,is fn of quantity: price_urb0 = B0_urb_p + B1_urb_p * pumping_urb_p
1962
1963 // After messy algebra, we solve for B0_urb_p and B1_urb_p, giving intcept and slope on (inferred)
1964 // linear demand
1965 // Those 2 parameters can be used to forecast linear demand at forecast pumping, cost, population,
1966 // and elasticity
1967 // Urban price is a linear fn of use, price elasticity of demand
1968
1969 B1_ind_p(z,j,n,t) $ (pumping_ind_p(z,j,n,t) > 0)    =    price_ind_p(j,n)/

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```

1970                                     (pumping_ind_p(z,j,n,t) * eta_ind_p(j,n)) + eps;
1971
1972 B0_ind_p(z,j,n,t) $ (pumping_ind_p(z,j,n,t) > 0) = price_ind_p(j,n) - B1_ind_p(z,j,n,t)
1973                                     * pumping_ind_p(z,j,n,t) + eps;
1974
1975 // Above finds B0_ind_p and B1_ind_p. It lets us calculate cons surplus and then optimized welfare:
1976
1977 Price_check_ind_p(z,j,n,t) = B0_ind_p (z,j,n,t) + B1_ind_p(z,j,n,t)
1978                             * pumping_ind_p(z,j,n,t) + eps;
1979
1980 C_sur_ind_p (z,j,n,t) = 0.5 * (B0_ind_p (z,j,n,t) - price_ind_p( j,n))
1981                             * pumping_ind_p(z,j,n,t) + eps;
1982                                     // note B0_ind depends on B1_ind
1983
1984 G_rev_ind_p (z,j,n,t) = price_ind_p ( j,n) * pumping_ind_p(z,j,n,t);
1985
1986 T_cost_ind_p (z,j,n,t) = ave_cost_ind_p( j,n) * pumping_ind_p(z,j,n,t);
1987
1988 // Next is total observed commercial welfare = consumer surplus + revenue - production cost
1989
1990 welfare_ind_p (z,j,n,t) = C_sur_ind_p(z,j,n,t) + G_rev_ind_p(z,j,n,t) - T_cost_ind_p(z,j,n,t) + eps;
1991
1992 T_welfare_ind_p( t) = sum((z,j,n), welfare_ind_p(z,j,n,t)) + eps;
1993
1994
1995 display pop_ind_p, pumping_ind_unit_p, pumping_ind_p, B1_ind_p, B0_ind_p, price_ind_p,
1996 Price_check_ind_p, C_sur_ind_p, G_rev_ind_p, T_cost_ind_p, tot_pump_ind_p
1997 ave_cost_ind_p, welfare_ind_p, T_welfare_ind_p
1998 ;
1999
2000 * ----- end industrial calculated parameters -----
2001
2002 * ----- hydrology, irrigated crop ag, livestock, urban, and industry parameters aggregated ---
2003
2004 tot_pumping_p(z,t) = sum((c,i), pumping_agr_p (z,c,i,t)) // agriculture pumping
2005                   + sum((v,l), pumping_lvstk_p(z,v,l,t)) // livestock pumping
2006                   + sum((u,k), pumping_urb_p (z,u,k,t)) // urban pumping
2007                   + sum((j,n), pumping_ind_p (z,j,n,t)) + eps; // commercial pumping
2008
2009 * ----- Begin Water Balance Calibration -----
2010

```

```

2011 * Below equations calculate recharge flux from precip that must have produced pumping depth
2012 * increases observed
2013 * The inferred recharge flux below is calculated based on porosity, total estimated pumping,
2014 * aquifer surface land area, and observed change in depth.
2015
2016 * A greater observed change in depth says a given estimated level of total pumping must have been
2017 * offset by a reduced level of precipitation flux, since the precip flux directly entering the
2018 * aquifer is unknown
2019
2020
2021 rechrg_flux_p(z,t) = tot_pumping_p(z,t)/aq_area_p(z)- change_depth_p(z,t) * porosity_p(z) + eps;
2022
2023 * below are 3 cross check validation equations to see if the above recharge flux calculation
2024 * produces the 'known' change in depth
2025
2026 tot_recharge_p(z,t) = rechrg_flux_p(z,t) * aq_area_p(z) + eps; // tot recharge / yr
2027
2028 change_storage_p(z,t) = tot_recharge_p(z,t) - tot_pumping_p(z,t) + eps; // calcs change storage
2029
2030
2031 net_recharge_p(z,t) = tot_recharge_p(z,t) - tot_pumping_p(z,t) + eps; //net rech = rech - pump
2032
2033 change_depth_check_p(z,t) = -(net_recharge_p(z,t)/(aq_area_p(z) * porosity_p(z))) + eps; //chg depth
2034
2035
2036 tot_econ_welfare_p = sum((z,c,i,t), disc_fact_p(t) * net_rev_agr_p(z,c,i,t) * land_agr_p(z,c,i,t))
2037 + sum((z,v,l,t), disc_fact_p(t) * net_rev_lvstk_p(z,v,l,t)* head_lvstk_p(z,v,l,t))
2038 + sum(t, disc_fact_p(t) * t_welfare_urb_p(t))
2039 + sum(t, disc_fact_p(t) * t_welfare_ind_p(t))+ eps;
2040 ;
2041
2042 * loops to find observed aquifer storage over time
2043
2044 storage_p(z,t) $ (ord(t) eq 1) = storage0_p(z) + eps;
2045
2046 loop (t, storage_p(z,t) $ (ord(t) gt 1) = storage_p(z,t-1) + change_storage_p(z,t));
2047
2048 * ----- End of Water Balance Calibration -----
2049
2050 display pumping_ind_p, pumping_ind_unit_p, pop_ind_p, price_ind_p, ave_cost_ind_p, welfare_ind_p,
2051 tot_pumping_p, tot_pumping_p, B1_ind_p, B0_ind_p, g_rev_ind_p, t_cost_ind_p, c_sur_ind_p,

```

```

2052         storage0_p, depth_p, t_welfare_ind_p, change_depth_p, rechrg_flux_p, tot_recharge_p,
2053         net_recharge_p, change_depth_check_p, change_storage_p;
2054     ;
2055
2056     option storage_p:0;           //formats without scientific notation;
2057     display storage_p;
2058
2059     option tot_econ_welfare_p:0; // formats without scientific notation;
2060     display tot_econ_welfare_p;
2061
2062     * ----- display total pumping for each of the 4 classes of use -----
2063
2064     display pumping_agr_p, tot_pump_agr_p, pumping_lvstk_p, tot_pump_lvstk_p, pumping_urb_p,
2065         tot_pump_urb_p,pumping_ind_p, tot_pump_ind_p;
2066
2067
2068     * ----- end of all read and calculated parameters -----
2069
2070     * -----
2071     * ----- prepare to loop for multiple policies -----
2072     * -----
2073
2074     set pp(p); // Policy responses: as many as you like
2075     pp(p) = no; // switches subsests off for now back on below
2076
2077     * -----
2078     * ----- end of loop preparation -----
2079     * -----
2080
2081     * ----- unknown variables follow -----
2082
2083
2084     variables
2085
2086     *hydrology
2087
2088     storage_v           (z, t,p)    aquifer storage                (million m3 by yr)
2089     recharge_v          (z, t,p)    recharge by Year              (million m3 \ yr)
2090     net_recharge_v      (z, t,p)    net recharge by yr            (million m3 \ yr)
2091     depth_v             (z, t,p)    depth                          (meters by Year)
2092     exports_v           (z, t,p)    exports overflow aquifer to river-ocean (million m3 \ yr)

```

2093				
2094	* agricultural			
2095	acres_agr_v	(z,i,c,t,p)	optimized land by crop (c and t)	(1000 HA per Year)
2096	resource_agr_v	(z,r,i,t,p)	optimized resource use by resource (r)	(million m3 \yr water))
2097	pumping_agr_v	(z,i,c,t,p)	pumping in agriculture	(million m3 \ yr)
2098	T_pumping_agr_v	(z, t,p)	total pumping in agriculture	(million m3 \ yr)
2099	pump_cost_ac_agr_depth_v	(z,i,c,t,p)	pumping cost per ha ag w depth	(US\$ per HA)
2100				
2101	* livestock			
2102	head_lvstk_v	(z,l,v,t,p)	optimized head by specie (v and t)	(1000 head per Year)
2103	resource_lvstk_v	(z,q,l,t,p)	optimized resource use by resource (q)	(million m3\yr water)
2104	pumping_lvstk_v	(z,l,v,t,p)	pumping in agriculture	(million m3\yr)
2105	T_pumping_lvstk_v	(z, t,p)	total pumping in agriculture	(million m3\yr)
2106	pump_cost_h_lvstk_depth_v	(z,l,v,t,p)	pumping cost per head lvstk w depth	(US\$ per head)
2107				
2108	* urban			
2109	pumping_urb_v	(z,k,u,t,p)	total pumping urban	(million m3\yr)
2110	pumping_cap_urb_v	(z,k,u,t,p)	per unit pumping urban use	(1000 m3 \ yr)
2111	T_pumping_urb_v	(z, t,p)	total urb pumping over urb uses	(million m3\yr)
2112				
2113	* commercial			
2114	pumping_ind_v	(z,n,j,t,p)	total pumping industry	(million m3\yr)
2115	pumping_unit_ind_v	(z,n,j,t,p)	per unit pumping industry	(1000 m3 \ yr)
2116	T_pumping_ind_v	(z, t,p)	total urb pumping over industry uses	(million m3\yr)
2117				
2118	*agricultural			
2119	Yield_agr_v	(z,i,c,t,p)	optimzied crop yields per unit land	(metric tons\HA)
2120	net_rev_agr_v	(z,i,c,t,p)	optimized net revenue per unit land	(US\$ per HA)
2121				
2122	income_agr_yr_v	(z,i,c,t,p)	income by crop region Year	(US\$ 1000 \yr)
2123	income_agr_v	(z, t,p)	income from all crops	(US\$ 1000 \yr)
2124				
2125	*livestock			
2126	Yield_lvstk_v	(z,l,v,t,p)	optimzied crop yields per unit head	(metric tons\head)
2127	net_rev_lvstk_v	(z,l,v,t,p)	optimized net revenue per unit head	(US\$ per head)
2128				
2129	income_lvstk_yr_v	(z,l,v,t,p)	income by crop region Year	(US\$ 1000 per yr)
2130	income_lvstk_v	(z, t,p)	income from all livestock	(US\$ 1000 per yr)
2131				
2132	*urban			
2133	price_urb_v	(z,k,u,t,p)	urban price	(US\$ \ 1000 m3)

2134	A_cost_urb_v	(z,k,u,t,p)	average cost urban	(US\$ \ 1000 m3)
2135	T_cost_urb_v	(z,k,u,t,p)	total cost urban	(US\$ 1000 \ yr)
2136	G_rev_urb_v	(z,k,u,t,p)	gross revenue urban	(US\$ 1000 \ yr)
2137	c_sur_urb_v	(z,k,u,t,p)	consumer surplus urban	(US\$ 1000 \ yr)
2138				
2139	pump_cost_af_urb_depth_v	(z,k,u,t,p)	pump cost per volume with more depth	(US\$ \ 1000 m3)
2140	welfare_urb_v	(z,k,u,t,p)	total welfare urban	(US\$ 1000 \ yr)
2141	T_welfare_urb_v	(z, t,p)	welfare summed over urban uses	(US\$ 1000 \ yr)
2142				
2143	*industrial			
2144	price_ind_v	(z,n,j,t,p)	industry water price	(US\$ \1000 m3)
2145	A_cost_ind_v	(z,n,j,t,p)	average cost industry water use	(US\$ \1000 m3)
2146	T_cost_ind_v	(z,n,j,t,p)	total cost industry water use	(US\$ 1000 \yr)
2147	G_rev_ind_v	(z,n,j,t,p)	gross revenue industry water use	(US\$ 1000 \yr)
2148	c_sur_ind_v	(z,n,j,t,p)	consumer surplus industry water use	(US\$ 1000 \yr)
2149				
2150	pump_cost_af_ind_depth_v	(z,n,j,t,p)	pump cost per volume indusry w\depth	(US\$ \1000 m3)
2151	welfare_ind_v	(z,n,j,t,p)	total welfare industry water use	(US\$ 1000 \yr)
2152	T_welfare_ind_v	(z, t,p)	welfare summed over all industry water use	(US\$ 1000 \yr)
2153				
2154				
2155	* post optimality urban variables. They do not affect optimal solution			
2156				
2157	MNB_urb_v	(z,k,u,t,p)	marginal net benefit urban - post opt	(US\$\1000 m3)
2158	DMNB_urb_v	(z,k,u,t,p)	discounted marginal net ben urb - post opt	(US\$\1000 m3)
2159				
2160	CS_cap_urb_v	(z,k,u,t,p)	consumer surplus per capita urban - post opt	(US\$\1000 m3)
2161	GR_cap_urb_v	(z,k,u,t,p)	total gross revenue per cap urban - post opt	(US\$\1000 m3)
2162	TC_cap_urb_v	(z,k,u,t,p)	total cost urban per capita - post opt	(US\$ 1000\yr)
2163	Wel_cap_urb_v	(z,k,u,t,p)	welfare per capita urban - post opt	(US\$ 1000\yr)
2164				
2165	MC_ag_v	(z,i,c,t,p)	marginal cost added output crop	(US\$\1000 m3)
2166	MC_lvstk_v	(z,l,v,t,p)	marginal cost added output livestock	(US\$\1000 m3)
2167				
2168	MNB_ind_v	(z,n,j,t,p)	marginal net benefit indus - post opt	(\$US\1000 m3)
2169	DMNB_ind_v	(z,n,j,t,p)	discounted marginal net ben indus - post opt	(\$US\1000 m3)
2170				
2171	CS_unit_ind_v	(z,n,j,t,p)	consumer surplus per capita indus - post opt	(\$US\1000 m3)
2172	GR_unit_ind_v	(z,n,j,t,p)	total gross revenue per cap indus - post opt	(\$US\1000 m3)
2173	TC_unit_ind_v	(z,n,j,t,p)	total cost indus per capita - post opt	(\$US 1000\yr)
2174	Wel_unit_ind_v	(z,n,j,t,p)	welfare per capita indus - post opt	(\$US\1000 m3)


```

2175
2176 * ----- next we combine all sectors variables: pumping and economic welfare -----
2177
2178 Tot_pumping_v      (z,   t,p)  total pumping summed over sectors      (million m3\yr)
2179 Ave_Tot_pumping_v  (z,     p)  average total pumping summed over later years (million m3\yr)
2180
2181 Tot_economic_welfare_v  (z,   t,p)  total economic welfare      (US$ 1000  yr)
2182
2183 DNPV_ag_tot_v      (z,   t,p)  dnpv ag welfare vary by time      (US$ 1000\yr)
2184 DNPV_lvstk_tot_v    (z,   t,p)  dnpv lvstk welfare vary by time      (US$ 1000\yr)
2185 DNPV_urb_tot_v      (z,   t,p)  dnpv ur welfare vary by time      (US$ 1000\yr)
2186 DNPV_ind_tot_v      (z,   t,p)  dnpv ind welfare vary by time      (US$ 1000\yr)
2187
2188 DNPV_ag_welfare_v   (z,     p)  dnpv ag welfare      (US$ 1000)
2189 DNPV_lvstk_welfare_v (z,     p)  dnpv lvstk welfare      (US$ 1000)
2190 DNPV_urb_welfare_v   (z,     p)  dnpv urban welfare      (US$ 1000)
2191 DNPV_ind_welfare_v   (z,     p)  dnpv industry economic welfare      ($US 1000)
2192
2193 DNPV_econ_welfare_v           dnpv all economic welfare      (US$ 1000)
2194 dnpv_looped_v                dnpv all economic welfare looped      (US$ 1000)
2195 ;
2196
2197 * many non economic variables cannot be negative.  Economic variables can be negative
2198
2199 positive variables
2200
2201 exports_v      (z,   t,p)  exports overflow aquifer to river      (million m3\yr)
2202 storage_v      (z,   t,p)  aquifer storage      (million m3 by yr)
2203 recharge_v     (z,   t,p)  recharge by year      (million m3\yr)
2204 depth_v      (z,   t,p)  depth to pumping      (meters by yr)
2205 acres_agr_v   (z,i,c,t,p)  ag land in production      (1000 HA by yr)
2206 head_lvstk_v  (z,l,v,t,p)  animals in livestock production      (1000 head by yr)
2207
2208 pumping_urb_v  (z,k,u,t,p)  total pumping urban      (million m3  yr)
2209 pumping_ind_v  (z,n,j,t,p)  total pumping commercial      (million m3\yr)
2210
2211
2212 * ----- Equations begin -----
2213
2214 Equations
2215

```

2216	*hydrology			
2217				
2218	storage0_e	(z, t,p)	initial aq storage	(1000 KM3 initial)
2219	storage_e	(z, t,p)	aquifer storage	(1000 KM3 by yr)
2220	recharge_e	(z, t,p)	recharge by year	(1000 KM3 by yr)
2221	net_recharge_e	(z, t,p)	net recharge by yr	(1000 KM3 \ yr)
2222	depth0_e	(z, t,p)	initital aquifer depth	(meter)
2223	depth_e	(z, t,p)	aquifer depth	(meter by yr)
2224				
2225				
2226	*irrig ag			
2227	Yield_agr_e	(z,i,c,t,p)	crop yield	(tons per HA)
2228	net_rev_agr_e	(z,i,c,t,p)	optimized net revenue per acre	(US\$ per HA)
2229	resource_agr_e	(z,r,i,t,p)	optimized use by resource	(HA-million m3 water)
2230	pumping_agr_e	(z,i,c,t,p)	pumping in agriculture	(million m3\yr)
2231	T_pumping_agr_e	(z, t,p)	total pumping in agriculture	(million m3\yr)
2232	pump_cost_ac_agr_depth_e	(z,i,c,t,p)	pumping cost per acre foot ag w depth	(US\$\HA by yr)
2233				
2234	income_agr_yr_e	(z,i,c,t,p)	income per year in agriculture by crop\reg	(US\$ 1000 \yr)
2235	income_agr_e	(z, t,p)	total income: farmer goal	(US\$ 1000 \yr)
2236				
2237				
2238	*livestock			
2239	Yield_lvstk_e	(z,l,v,t,p)	livestock yield	(tons \ head)
2240	net_rev_lvstk_e	(z,l,v,t,p)	optimized net revenue per unit	(US\$ \ head)
2241	resource_lvstk_e	(z,q,l,t,p)	optimized use by resource	(head - million m3 water)
2242	pumping_lvstk_e	(z,l,v,t,p)	pumping for livestock	(million m3\ yr)
2243	T_pumping_lvstk_e	(z, t,p)	total pumping for livestock	(million m3\ yr)
2244	pump_cost_h_lvstk_depth_e	(z,l,v,t,p)	pumping cost per k m3 w depth	(US\$\k m3\m by yr)
2245				
2246	income_lvstk_yr_e	(z,l,v,t,p)	income per year in agriculture by crop\reg	(US\$ 1000 \yr)
2247	income_lvstk_e	(z, t,p)	total income: farmer goal	(US\$ 1000 \yr)
2248				
2249				
2250	*urban			
2251	price_urb_e	(z,k,u,t,p)	price urban	(US\$ per 1000 m3)
2252	C_sur_urb_e	(z,k,u,t,p)	consumer surplus urban	(US\$ 1000 per yr)
2253	G_rev_urb_e	(z,k,u,t,p)	gross revenue urban	(US\$ 1000 per yr)
2254	T_cost_urb_e	(z,k,u,t,p)	total cost urban	(US\$ 1000 per yr)
2255	A_cost_urb_e	(z,k,u,t,p)	ave cost urban	(US\$ per 1000 m3)
2256	pumping_urb_e	(z,k,u,t,p)	total pumping urban	(1000 M3 per yr)

2257	T_pumping_urb_e	(z, t,p)	total urb pumping over urb uses	(1000 M3 per yr)
2258	pump_cost_af_urb_depth_e	(z,k,u,t,p)	pump cost per unit volume urban	(US\$ per 1000 m3)
2259				
2260	Welfare_urb_e	(z,k,u,t,p)	total welfare urban	(US\$ 1000 per yr)
2261	T_welfare_urb_e	(z, t,p)	summed total welfare urbanr uses	(US\$ 1000 per yr)
2262				
2263	*industry			
2264	price_ind_e	(z,n,j,t,p)	price indus	(US\$ per 1000 m3)
2265	C_sur_ind_e	(z,n,j,t,p)	consumer surplus indus	(US\$ 1000 per yr)
2266	G_rev_ind_e	(z,n,j,t,p)	gross revenue indus	(US\$ 1000 per yr)
2267	T_cost_ind_e	(z,n,j,t,p)	total cost indus	(US\$ 1000 per yr)
2268	A_cost_ind_e	(z,n,j,t,p)	ave cost indus	(US\$ per 1000 m3)
2269	pumping_ind_e	(z,n,j,t,p)	total pumping indus	(1000 m3 per yr)
2270	T_pumping_ind_e	(z, t,p)	total ind pumping over ind uses	(1000 m3 per yr)
2271	pump_cost_af_ind_depth_e	(z,n,j,t,p)	pump cost per acre ft indus	(US\$ per 1000 m3)
2272				
2273	Welfare_ind_e	(z,n,j,t,p)	total welfare indus	(US\$ 1000 per yr)
2274	T_welfare_ind_e	(z, t,p)	summed total welfare indus uses	(US\$ 1000 per yr)
2275				
2276				
2277	* ----- post optimality all sectors -----			
2278				
2279	* ag post optimality			
2280	MC_ag_e	(z,i,c,t,p)	marginal cost of added output irrig ag	(US\$\unit output)
2281	MC_lvstk_e	(z,l,v,t,p)	marginal cost of added output lvstk	(US\$\unit output)
2282				
2283	* urban post optimality			
2284	MNB_urb_e	(z,k,u,t,p)	marginal net benefit urban - post opt	(US\$ per 1000 m3)
2285	DMNB_urb_e	(z,k,u,t,p)	discounted marg net ben urb - post opt	(US\$ per 1000 m3)
2286				
2287	CS_cap_urb_e	(z,k,u,t,p)	cons surplus per capita urban - post opt	(US\$\unit per yr)
2288	GR_cap_urb_e	(z,k,u,t,p)	total gross rev per cap urban - post opt	(US\$\unit per yr)
2289	TC_cap_urb_e	(z,k,u,t,p)	total cost per capita urban - post opt	(US\$\unit per yr)
2290	Wel_cap_urb_e	(z,k,u,t,p)	total welfare per capita urban - post opt	(US\$\unit per yr)
2291				
2292	* industry post optimality			
2293	MNB_ind_e	(z,n,j,t,p)	marginal net benefit ind - post opt	(US\$ per 1000 m3)
2294	DMNB_ind_e	(z,n,j,t,p)	discounted marg net ben ind - post opt	(US\$ per 1000 m3)
2295				
2296	CS_unit_ind_e	(z,n,j,t,p)	cons surplus per capita ind - post opt	(US\$\unit per yr)
2297	GR_unit_ind_e	(z,n,j,t,p)	total gross rev per capita ind - post opt	(US\$\unit per yr)

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2298 TC_unit_ind_e      (z,n,j,t,p)  total cost per capita ind - post opt      (US$\unit per yr)
2299 Wel_unit_ind_e      (z,n,j,t,p)  total welfare per capita ind - post opt    (US$\unit per yr)
2300
2301
2302 * ----- next combines equations for both sectors: pumping and economics -----
2303
2304 Tot_pumping_e         (z,      t,p) total pumping over sectors              ( 1000 M3 \yr)
2305 Ave_Tot_pumping_e     (z,      p) ave total pumping summed over later years    (million m3\yr)
2306
2307 pump_equal_all_periods_e (z,      t ) total pumping equal in all periods        (1000 m3 \yr)
2308
2309 Tot_economic_welfare_e (z,      t,p) total economic welfare                    (US$ 1000 \yr)
2310
2311 DNPV_ag_tot_e         (z,      t,p) total irrig ag benefit vary by time        (US$ 1000)
2312 DNPV_lvstk_tot_e      (z,      t,p) total lvstk benefits vary by time          (US$ 1000)
2313 DNPV_urb_tot_e        (z,      t,p) total urban welfare vary by time           (US$ 1000)
2314 DNPV_ind_tot_e        (z,      t,p) total commercial welfare vary by time      (US$ 1000)
2315
2316 DNPV_ag_welfare_e     (z,      p) discounted npv ag welfare                  (US$ 1000)
2317 DNPV_lvstk_welfare_e  (z,      p) discounted npv lvstk welfare                (US$ 1000)
2318 DNPV_urb_welfare_e    (z,      p) discounted npv urban welfare                (US$ 1000)
2319 DNPV_ind_welfare_e    (z,      p) discounted npv industry welfare              (US$ 1000)
2320
2321 DNPV_econ_welfare_e           dnpv all economic welfare                    (US$ 1000)
2322 dnpv_looped_e                dnpv all economic welfare looped              (US$ 1000)
2323 ;
2324
2325
2326 * ----- equations written algebraically -----
2327
2328 * ----- water (hydrology) -----
2329
2330 storage0_e      (z,  t,pp)  $ (ord(t) eq 1)..  storage_v(z,t,pp)      =e=  storage0_p(z);
2331 *                                     // starting aquifer storage
2332
2333 storage_e      (z,  t,pp)  $ (ord(t) gt 1)..  storage_v(z,t,pp) - storage_v(z,t-1,pp)
2334 =e= recharge_v(z,t,pp)
2335 - sum((i,c),  pumping_agr_v(z,i,c,t,pp))
2336 - sum((l,v),  pumping_lvstk_v(z,l,v,t,pp))
2337 - sum((k,u),  pumping_urb_v(z,k,u,t,pp))
2338 - sum((j,n),  pumping_ind_v(z,n,j,t,pp))

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```

2339                                     - exports_v(z,t,pp)
2340                                     ;
2341
2342 recharge_e      (z,  t,pp).. recharge_v(z,t,pp)  =e=  rechrg_flux_p(z,t) *  aq_area_p(z);
2343
2344 */ recharge flux calculated in water balance in parameters above
2345
2346 net_recharge_e   (z,  t,pp).. net_recharge_v(z,t,pp) =e=  recharge_v(z,t,pp)
2347                                     - sum((i,c),  pumping_agr_v(z,i,c,t,pp))
2348                                     - sum((l,v),  pumping_lvstk_v(z,l,v,t,pp))
2349                                     - sum((k,u),  pumping_urb_v(z,k,u,t,pp))
2350                                     - sum((j,n),  pumping_ind_v(z,n,j,t,pp));
2351
2352
2353 depth0_e         (z,  t,pp) $ (ord(t) eq 1).. depth_v(z, t,pp) =e= depth0_p(z);
2354 *                                                         // start aq depth
2355
2356 depth_e          (z,  t,pp) $ (ord(t) gt 1).. depth_v(z,  t,pp) - depth_v(z,  t-1,pp)
2357                                     =e= -[storage_v(z,t,pp) - storage_v(z,t-1,pp)]
2358                                     / [porosity_p(z) * aq_area_p(z)];
2359
2360 * simple rectangle bathub bucket aquifer filled with sand, pebbles, cobbles,
2361 * and gravel with known storage coefficient
2362
2363 * -----agriculture (crop irrigation) -----
2364
2365 Yield_agr_e      (z,i,c,t,pp) $ zi(z,i) .. Yield_agr_v      (z,i,c,t,pp) $ zi(z,i)
2366 =e= B0_agr_p(z,c,i,t) $ zi(z,i) + B1_agr_p(z,c,i,t) $ zi(z,i)* acres_agr_v (z,i,c,t,pp) $zi(z,i);
2367
2368
2369 net_rev_agr_e     (z,i,c,t,pp) .. net_rev_agr_v      (z,i,c,t,pp) =e=[price_agr_p(c,t)
2370 * yield_agr_v(z,i,c,t,pp) - cost_agr_p(c,i,t) - pump_cost_ac_agr_depth_v(z,i,c,t,pp)];
2371
2372
2373 resource_agr_e    (z,r,i,t,pp) .. resource_agr_v (z,r,i,t,pp) =e=
2374                                     sum(c, res_use_agr_p(c,r,i)  * acres_agr_v(z,i,c,t,pp));
2375
2376 pumping_agr_e     (z,i,c,t,pp) .. pumping_agr_v (z,i,c,t,pp) =e= res_use_agr_p(c,'ag_water', i)
2377                                     * acres_agr_v(z,i,c,t,pp);
2378
2379 T_pumping_agr_e   (z,      t,pp) .. T_pumping_agr_v(z,t,pp) =e= sum((i,c), pumping_agr_v(z,i,c,t,pp));

```

```

2380
2381
2382 pump_cost_ac_agr_depth_e (z,i,c,t,pp) .. pump_cost_ac_agr_depth_v(z,i,c,t,pp) =e= pc_af_f_p(z)
2383 * res_use_agr_p(c,'ag_water',i) // cost per m3 x m3 per ha of land in prodn
2384 * (depth_p(z,t) - depth0_p(z));
2385
2386
2387 income_agr_yr_e (z,i,c,t,pp) .. income_agr_yr_v (z,i,c,t,pp) =e= net_rev_agr_v(z,i,c,t,pp)
2388 * acres_agr_v(z,i,c,t,pp);
2389
2390 income_agr_e (z, t,pp) .. income_agr_v (z, t,pp) =e= sum((i,c), net_rev_agr_v(z,i,c,t,pp)
2391 * acres_agr_v(z,i,c,t,pp));
2392
2393 *-----agriculture (livestock) -----
2394
2395 Yield_lvstk_e (z,l,v,t,pp) $ zl(z,l) .. Yield_lvstk_v (z,l,v,t,pp) $ zl(z,l) =e=
2396 B0_lvstk_p(z,v,l,t) $ zl(z,l)+ B1_lvstk_p(z,v,l,t) $ zl(z,l) * head_lvstk_v(z,l,v,t,pp) $ zl(z,l);
2397
2398 net_rev_lvstk_e (z,l,v,t,pp) .. net_rev_lvstk_v (z,l,v,t,pp) =e= [price_lvstk_p(v,t)
2399 * yield_lvstk_v(z,l,v,t,pp) - cost_lvstk_p(v,l,t) - pump_cost_h_lvstk_depth_v(z,l,v,t,pp)];
2400
2401 resource_lvstk_e (z,q,l,t,pp) .. resource_lvstk_v(z,q,l,t,pp) =e=
2402 sum(v, res_use_lvstk_p(v,q,l) * head_lvstk_v(z,l,v,t,pp));
2403
2404 pumping_lvstk_e (z,l,v,t,pp) .. pumping_lvstk_v(z,l,v,t,pp) =e= res_use_lvstk_p(v,'lv_water', l)
2405 * head_lvstk_v(z,l,v,t,pp);
2406
2407 T_pumping_lvstk_e (z,t,pp) .. T_pumping_lvstk_v (z,t,pp)=e=sum((l,v), pumping_lvstk_v(z,l,v,t,pp));
2408
2409 pump_cost_h_lvstk_depth_e (z,l,v,t,pp) .. pump_cost_h_lvstk_depth_v(z,l,v,t,pp)=e= pc_af_f_p(z) *
2410 res_use_lvstk_p(v,'lv_water',l) // cost per m3 x m3 per head
2411 * (depth_p(z,t) - depth0_p(z));
2412
2413 income_lvstk_yr_e (z,l,v,t,pp) .. income_lvstk_yr_v(z,l,v,t,pp) =e= net_rev_lvstk_v(z,l,v,t,pp)
2414 * head_lvstk_v(z,l,v,t,pp);
2415
2416 income_lvstk_e (z, t,pp) .. income_lvstk_v (z, t,pp) =e=
2417 sum((l,v), net_rev_lvstk_v(z,l,v,t,pp) * head_lvstk_v(z,l,v,t,pp));
2418
2419 * ----- urban (residential ) -----
2420

```

```

2421 pumping_urb_e      (z,k,u,t,pp) ..      pumping_urb_v      (z,k,u,t,pp) =e=
2422 pumping_cap_urb_v(z,k,u,t,pp) * pop_urb_p(z,u,k,t);
2423
2424 price_urb_e      (z,k,u,t,pp) ..      price_urb_v      (z,k,u,t,pp) =e= B0_urb_p(z,u,k,t)
2425 + B1_urb_p(z,u,k,t) * pumping_urb_v(z,k,u,t,pp);
2426
2427 C_sur_urb_e      (z,k,u,t,pp) .. C_sur_urb_v (z,k,u,t,pp) =e= 0.5 * (B0_urb_p(z,u,k,t)
2428 - price_urb_v(z,k,u,t,pp)) * pumping_urb_v(z,k,u,t,pp);
2429
2430 G_rev_urb_e      (z,k,u,t,pp) .. G_rev_urb_v (z,k,u,t,pp) =e= price_urb_v(z,k,u,t,pp)
2431 * pumping_urb_v(z,k,u,t,pp);
2432
2433 A_cost_urb_e      (z,k,u,t,pp) $ zk(z,k).. A_cost_urb_v (z,k,u,t,pp) =e= ave_cost_urb_p(u,k)
2434 + pump_cost_af_urb_depth_v(z,k,u,t,pp);
2435
2436 T_cost_urb_e      (z,k,u,t,pp) .. T_cost_urb_v      (z,k,u,t,pp) =e= ave_cost_urb_p(u,k)
2437 * pumping_urb_v(z,k,u,t,pp);
2438
2439 T_pumping_urb_e   (z,t,pp) .. T_pumping_urb_v(z, t,pp) =e= sum((k,u), pumping_urb_v(z,k,u,t,pp));
2440
2441 pump_cost_af_urb_depth_e (z,k,u,t,pp) .. pump_cost_af_urb_depth_v(z,k,u,t,pp) =e= pc_af_f_p(z) * 1
2442 * (depth_p(z,t) - depth0_p(z)); // k m3 - pump cost/k m3 depends on depth diff from base
2443
2444 Welfare_urb_e (z,k,u,t,pp) .. Welfare_urb_v      (z,k,u,t,pp) =e= C_sur_urb_v(z,k,u,t,pp)
2445 + G_rev_urb_v(z,k,u,t,pp) - T_cost_urb_v(z,k,u,t,pp);
2446
2447 T_welfare_urb_e (z,t,pp) .. T_welfare_urb_v (z,t,pp) =e= sum((k,u), welfare_urb_v(z,k,u,t,pp));
2448
2449 * ----- commercial uses of water -----
2450
2451 pumping_ind_e      (z,n,j,t,pp) .. pumping_ind_v (z,n,j,t,pp) =e= pumping_unit_ind_v(z,n,j,t,pp)
2452 * pop_ind_p(z,j,n,t);
2453
2454
2455 price_ind_e      (z,n,j,t,pp) .. price_ind_v (z,n,j,t,pp) =e= B0_ind_p(z,j,n,t)
2456 + B1_ind_p(z,j,n,t) * pumping_ind_v(z,n,j,t,pp);
2457
2458
2459 C_sur_ind_e      (z,n,j,t,pp) .. C_sur_ind_v (z,n,j,t,pp) =e= 0.5 * (B0_ind_p(z,j,n,t)
2460 - price_ind_v(z,n,j,t,pp)) * pumping_ind_v(z,n,j,t,pp);
2461

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```

2462
2463 G_rev_ind_e      (z,n,j,t,pp) .. G_rev_ind_v (z,n,j,t,pp) =e= price_ind_v(z,n,j,t,pp)
2464                                     * pumping_ind_v(z,n,j,t,pp);
2465
2466
2467 A_cost_ind_e      (z,n,j,t,pp) $  zn(z,n).. A_cost_ind_v (z,n,j,t,pp) =e= ave_cost_ind_p(j,n)
2468                                     + pump_cost_af_ind_depth_v(z,n,j,t,pp);
2469
2470
2471 T_cost_ind_e      (z,n,j,t,pp) .. T_cost_ind_v      (z,n,j,t,pp) =e= ave_cost_ind_p(j,n)
2472                                     * pumping_ind_v(z,n,j,t,pp);
2473
2474
2475 T_pumping_ind_e    (z,      t,pp) .. T_pumping_ind_v (z,      t,pp) =e=
2476                                     sum((n,j), pumping_ind_v(z,n,j,t,pp));
2477
2478
2479 pump_cost_af_ind_depth_e (z,n,j,t,pp) .. pump_cost_af_ind_depth_v(z,n,j,t,pp) =e= pc_af_f_p(z)
2480                                     * 1 * (depth_p(z,t) - depth0_p(z));
2481
2482
2483 Welfare_ind_e (z,n,j,t,pp) .. Welfare_ind_v (z,n,j,t,pp) =e= C_sur_ind_v(z,n,j,t,pp)
2484                                     + G_rev_ind_v(z,n,j,t,pp) - T_cost_ind_v(z,n,j,t,pp);
2485
2486
2487 T_welfare_ind_e (z,t,pp) .. T_welfare_ind_v(z,t,pp) =e= sum((n,j), welfare_ind_v(z,n,j,t,pp));
2488
2489 * - start post optimality ag, urban, and industry - passenger variables not used for optimal soln -
2490
2491 * ----- agriculture post optimality -----
2492
2493 MC_ag_e      (z,i,c,t,pp) $  zi(z,i) .. MC_ag_v(z,i,c,t,pp)      =e= cost_agr_p(c,i,t) / [.001
2494                                     + (acres_agr_v(z,i,c,t,pp) * Bl_agr_p(z,c,i,t) + yield_agr_v(z,i,c,t,pp))];
2495 *
2496                                     // marg cost cross check
2497
2497 MC_lvstk_e(z,l,v,t,pp) $  zl(z,l) .. MC_lvstk_v(z,l,v,t,pp) =e= cost_lvstk_p(v,l,t)/ [.001
2498                                     + (head_lvstk_v(z,l,v,t,pp)* Bl_lvstk_p(z,v,l,t) + yield_lvstk_v(z,l,v,t,pp))];
2499 *
2500                                     // marg cost cross check
2501
2501 * ----- urban post optimality -----
2502

```



```

2503 MNB_urb_e      (z,k,u,t,pp) $ zk(z,k).. MNB_urb_v (z,k,u,t,pp) =e= price_urb_v(z,k,u,t,pp)
2504                                     - A_cost_urb_v(z,k,u,t,pp);
2505
2506 DMNB_urb_e      (z,k,u,t,pp) $ zk(z,k).. DMNB_urb_v (z,k,u,t,pp) =e=
2507                                     sum(tp $ [ord(tp) ge ord(t)], disc_fact_p(t) * MNB_urb_v(z,k,u,t,pp));
2508
2509
2510 CS_cap_urb_e    (z,k,u,t,pp) .. CS_cap_urb_v(z,k,u,t,pp) =e= C_sur_urb_v(z,k,u,t,pp) / (.001
2511                                                         + pop_urb_p(z,u,k,t));
2512
2513
2514 GR_cap_urb_e    (z,k,u,t,pp) .. GR_cap_urb_v(z,k,u,t,pp) =e= G_rev_urb_v(z,k,u,t,pp) / (.001
2515                                                         + pop_urb_p(z,u,k,t));
2516
2517
2518 TC_cap_urb_e    (z,k,u,t,pp) .. TC_cap_urb_v(z,k,u,t,pp) =e= T_cost_urb_v(z,k,u,t,pp) / (.001
2519                                                         + pop_urb_p(z,u,k,t));
2520
2521
2522 Wel_cap_urb_e    (z,k,u,t,pp) .. Wel_cap_urb_v(z,k,u,t,pp) =e= Welfare_urb_v(z,k,u,t,pp) / (.001
2523                                                         + pop_urb_p(z,u,k,t));
2524
2525
2526 * ----- indusry post optimality -----
2527
2528 MNB_ind_e      (z,n,j,t,pp) $ zn(z,n).. MNB_ind_v (z,n,j,t,pp) =e= price_ind_v(z,n,j,t,pp)
2529                                     - A_cost_ind_v(z,n,j,t,pp);
2530
2531
2532 DMNB_ind_e      (z,n,j,t,pp) $ zn(z,n).. DMNB_ind_v (z,n,j,t,pp) =e=
2533                                     sum(tp $ [ord(tp) ge ord(t)], disc_fact_p(t) * MNB_ind_v(z,n,j,t,pp));
2534
2535
2536 CS_unit_ind_e   (z,n,j,t,pp) .. CS_unit_ind_v(z,n,j,t,pp) =e= C_sur_ind_v(z,n,j,t,pp) / (.001
2537                                                         + pop_ind_p(z,j,n,t));
2538
2539
2540 GR_unit_ind_e   (z,n,j,t,pp) .. GR_unit_ind_v (z,n,j,t,pp) =e= G_rev_ind_v(z,n,j,t,pp) / (.001
2541                                                         + pop_ind_p(z,j,n,t));
2542
2543

```

```

2544 TC_unit_ind_e (z,n,j,t,pp) .. TC_unit_ind_v (z,n,j,t,pp) == T_cost_ind_v(z,n,j,t,pp) / (.001
2545                                     + pop_ind_p(z,j,n,t));
2546
2547
2548 Wel_unit_ind_e(z,n,j,t,pp) .. Wel_unit_ind_v(z,n,j,t,pp) == Welfare_ind_v(z,n,j,t,pp) / (.001
2549                                     + pop_ind_p(z,j,n,t));
2550
2551
2552
2553 * --- Combine equations algebraically: sums economic benefits over aquifers, uses, time periods ---
2554
2555 Tot_pumping_e      (z, t,pp)  .. Tot_pumping_v (z,t,pp)   == T_pumping_agr_v   (z,t,pp)
2556                                     + T_pumping_lvstk_v(z,t,pp)
2557                                     + T_pumping_urb_v   (z,t,pp)
2558                                     + T_pumping_ind_v   (z,t,pp);
2559 *                               // allows various kinds of pumping policy adjustments with and without trading
2560
2561
2562 Ave_Tot_pumping_e      (z,      pp)  .. Ave_Tot_pumping_v      (z,      pp) ==
2563                                     sum(tlater, tot_pumping_v(z,tlater,pp) / (card(tlater)));
2564
2565
2566
2567 Tot_economic_welfare_e (z,      t,pp) .. Tot_economic_welfare_v(z,t,pp) == income_agr_v(z,t,pp)
2568                                     + income_lvstk_v(z,t,pp)
2569                                     + T_welfare_urb_v(z,t,pp)
2570                                     + T_welfare_ind_v(z,t,pp)
2571                                     - cost_export_p * exports_v(z,t,pp);
2572
2573
2574
2575 DNPV_ag_tot_e      (z,      t,pp)  .. DNPV_ag_tot_v      (z,t,pp)   == disc_fact_p(t) *
2576                                     income_agr_v(z,t,pp);
2577
2578
2579 DNPV_lvstk_tot_e      (z,      t,pp)  .. DNPV_lvstk_tot_v(z,t,pp)   == disc_fact_p(t) *
2580                                     income_lvstk_v(z,t,pp);
2581
2582
2583 DNPV_urb_tot_e      (z,      t,pp)  .. DNPV_urb_tot_v      (z,t,pp)   == disc_fact_p(t) *
2584                                     T_welfare_urb_v(z,t,pp);

```

```

2585
2586
2587
2588 DNPV_ind_tot_e      (z,      t,pp) .. DNPV_ind_tot_v   (z,t,pp)   =e= disc_fact_p(t) *
2589                                     T_welfare_ind_v(z,t,pp);
2590
2591
2592
2593 DNPV_ag_welfare_e    (z,      pp) .. DNPV_ag_welfare_v      (z,  pp)   =e= sum(t,  disc_fact_p(t) *
2594                                     income_agr_v(z,t,pp));
2595
2596
2597 DNPV_lvstk_welfare_e(z,      pp) .. DNPV_lvstk_welfare_v   (z,  pp)   =e= sum(t,  disc_fact_p(t) *
2598                                     income_lvstk_v(z,t,pp));
2599
2600
2601 DNPV_urb_welfare_e   (z,      pp) .. DNPV_urb_welfare_v      (z,  pp)   =e= sum(t,  disc_fact_p(t) *
2602                                     T_welfare_urb_v(z,t,pp));
2603
2604
2605 DNPV_ind_welfare_e   (z,      pp) .. DNPV_ind_welfare_v      (z,  pp)   =e= sum(t,  disc_fact_p(t) *
2606                                     T_welfare_ind_v(z,t,pp));
2607
2608
2609
2610 DNPV_econ_welfare_e  (      pp) .. DNPV_econ_welfare_v      (      pp) =e= sum((z,t), disc_fact_p(t) *
2611                                     tot_economic_welfare_v(z,t,pp));
2612
2613
2614
2615 dnpv_looped_e        ..          dnpv_looped_v =e= sum((pp), dnpv_econ_welfare_v(pp));
2616                                     // sums economic welfare for each Policy loop chosen
2617
2618
2619 pump_equal_all_periods_e (z,tlater ) .. tot_pumping_v(z,tlater,'02_cap_and_trade') =n=
2620                                     ave_tot_pumping_v(z,'02_cap_and_trade');
2621                                     // requires each year's pumping to be identical after 1st year
2622
2623 * ----- end of equations -----
2624
2625 MODEL Kenya_aquifer_competition /all/; // This model uses ALL equations

```

```

2626
2627 * ----- begin setting bounds on optimized variables -----
2628
2629 storage_v.l(z,t,p)          = 1.00 * storage_p(z,t); // simple starting value helps optimize
2630
2631 acres_agr_v.fx      (z,i,c,t,p) $ (not zi(z,i)) = eps;
2632 // no acreage for wrong aquifer-farming area combination
2633
2634 head_lvstk_v.fx     (z,l,v,t,p) $ (not zl(z,l)) = eps;
2635 // no head for wrong aquifer-livestock combination
2636
2637 pumping_urb_v.fx    (z,k,u,t,p) $ (not zk(z,k)) = eps;
2638 // no pumping for wrong aquifer-urban area combination
2639
2640 pumping_ind_v.fx    (z,n,j,t,p) $ (not zn(z,n)) = eps;
2641 // no pumping for wrong aquifer-industry area combination
2642
2643 net_rev_agr_v.fx    (z,i,c,t,p) $ (not zi(z,i)) = eps;
2644 // no net revenue for wrong aquifer-farming area combinations
2645
2646 net_rev_lvstk_v.fx  (z,l,v,t,p) $ (not zl(z,l)) = eps;
2647 // no net revenue for wrong aquifer-livestock area combinations
2648
2649 MC_ag_v.fx          (z,i,c,t,p) $ (not zi(z,i)) = eps;
2650 // no defined marginal cost for crop production from wrong aquifer farming area combination
2651
2652 MC_lvstk_v.fx       (z,l,v,t,p) $ (not zl(z,l)) = eps;
2653 // no defined marginal cost for livestock from wrong aquifer lvstk area combination
2654
2655 MNB_urb_v.fx        (z,k,u,t,p) $ (not zk(z,k)) = eps;
2656 // no defined marginal net benefits from wrong aquifer urban area combination
2657
2658 MNB_ind_v.fx        (z,n,j,t,p) $ (not zn(z,n)) = eps;
2659 // no defined marginal net benefits from wrong aquifer industry combination
2660
2661 * end of bounds on optimized variables
2662
2663 parameter
2664
2665 mod_stat_p(p)                model status                (unitless)
2666

```

```

2667 * begin solving optimized model inside loops
2668
2669 * ----- begin loop -----
2670
2671 loop(p,
2672
2673     pp(p)  = yes;
2674
2675 * ----- optimization model 1 starts here  base Policy -----
2676
2677 solve Kenya_Aquifer_Competition using NLP maximizing dnpv_looped_v;
2678 // nonlinear objective and constraint requires nonlinear solver
2679
2680 options nlp = conopt;
2681
2682 mod_stat_p(p) = kenya_aquifer_competition.Modelstat + eps;
2683
2684 * ----- end of model 1 -----
2685
2686 * ----- begin optimization model 2.
2687 *Seeks the least cost measure to return all aquifers to starting depths for 1st alternative policy
2688
2689 Depth_v.up(z,tlast, '02_cap_and_trade') = Depth0_p(z);
2690 // requires returning aquifers to starting values by last year
2691
2692 * ----- end of model 2 -----
2693
2694 * ----- begin model 3 -----
2695
2696 * below code for model 3 states that total pumping identical in last 3 years to allow pumping
2697 * permits to be cut be a constant proportion by year;
2698
2699 * optimization model 3 -- implement pumping permit reductions that return aquifers to starting
2700 * depths through proportional sharing of shortages for all users
2701
2702 Depth_v.up          (z,tlast, '03_cap_and_share') = Depth0_p(z);
2703
2704 * irrigated ag
2705 T_pumping_agr_v.fx  (z,tlater,'03_cap_and_share') =
2706                     [ave_tot_pumping_v.l(z,'02_cap_and_trade')/ tot_pumping_p(z,tlater)]
2707                     * tot_pump_agr_p  (z,tlater) + eps;

```

```

2708
2709 * livestock
2710 T_pumping_lvstk_v.fx(z,tlater,'03_cap_and_share') =
2711     [ave_tot_pumping_v.l(z,'02_cap_and_trade')/ tot_pumping_p(z,tlater)]
2712     * tot_pump_lvstk_p(z,tlater) + eps;
2713
2714 * domestic use
2715 T_pumping_urb_v.fx (z,tlater,'03_cap_and_share') =
2716     [ave_tot_pumping_v.l(z,'02_cap_and_trade')/ tot_pumping_p(z,tlater)]
2717     * tot_pump_urb_p (z,tlater) + eps;
2718
2719 * commercial use
2720 T_pumping_ind_v.fx (z,tlater,'03_cap_and_share') =
2721     [ave_tot_pumping_v.l(z,'02_cap_and_trade')/ tot_pumping_p(z,tlater)]
2722     * tot_pump_ind_p( z,tlater) + eps;
2723
2724 * ----- begin model 4 -----
2725 * --- assigns top priority to urban uses -----
2726
2727 Depth_v.up(          z,tlast, '04_domestic_priority') = Depth0_p(z);
2728
2729 T_pumping_urb_v.fx ('1_NAS_Aqf',tlater,'04_domestic_priority') =
2730     1.00 * tot_pump_urb_p ('1_NAS_Aqf', tlater) + eps;
2731     // must meet base + urban pump needs
2732
2733 T_pumping_urb_v.fx ('2_MAS_Aqf',tlater,'04_domestic_priority') =
2734     1.00 * tot_pump_urb_p ('2_MAS_Aqf', tlater) + eps;
2735     // ditto
2736
2737 Tot_pumping_v.up(z,tlater,'04_domestic_priority')= ave_tot_pumping_v.l(z,'02_cap_and_trade') + eps;
2738     //each years tot = average over last 3 years needed to return to start depth
2739
2740 * ----- end model 5 -----
2741
2742 * ----- begin model 5 -----
2743 * --- assigns top priority to commercial uses when reducing overall use to protect aquifers -----
2744
2745
2746 Depth_v.up(          z,tlast, '05_commercial_priority') = Depth0_p(z);
2747
2748 T_pumping_ind_v.fx ('1_NAS_Aqf',tlater,'05_commercial_priority') =

```

```

2749             1.00 * tot_pump_ind_p ('1_NAS_Aqf', tlater) + eps;
2750             // must meet base + industry pump needs
2751
2752 T_pumping_ind_v.fx ('2_MAS_Aqf',tlater,'05_commercial_priority') =
2753             1.00 * tot_pump_ind_p ('2_MAS_Aqf', tlater) + eps;
2754             // ditto
2755
2756 Tot_pumping_v.up(z,tlater,'05_commercial_priority')=ave_tot_pumping_v.l(z,'02_cap_and_trade') +eps;
2757 //each years tot = average over last 3 years needed to return to start depth
2758 * -----end model 5 -----
2759
2760 * ----- begin model 6 -----
2761 * --- assigns top priority to livestock when reducing overall use to protect aquifers -----
2762
2763 Depth_v.up(          z,tlast, '06_livestock_priority') = Depth0_p(z);
2764
2765 T_pumping_lvstk_v.fx ('1_NAS_Aqf',tlater,'06_livestock_priority') =
2766             1.00 * tot_pump_lvstk_p ('1_NAS_Aqf', tlater) + eps;
2767             // must meet base + livestock pump needs
2768 T_pumping_lvstk_v.fx ('2_MAS_Aqf',tlater,'06_livestock_priority') =
2769             1.00 * tot_pump_lvstk_p ('2_MAS_Aqf', tlater) + eps;
2770             // ditto
2771
2772 Tot_pumping_v.up(z,tlater,'06_livestock_priority') = ave_tot_pumping_v.l(z,'02_cap_and_trade')+eps;
2773 //each years tot = average over last 3 years needed to return to start depth
2774
2775 * -----end model 6 -----
2776
2777 * ----- begin model 7 -----
2778 * --- assigns top priority to irrigated ag when reducing overall use to protect aquifers -----
2779
2780 Depth_v.up(          z,tlast, '07_crop_irrigation_priority') = Depth0_p(z);
2781
2782 T_pumping_agr_v.fx ('1_NAS_Aqf',tlater,'07_crop_irrigation_priority') =
2783             1.00 * tot_pump_agr_p ('1_NAS_Aqf', tlater) + eps;
2784             // must meet base + livestock pump needs
2785 T_pumping_agr_v.fx ('2_MAS_Aqf',tlater,'07_crop_irrigation_priority') =
2786             1.00 * tot_pump_agr_p ('2_MAS_Aqf', tlater) + eps;
2787             // ditto
2788
2789 Tot_pumping_v.up(z,tlater,'07_crop_irrigation_priority') =

```

```

2790                                     ave_tot_pumping_v.l(z,'02_cap_and_trade')+eps;
2791 * each years tot = average over last 3 years needed to return to start depth
2792
2793 * -----end model 7 -----
2794
2795 * ----- end of all models: 1 Policy for each model -----
2796
2797 * prepare to close off last loop
2798
2799 pp(p) = no;
2800
2801     );
2802 * ----- end loops over policies -----
2803
2804
2805 Parameter
2806
2807 * Below are parameters that come from the optimal solution (.l) levels ended as _vp
2808
2809 *hydrology
2810 storage_vp           (z,    t,p)    optimized storage                (million m3 by yr)
2811 recharge_vp         (z,    t,p)    optimized recharge                (million m3 by yr)
2812 net_recharge_vp     (z,    t,p)    optimized net recharge            (million m3 by yr)
2813 depth_vp            (z,    t,p)    optimized depth to pumping        (meter by year  )
2814 Tot_pumping_vp      (z,    t,p)    optimized total pumping            (million m3 by yr)
2815
2816 * agricultural
2817 acres_agr_vp        (z,i,c,t,p)    optimized land by crop (c and t)      (1000 ha yr)
2818 resource_agr_vp     (z,r,i,t,p)    optimized resource use by resource (r) (million m3 and k HA)
2819 pumping_agr_vp      (z,i,c,t,p)    pumping in agriculture              (million m3 per yr)
2820 T_pumping_agr_vp    (z,    t,p)    total pumping in agriculture        (million m3 per yr)
2821 pump_cost_ac_agr_depth_vp (z,i,c,t,p) pumping cost per ac ag w depth    (US$ per HA per M by yr)
2822
2823
2824 * livestock
2825 head_lvstk_vp       (z,l,v,t,p)    optimized head by specie (v and t)      (1000 head year)
2826 resource_lvstk_vp   (z,q,l,t,p)    optimized resource use by resource(q) (million m3 & k head)
2827 pumping_lvstk_vp    (z,l,v,t,p)    pumping in livestock production        (million m3 per yr)
2828 T_pumping_lvstk_vp  (z,    t,p)    total pumping in agriculture        (million m3 per yr)
2829 pump_cost_h_lvstk_depth_vp (z,l,v,t,p) pumping cost per ac ag w depth    (US$ per head per M by yr)
2830

```


2831				
2832	* urban			
2833	pumping_urb_vp	(z,k,u,t,p)	total pumping urban	(million m3 per yr)
2834	pumping_cap_urb_vp	(z,k,u,t,p)	per unit pumping urban use	(1000 m3 by unit & yr)
2835	T_pumping_urb_vp	(z, t,p)	total urb pumping over urb uses	(million m3 per yr)
2836				
2837	* industry			
2838	pumping_ind_vp	(z,n,j,t,p)	total pumping industry use	(million m3 per yr)
2839	pumping_unit_ind_vp	(z,n,j,t,p)	per unit pumping industry use	(1000 m3 per unit & yr)
2840	T_pumping_ind_vp	(z, t,p)	total indus pumping over indus uses	(million m3 per yr)
2841				
2842				
2843	*agricultural			
2844	Yield_agr_vp	(z,i,c,t,p)	optimzied crop yields	(m tons per HA)
2845	net_rev_agr_vp	(z,i,c,t,p)	optimized net revenue per acre	(\$US per HA)
2846	income_agr_yr_vp	(z,i,c,t,p)	income by crop region year	(\$US 1000 per yr)
2847	income_agr_vp	(z, t,p)	income from all crops	(\$US 1000 per yr)
2848				
2849	*livestock			
2850	Yield_lvstk_vp	(z,l,v,t,p)	optimzied crop yields	(m tons per head)
2851	net_rev_lvstk_vp	(z,l,v,t,p)	optimized net revenue per acre	(US\$ per head)
2852	income_lvstk_yr_vp	(z,l,v,t,p)	income by crop region year	(US\$ 1000 per yr)
2853	income_lvstk_vp	(z, t,p)	income from all crops	(US\$ 1000 per yr)
2854				
2855	*urban			
2856	price_urb_vp	(z,k,u,t,p)	urban price	(US\$ per 1000 m3)
2857	A_cost_urb_vp	(z,k,u,t,p)	average cost urban	(US\$ per 1000 m3)
2858	T_cost_urb_vp	(z,k,u,t,p)	total cost urban	(US\$ 1000 per yr)
2859	G_rev_urb_vp	(z,k,u,t,p)	gross revenue urban	(US\$ 1000 per yr)
2860	c_sur_urb_vp	(z,k,u,t,p)	consumer surplus urban	(US\$ 1000 per yr)
2861				
2862	pump_cost_af_urb_depth_vp	(z,k,u,t,p)	pump cost per af urban depth	(US\$ per k m3 per m)
2863	welfare_urb_vp	(z,k,u,t,p)	total welfare urban	(US\$ 1000 per yr)
2864	T_welfare_urb_vp	(z, t,p)	welfare summed over urban uses	(US\$ 1000 per yr)
2865				
2866				
2867	*industry			
2868	price_ind_vp	(z,n,j,t,p)	industry price	(US\$ per 1000 m3)
2869	A_cost_ind_vp	(z,n,j,t,p)	average cost industry	(US\$ per 1000 m3)
2870	T_cost_ind_vp	(z,n,j,t,p)	total cost industry	(US\$ 1000 per yr)
2871	G_rev_ind_vp	(z,n,j,t,p)	gross revenue industry	(US\$ 1000 per yr)

2872	c_sur_ind_vp	(z,n,j,t,p)	consumer surplus industry	(US\$ 1000 per yr)
2873				
2874	pump_cost_af_ind_depth_vp	(z,n,j,t,p)	pump cost per af urban depth	(US\$ per k m3 per m)
2875	welfare_ind_vp	(z,n,j,t,p)	total welfare urban	(US\$ 1000 per yr)
2876	T_welfare_ind_vp	(z, t,p)	welfare summed over urban uses	(US\$ 1000 per yr)
2877				
2878				
2879	* post optimality variables. They come from but do not affect optimal solution			
2880				
2881	*ag			
2882				
2883	MC_ag_vp	(z,i,c,t,p)	marginal cost added output agriculture	(US\$\1000 m3)
2884	MC_lvstk_vp	(z,l,v,t,p)		
2885				
2886	*urb			
2887	MNB_urb_vp	(z,k,u,t,p)	marginal net benefit urban - post opt	(US\$\unit)
2888	CS_cap_urb_vp	(z,k,u,t,p)	consumer surplus per capita urban - post opt	(US\$\unit)
2889	GR_cap_urb_vp	(z,k,u,t,p)	total gross revenue per capita urban - post opt	(US\$\unit)
2890	TC_cap_urb_vp	(z,k,u,t,p)	total cost urban per capita - post opt	(US\$\unit)
2891	Wel_cap_urb_vp	(z,k,u,t,p)	welfare per capita urban - post opt	(US\$\unit)
2892				
2893	*ind			
2894	MNB_ind_vp	(z,n,j,t,p)	marginal net benefit industry - post opt	(US\$\unit)
2895	CS_unit_ind_vp	(z,n,j,t,p)	consumer surplus per unit industry - post opt	(US\$\unit)
2896	GR_unit_ind_vp	(z,n,j,t,p)	tot gross revenue per unit industry - post opt	(US\$\unit)
2897	TC_unit_ind_vp	(z,n,j,t,p)	tot cost industry per unit - post opt	(US\$\unit)
2898	Wel_unit_ind_vp	(z,n,j,t,p)	welfare per unit industry - post opt	(US\$\unit)
2899				
2900	DNPV_ag_tot_vp	(z, t,p)	dnpv ag economic welfare year	(US\$ 1000)
2901	DNPV_lvstk_tot_vp	(z, t,p)	dnpv lvstk economic welfare year	(US\$ 1000)
2902	DNPV_urb_tot_vp	(z, t,p)	dnpv urban economic welfare year	(US\$ 1000)
2903	DNPV_ind_tot_vp	(z, t,p)	dnpv commercial economic welfare	(US\$ 1000)
2904				
2905	DNPV_ag_welfare_vp	(z, p)	dnpv ag economic welfare	(US\$ 1000)
2906	DNPV_lvstk_welfare_vp	(z, p)	dnpv lvstk economic welfare	(US\$ 1000)
2907	DNPV_urb_welfare_vp	(z, p)	dnpv urban economic welfare	(US\$ 1000)
2908	DNPV_ind_welfare_vp	(z, p)	dnpv commercial welfare	(US\$ 1000)
2909				
2910	DNPV_econ_welfare_vp	(p)	dnpv total multi sector welfare by Policy	(US\$ 1000)
2911	;			
2912				

```

2913 * next are optimized variables saved as parameters
2914
2915 * vp endings are optimized variables
2916
2917 *hydrology
2918
2919 storage_vp          (z,    t,p)          =  storage_v.l          (z,    t,p) + eps;
2920 recharge_vp         (z,    t,p)          =  recharge_v.l         (z,    t,p) + eps;
2921 net_recharge_vp     (z,    t,p)          =  net_recharge_v.l     (z,    t,p) + eps;
2922 depth_vp            (z,    t,p)          =  depth_v.l           (z,    t,p) + eps;
2923 Tot_pumping_vp      (z,    t,p)          =  tot_pumping_v.l       (z,    t,p) + eps;
2924
2925 * Agricultural
2926 * crop
2927 acres_agr_vp        (z,i,c,t,p) $ zi(z,i) = acres_agr_v.l          (z,i,c,t,p) $ zi(z,i) + eps;
2928 resource_agr_vp     (z,r,i,t,p)          =  resource_agr_v.l     (z,r,i,t,p)          + eps;
2929 pumping_agr_vp      (z,i,c,t,p) $ zi(z,i) =  pumping_agr_v.l      (z,i,c,t,p) $ zi(z,i) + eps;
2930 T_pumping_agr_vp    (z,    t,p)          =  T_pumping_agr_v.l    (z,    t,p)          + eps;
2931 pump_cost_ac_agr_depth_vp (z,i,c,t,p)    =  pump_cost_ac_agr_depth_v.l (z,i,c,t,p)    + eps;
2932
2933 * livestock
2934 head_lvstk_vp       (z,l,v,t,p) $ zl(z,l) = head_lvstk_v.l         (z,l,v,t,p) $ zl(z,l) + eps;
2935 resource_lvstk_vp   (z,q,l,t,p)          =  resource_lvstk_v.l   (z,q,l,t,p)          + eps;
2936 pumping_lvstk_vp    (z,l,v,t,p) $ zl(z,l) =  pumping_lvstk_v.l    (z,l,v,t,p) $ zl(z,l) + eps;
2937 T_pumping_lvstk_vp  (z,    t,p)          =  T_pumping_lvstk_v.l   (z,    t,p)          + eps;
2938 pump_cost_h_lvstk_depth_vp (z,l,v,t,p)    =  pump_cost_h_lvstk_depth_v.l (z,l,v,t,p)    + eps;
2939
2940 * Residential
2941 pumping_urb_vp      (z,k,u,t,p) $ zk(z,k) = pumping_urb_v.l        (z,k,u,t,p) $ zk(z,k) + eps;
2942 pumping_cap_urb_vp  (z,k,u,t,p)          =  pumping_cap_urb_v.l   (z,k,u,t,p)          + eps;
2943 T_pumping_urb_vp    (z,    t,p)          =  T_pumping_urb_v.l     (z,    t,p)          + eps;
2944
2945 * industry
2946 pumping_ind_vp      (z,n,j,t,p) $ zn(z,n) =  pumping_ind_v.l      (z,n,j,t,p) $ zn(z,n) + eps;
2947 pumping_unit_ind_vp (z,n,j,t,p)          =  pumping_unit_ind_v.l   (z,n,j,t,p)          + eps;
2948 T_pumping_ind_vp    (z,    t,p)          =  T_pumping_ind_v.l     (z,    t,p)          + eps;
2949
2950 *Agriculture
2951
2952 *crop
2953 Yield_agr_vp        (z,i,c,t,p)          =  Yield_agr_v.l          (z,i,c,t,p) + eps;

```

```

2954 net_rev_agr_vp      (z,i,c,t,p) = net_rev_agr_v.1      (z,i,c,t,p) + eps;
2955 income_agr_yr_vp    (z,i,c,t,p) = income_agr_yr_v.1    (z,i,c,t,p) + eps;
2956 income_agr_vp       (z,      t,p) = income_agr_v.1      (z,      t,p) + eps;
2957
2958 *livestock
2959 Yield_lvstk_vp      (z,l,v,t,p) = Yield_lvstk_v.1      (z,l,v,t,p) + eps;
2960 net_rev_lvstk_vp    (z,l,v,t,p) = net_rev_lvstk_v.1    (z,l,v,t,p) + eps;
2961 income_lvstk_yr_vp  (z,l,v,t,p) = income_lvstk_yr_v.1  (z,l,v,t,p) + eps;
2962
2963
2964 *residential
2965 price_urb_vp        (z,k,u,t,p) = price_urb_v.1        (z,k,u,t,p) + eps;
2966 A_cost_urb_vp       (z,k,u,t,p) = A_cost_urb_v.1        (z,k,u,t,p) + eps;
2967 T_cost_urb_vp       (z,k,u,t,p) = T_cost_urb_v.1        (z,k,u,t,p) + eps;
2968 G_rev_urb_vp        (z,k,u,t,p) = G_rev_urb_v.1        (z,k,u,t,p) + eps;
2969 c_sur_urb_vp        (z,k,u,t,p) = c_sur_urb_v.1        (z,k,u,t,p) + eps;
2970
2971 pump_cost_af_urb_depth_vp (z,k,u,t,p) = pump_cost_af_urb_depth_v.1 (z,k,u,t,p) + eps;
2972 welfare_urb_vp      (z,k,u,t,p) = welfare_urb_v.1      (z,k,u,t,p) + eps;
2973 T_welfare_urb_vp    (z,      t,p) = T_welfare_urb_v.1    (z,      t,p) + eps;
2974
2975 *industry
2976 price_ind_vp        (z,n,j,t,p) = price_ind_v.1        (z,n,j,t,p) + eps;
2977 A_cost_ind_vp       (z,n,j,t,p) = A_cost_ind_v.1        (z,n,j,t,p) + eps;
2978 T_cost_ind_vp       (z,n,j,t,p) = T_cost_ind_v.1        (z,n,j,t,p) + eps;
2979 G_rev_ind_vp        (z,n,j,t,p) = G_rev_ind_v.1        (z,n,j,t,p) + eps;
2980 c_sur_ind_vp        (z,n,j,t,p) = c_sur_ind_v.1        (z,n,j,t,p) + eps;
2981
2982 pump_cost_af_ind_depth_vp (z,n,j,t,p) = pump_cost_af_ind_depth_v.1 (z,n,j,t,p) + eps;
2983 welfare_ind_vp      (z,n,j,t,p) = welfare_ind_v.1      (z,n,j,t,p) + eps;
2984 T_welfare_ind_vp    (z,      t,p) = T_welfare_ind_v.1    (z,      t,p) + eps;
2985
2986
2987 * post optimality variables
2988
2989 *ag
2990 MC_ag_vp            (z,i,c,t,p) = MC_ag_v.1            (z,i,c,t,p) + eps;
2991 MC_lvstk_vp         (z,l,v,t,p) = MC_lvstk_v.1         (z,l,v,t,p) + eps;
2992
2993 *urban
2994 MNB_urb_vp          (z,k,u,t,p) = MNB_urb_v.1          (z,k,u,t,p) + eps;

```

```

2995 CS_cap_urb_vp      (z,k,u,t,p) = CS_cap_urb_v.l      (z,k,u,t,p) + eps;
2996 GR_cap_urb_vp      (z,k,u,t,p) = GR_cap_urb_v.l      (z,k,u,t,p) + eps;
2997 TC_cap_urb_vp      (z,k,u,t,p) = TC_cap_urb_v.l      (z,k,u,t,p) + eps;
2998 Wel_cap_urb_vp      (z,k,u,t,p) = Wel_cap_urb_v.l      (z,k,u,t,p) + eps;
2999
3000 *industry
3001 MNB_ind_vp          (z,n,j,t,p) = MNB_ind_v.l          (z,n,j,t,p) + eps;
3002 CS_unit_ind_vp      (z,n,j,t,p) = CS_unit_ind_v.l      (z,n,j,t,p) + eps;
3003 GR_unit_ind_vp      (z,n,j,t,p) = GR_unit_ind_v.l      (z,n,j,t,p) + eps;
3004 TC_unit_ind_vp      (z,n,j,t,p) = TC_unit_ind_v.l      (z,n,j,t,p) + eps;
3005 Wel_unit_ind_vp      (z,n,j,t,p) = Wel_unit_ind_v.l      (z,n,j,t,p) + eps;
3006
3007 *Discounted Net Present Values
3008 DNPV_ag_tot_vp      (z,      t,p) = DNPV_ag_tot_v.l      (z,      t,p) + eps;
3009 DNPV_lvstk_tot_vp    (z,      t,p) = DNPV_lvstk_tot_v.l    (z,      t,p) + eps;
3010 DNPV_urb_tot_vp      (z,      t,p) = DNPV_urb_tot_v.l      (z,      t,p) + eps;
3011 DNPV_ind_tot_vp      (z,      t,p) = DNPV_ind_tot_v.l      (z,      t,p) + eps;
3012
3013 DNPV_ag_welfare_vp   (z,      p) = DNPV_ag_welfare_v.l   (z,      p) + eps;
3014 DNPV_lvstk_welfare_vp (z,      p) = DNPV_lvstk_welfare_v.l   (z,      p) + eps;
3015 DNPV_urb_welfare_vp   (z,      p) = DNPV_urb_welfare_v.l   (z,      p) + eps;
3016 DNPV_ind_welfare_vp   (z,      p) = DNPV_ind_welfare_v.l   (z,      p) + eps;
3017
3018 DNPV_econ_welfare_vp (      p) = dnpv_econ_welfare_v.l (      p) + eps;
3019 ;
3020
3021 execute_unload
3022
3023 "Kenya_Oct_02_2020_1234pm_usmdt"
3024
3025 * read data
3026 rho_p   rechrg_flux_p aq_area_p porosity_p storage0_p pc_af_p pc_af_f_p depth0_p depth_p
3027 change_depth_p
3028
3029 *Crop
3030 yield_agr_p price_agr_p cost_agr_p res_use_agr_p net_rev_agr_p land_agr_p net_welfare_agr_p
3031 pumping_agr_p net_welfare_yr_agr_p ag_crop_cost_prop_p
3032
3033 *Livestock
3034 yield_lvstk_p price_lvstk_p cost_lvstk_p res_use_lvstk_p net_rev_lvstk_p head_lvstk_p
3035 pumping_lvstk_p net_welfare_yr_lvstk_p ag_lvstk_cost_prop_p

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3036
 3037 *Urban
 3038 pumping_urb_p pumping_urb_cap_p pop_urb_p price_urb_p ave_cost_urb_p B0_urb_p B1_urb_p eta_urb_p
 3039 c_sur_urb_p G_rev_urb_p T_cost_urb_p welfare_urb_p T_welfare_urb_p price_check_urb_p
 3040
 3041 *industry
 3042 pumping_ind_p pumping_ind_unit_p pop_ind_p price_ind_p ave_cost_ind_p B0_ind_p B1_ind_p eta_ind_p
 3043 c_sur_ind_p G_rev_ind_p T_cost_ind_p welfare_ind_p T_welfare_ind_p price_check_ind_p
 3044
 3045 *total pumping
 3046 tot_pumping_p
 3047
 3048 *total economic benefits
 3049 tot_econ_welfare_p
 3050
 3051 *optimized results
 3052
 3053 *hydrology
 3054
 3055 storage_vp recharge_vp net_recharge_vp depth_vp depth_vp Tot_pumping_vp
 3056
 3057 * ag
 3058 * crop
 3059 acres_agr_vp resource_agr_vp pumping_agr_vp T_pumping_agr_vp pump_cost_ac_agr_depth_vp
 3060
 3061 * lvstk
 3062 head_lvstk_vp resource_lvstk_vp pumping_lvstk_vp T_pumping_lvstk_vp pump_cost_h_lvstk_depth_vp
 3063
 3064 *urban
 3065 pumping_urb_vp pumping_cap_urb_vp T_pumping_urb_vp
 3066
 3067 *industry
 3068 pumping_ind_vp pumping_unit_ind_vp T_pumping_ind_vp
 3069
 3070 * economics
 3071 *ag
 3072 *crop
 3073
 3074 Yield_agr_vp net_rev_agr_vp income_agr_yr_vp income_agr_vp MC_ag_vp
 3075
 3076 *lvstk

```

3077 Yield_lvstk_vp net_rev_lvstk_vp income_lvstk_yr_vp MC_lvstk_vp
3078
3079 *urban
3080 price_urb_vp A_cost_urb_vp T_cost_urb_vp G_rev_urb_vp c_sur_urb_vp
3081 pump_cost_af_urb_depth_vp welfare_urb_vp T_welfare_urb_vp MNB_urb_vp
3082 CS_cap_urb_vp GR_cap_urb_vp TC_cap_urb_vp Wel_cap_urb_vp
3083
3084 *industry
3085 price_ind_vp A_cost_ind_vp T_cost_ind_vp G_rev_ind_vp c_sur_ind_vp
3086 pump_cost_af_ind_depth_vp welfare_ind_vp T_welfare_ind_vp MNB_ind_vp
3087 CS_unit_ind_vp GR_unit_ind_vp TC_unit_ind_vp Wel_unit_ind_vp
3088
3089 *total
3090 DNPV_ag_tot_vp DNPV_lvstk_tot_vp DNPV_urb_tot_vp DNPV_ind_tot_vp
3091 DNPV_ag_welfare_vp DNPV_lvstk_welfare_vp DNPV_urb_welfare_vp DNPV_ind_welfare_vp
3092 DNPV_econ_welfare_vp mod_stat_p
3093 ;
3094
3095 $onecho > gdxrwout.txt
3096
3097 i=Kenya_Oct_02_2020_1234pm_usmdt.gdx
3098 o=Kenya_Oct_02_2020_1234pm_usmdt.xlsm
3099
3100 epsout = 0
3101
3102
3103 * parameters read or calculated by the model (not optimized)
3104
3105 par = rechrg_flux_p          rng = data_aqf_flux(L)!c4          cdim = 0
3106 par = aq_area_p             rng = data_aqf_area_L2!c4          cdim = 0
3107 par = porosity_p            rng = data_aqf_porosity!c4          cdim = 0
3108 par = storage0_p            rng = data_aqf_start_storage!c4      cdim = 0
3109 par = pc_af_p               rng = data_aqf_cost_per_af_base_depth!c4 cdim = 0
3110 par = pc_af_f_p             rng = data_aqf_cost_per_af_w_depth!c4  cdim = 0
3111 par = depth0_p              rng = data_aqf_start_depth!c4       cdim = 0
3112 par = change_depth_p        rng = data_aqf_change_depth!c4      cdim = 0
3113 par = depth_p               rng = data_observed_depth!c4        cdim = 0
3114
3115 par = rho_p                 rng = data_discount_rate!c4          cdim = 0
3116 par = ag_crop_cost_prop_p   rng = data_ag_crop_cost_proportion!c4      cdim = 0
3117

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```

3118 *Crop production
3119 par = yield_agr_p          rng = data_yield_agr!c4          cdim = 0
3120 par = price_agr_p          rng = data_price_agr!c4          cdim = 0
3121 par = cost_agr_p           rng = data_cost_agr!c4           cdim = 0
3122 par = res_use_agr_p        rng = data_res_use_agr!c4        cdim = 0
3123 par = net_rev_agr_p        rng = data_net_rev_agr!c4        cdim = 0
3124 par = land_agr_p           rng = data_land_agr!c4           cdim = 0
3125 par = pumping_agr_p        rng = data_pumping_agr!c4        cdim = 0
3126 par = net_welfare_yr_agr_p rng = data_net_welfare_agr!c4        cdim = 0
3127
3128 *Livestock
3129 par = yield_lvstk_p        rng = data_yield_lvstk!c4          cdim = 0
3130 par = price_lvstk_p        rng = data_price_lvstk!c4          cdim = 0
3131 par = cost_lvstk_p         rng = data_cost_lvstk!c4          cdim = 0
3132 par = res_use_lvstk_p      rng = data_res_use_lvstk!c4        cdim = 0
3133 par = net_rev_lvstk_p      rng = data_net_rev_lvstk!c4        cdim = 0
3134 par = head_lvstk_p         rng = data_head_lvstk!c4          cdim = 0
3135 par = pumping_lvstk_p      rng = data_pumping_lvstk!c4        cdim = 0
3136 par = net_welfare_yr_lvstk_p rng = data_net_welfare_lvstk!c4        cdim = 0
3137 par = ag_lvstk_cost_prop_p rng = data_ag_lvstk_cost_prop!c4        cdim = 0
3138
3139 * Urban
3140 par = pumping_urb_p        rng = data_pumping_urb!c4          cdim = 0
3141 par = pumping_urb_cap_p    rng = data_pumping_urb_cap!c4        cdim = 0
3142 par = pop_urb_p            rng = data_pop_urb!c4            cdim = 0
3143 par = price_urb_p          rng = data_price_urb!c4          cdim = 0
3144 par = ave_cost_urb_p       rng = data_ave_cost_urb!c4        cdim = 0
3145 par = B0_urb_p             rng = data_B0_urb!c4             cdim = 0
3146 par = B1_urb_p             rng = data_B1_urb!c4             cdim = 0
3147 par = eta_urb_p           rng = data_eta_urb!c4           cdim = 0
3148
3149 par = c_sur_urb_p          rng = data_c_sur_urb!c4          cdim = 0
3150 par = G_rev_urb_p          rng = data_G_rev_urb!c4          cdim = 0
3151 par = T_cost_urb_p         rng = data_T_cost_urb!c4         cdim = 0
3152 par = welfare_urb_p        rng = data_welfare_urb!c4        cdim = 0
3153 par = T_welfare_urb_p      rng = data_T_welfare_urb!c4      cdim = 0
3154 par = price_check_urb_p    rng = data_price_check!c4        cdim = 0
3155
3156 *Industry
3157 par = pumping_ind_p        rng = data_pumping_ind!c4          cdim = 0
3158 par = pumping_ind_unit_p   rng = data_pumping_ind_unit!c4        cdim = 0

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3159	par = pop_ind_p	rng = data_pop_ind!c4	cdim = 0
3160	par = price_ind_p	rng = data_price_ind!c4	cdim = 0
3161	par = ave_cost_ind_p	rng = data_ave_cost_ind!c4	cdim = 0
3162	par = B0_ind_p	rng = data_B0_ind!c4	cdim = 0
3163	par = B1_ind_p	rng = data_B1_ind!c4	cdim = 0
3164	par = eta_ind_p	rng = data_eta_ind!c4	cdim = 0
3165			
3166	par = c_sur_ind_p	rng = data_c_sur_ind!c4	cdim = 0
3167	par = G_rev_ind_p	rng = data_G_rev_ind!c4	cdim = 0
3168	par = T_cost_ind_p	rng = data_T_cost_ind!c4	cdim = 0
3169	par = welfare_ind_p	rng = data_welfare_ind!c4	cdim = 0
3170	par = T_welfare_ind_p	rng = data_T_welfare_ind!c4	cdim = 0
3171	par = price_check_ind_p	rng = data_price_check_ind!c4	cdim = 0
3172			
3173	*Pumping		
3174	par = tot_pumping_p	rng = data_total_pumping!c4	cdim = 0
3175			
3176	*Economics		
3177	par = tot_econ_welfare_p	rng = data_tot_econ_welfare!c4	cdim = 0
3178			
3179			
3180	* Optimized values sent to a spreadsheet		
3181			
3182	*hydrology		
3183			
3184	par = storage_vp	rng = opt_aqf_storage!c4	cdim = 0
3185	par = recharge_vp	rng = opt_gross_aqf_recharge!c4	cdim = 0
3186	par = net_recharge_vp	rng = opt_net_agr_recharge!c4	cdim = 0
3187	par = depth_vp	rng = opt_aqf_depth!c4	cdim = 0
3188	par = Tot_pumping_vp	rng = opt_tot_pumping_by_aquifer!c4	cdim = 0
3189			
3190	*agriculture		
3191	*crop		
3192	par = acres_agr_vp	rng = opt_ha_in_prodn_agr!c4	cdim = 0
3193	par = resource_agr_vp	rng = opt_resource_use_agr!c4	cdim = 0
3194	par = pumping_agr_vp	rng = opt_aqf_pumping_agr!c4	cdim = 0
3195	par = T_pumping_agr_vp	rng = opt_total_aqf_pumping_agr!c4	cdim = 0
3196	par = pump_cost_ac_agr_depth_vp	rng = opt_pump_cost_ac_agr_depth!c4	cdim = 0
3197	par = Yield_agr_vp	rng = opt_crop_yield_agr!c4	cdim = 0
3198			
3199	par = net_rev_agr_vp	rng = opt_net_rev_agr!c4	cdim = 0

3200	par = income_agr_yr_vp	rng = opt_farm_income_year!c4	cdim = 0
3201	par = DNPV_ag_tot_vp	rng = opt_farm_income_agr!c4	cdim = 0
3202			
3203	*livestock		
3204	par = head_lvstk_vp	rng = opt_no_of_head!c4	cdim = 0
3205	par = resource_lvstk_vp	rng = opt_lvstk_Wat_use!c4	cdim = 0
3206	par = pumping_lvstk_vp	rng = opt_aqf_pumping_lvstk!c4	cdim = 0
3207	par = T_pumping_lvstk_vp	rng = opt_total_aqf_pumping_lvstk!c4	cdim = 0
3208	par = pump_cost_h_lvstk_depth_vp	rng = opt_pump_cost_h_lvstk_depth!c4	cdim = 0
3209	par = Yield_lvstk_vp	rng = opt_lvstk_productivity!c4	cdim = 0
3210			
3211	par = net_rev_lvstk_vp	rng = opt_net_rev_lvstk!c4	cdim = 0
3212	par = income_lvstk_yr_vp	rng = opt_farm_lvstk_income_year!c4	cdim = 0
3213	par = DNPV_lvstk_tot_vp	rng = opt_farm_income_lvstk!c4	cdim = 0
3214			
3215	*urban		
3216	par = price_urb_vp	rng = opt_water_price_urb!c4	cdim = 0
3217	par = A_cost_urb_vp	rng = opt_ave_cost_urb!c4	cdim = 0
3218	par = T_cost_urb_vp	rng = opt_tot_cost_urb!c4	cdim = 0
3219	par = G_rev_urb_vp	rng = opt_gross_rev_urb!c4	cdim = 0
3220	par = c_sur_urb_vp	rng = opt_cons_surplus_urb!c4	cdim = 0
3221			
3222	par = pumping_urb_vp	rng = opt_aqf_pumping_urb!c4	cdim = 0
3223	par = pumping_cap_urb_vp	rng = opt_aqf_pumping_per_unit_urb!c4	cdim = 0
3224	par = T_pumping_urb_vp	rng = opt_total_aqf_pumping_urb!c4	cdim = 0
3225			
3226	par = pump_cost_af_urb_depth_vp	rng = opt_pump_cost_af_urb_w_depth!c4	cdim = 0
3227	par = welfare_urb_vp	rng = opt_welfare_by_use_urb!c4	cdim = 0
3228	par = DNPV_urb_tot_vp	rng = opt_tot_welfare_urb!c4	cdim = 0
3229	par = MNB_urb_vp	rng = opt_Marg_net_ben_urb!c4	cdim = 0
3230	par = CS_cap_urb_vp	rng = opt_con_surplus_unit_urb!c4	cdim = 0
3231	par = GR_cap_urb_vp	rng = opt_gross_rev_per_cap_urb!c4	cdim = 0
3232	par = TC_cap_urb_vp	rng = opt_total_cost_per_unit_urb!c4	cdim = 0
3233	par = Wel_cap_urb_vp	rng = opt_welfare_per_unit_urb!c4	cdim = 0
3234			
3235	*industry		
3236	par = price_ind_vp	rng = opt_water_price_ind!c4	cdim = 0
3237	par = A_cost_ind_vp	rng = opt_ave_cost_ind!c4	cdim = 0
3238	par = T_cost_ind_vp	rng = opt_tot_cost_ind!c4	cdim = 0
3239	par = G_rev_ind_vp	rng = opt_gross_rev_ind!c4	cdim = 0
3240	par = c_sur_ind_vp	rng = opt_cons_surplus_ind!c4	cdim = 0

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3241
3242 par = pumping_ind_vp      rng = opt_aqf_pumping_ind!c4      cdim = 0
3243 par = pumping_unit_ind_vp  rng = opt_aqf_pumping_per_unit_ind!c4    cdim = 0
3244 par = T_pumping_ind_vp    rng = opt_total_aqf_pumping_ind!c4    cdim = 0
3245
3246 par = pump_cost_af_ind_depth_vp  rng = opt_pump_cost_af_ind_w_depth!c4    cdim = 0
3247 par = welfare_ind_vp            rng = opt_welfare_by_use_ind!c4      cdim = 0
3248 par = DNPV_ind_tot_vp          rng = opt_tot_welfare_ind!c4      cdim = 0
3249 par = MNB_ind_vp              rng = opt_Marg_net_ben_ind!c4      cdim = 0
3250 par = CS_unit_ind_vp          rng = opt_con_surplus_unit_ind!c4    cdim = 0
3251 par = GR_unit_ind_vp          rng = opt_gross_rev_per_cap_ind!c4    cdim = 0
3252 par = TC_unit_ind_vp          rng = opt_total_cost_per_unit_ind!c4    cdim = 0
3253 par = Wel_unit_ind_vp         rng = opt_welfare_per_unit_ind!c4    cdim = 0
3254
3255
3256 *total
3257
3258 par = DNPV_ag_welfare_vp      rng = opt_DNPV_ag_crop_welfare!c4      cdim = 0
3259 par = DNPV_lvstk_welfare_vp   rng = opt_DNPV_lvstk_welfare!c4      cdim = 0
3260 par = DNPV_urb_welfare_vp     rng = opt_DNPV_urb_welfare!c4      cdim = 0
3261 par = DNPV_ind_welfare_vp     rng = opt_DNPV_ind_welfare!c4      cdim = 0
3262
3263 par = DNPV_econ_welfare_vp     rng = opt_DNPV_econ_welfare!c4      cdim = 0
3264 par = mod_stat_p              rng = mod_stat_p!c4              cdim = 0
3265 $offecho
3266 execute 'gdxxrw.exe @gdxxrwout.txt trace=2';
3267
3268 * -----
3269 *                                     THE END                                     *
3270 * -----
3271

```

Figures

Figure 1

Nairobi and Merti Aquifer Study Regions in Kenya. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.