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Concentration changes of conserved components such as chloride are important as indicators of the principal processes affecting the fluid; boiling, dilution or conductive heat transfer, and geothermometry also provides important information. Early data are reviewed to obtain an estimate of the "deep" water feeding the field. Data for the succeeding 30 year period are used to assess the gross changes in the production field. This data analysis must filter out the chemical changes induced by local boiling and vapour loss. A technique is therefore proposed which permits comparison of data from individual wells and the field as a whole so that conclusions can be drawn concerning the principal changes and their relative rates.

CHEMICAL DATA Chemical data for

This geological map of the Taupo area shows the Western and Eastern Borefields, which are delineated by dashed lines. A solid line labeled 'STEAM LINE' runs through the Eastern Borefield. The map includes several geographical features: ALUM LAKE, SULPHUR CRATER, and the GEYSER VALLEY. A 'TRANSMISSION LINE' is shown running from the top left towards the center. Other features include 'WAIKARE STRM' and 'TAUPO'. Numerous numbered points (e.g., 203, 206, 207, 208, 209, 210, 211, 213, 215, 216, 217, 218, 219, 220, 221, 222, 223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 266, 267, 268, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 313, 314, 315, 316, 317, 318, 319, 320, 321, 322, 323, 324, 325, 326, 327, 328, 329, 330, 331, 332, 333, 334, 335, 336, 337, 338, 339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360, 361, 362, 363, 364, 365, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375, 376, 377, 378, 379, 380, 381, 382, 383, 384, 385, 386, 387, 388, 389, 390, 391, 392, 393, 394, 395, 396, 397, 398, 399, 400, 401, 402, 403, 404, 405, 406, 407, 408, 409, 410, 411, 412, 413, 414, 415, 416, 417, 418, 419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 431, 432, 433, 434, 435, 436, 437, 438, 439, 440, 441, 442, 443, 444, 445, 446, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 460, 461, 462, 463, 464, 465, 466, 467, 468, 469, 470, 471, 472, 473, 474, 475, 476, 477, 478, 479, 480, 481, 482, 483, 484, 485, 486, 487, 488, 489, 490, 491, 492, 493, 494, 495, 496, 497, 498, 499, 500, 501, 502, 503, 504, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 528, 529, 530, 531, 532, 533, 534, 535, 536, 537, 538, 539, 540, 541, 542, 543, 544, 545, 546, 547, 548, 549, 550, 551, 552, 553, 554, 555, 556, 557, 558, 559, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 570, 571, 572, 573, 574, 575, 576, 577, 578, 579, 580, 581, 582, 583, 584, 585, 586, 587, 588, 589, 590, 591, 592, 593, 594, 595, 596, 597, 598, 599, 600, 601, 602, 603, 604, 605, 606, 607, 608, 609, 610, 611, 612, 613, 614, 615, 616, 617, 618, 619, 620, 621, 622, 623, 624, 625, 626, 627, 628, 629, 630, 631, 632, 633, 634, 635, 636, 637, 638, 639, 640, 641, 642, 643, 644, 645, 646, 647, 648, 649, 650, 651, 652, 653, 654, 655, 656, 657, 658, 659, 660, 661, 662, 663, 664, 665, 666, 667, 668, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 680, 681, 682, 683, 684, 685, 686, 687, 688, 689, 690, 691, 692, 693, 694, 695, 696, 697, 698, 699, 700, 701, 702, 703, 704, 705, 706, 707, 708, 709, 710, 711, 712, 713, 714, 715, 716, 717, 718, 719, 720, 721, 722, 723, 724, 725, 726, 727, 728, 729, 730, 731, 732, 733, 734, 735, 736, 737, 738, 739, 740, 741, 742, 743, 744, 745, 746, 747, 748, 749, 750, 751, 752, 753, 754, 755, 756, 757, 758, 759, 760, 761, 762, 763, 764, 765, 766, 767, 768, 769, 770, 771, 772, 773, 774, 775, 776, 777, 778, 779, 780, 781, 782, 783, 784, 785, 786, 787, 788, 789, 790, 791, 792, 793, 794, 795, 796, 797, 798, 799, 800, 801, 802, 803, 804, 805, 806, 807, 808, 809, 810, 811, 812, 813, 814, 815, 816, 817, 818, 819, 820, 821, 822, 823, 824, 825, 826, 827, 828, 829, 830, 831, 832, 833, 834, 835, 836, 837, 838, 839, 840, 841, 842, 843, 844, 845, 846, 847, 848, 849, 850, 851, 852, 853, 854, 855, 856, 857, 858, 859, 860, 861, 862, 863, 864, 865, 866, 867, 868, 869, 870, 871, 872, 873, 874, 875, 876, 877, 878, 879, 880, 881, 882, 883, 884, 885, 886, 887, 888, 889, 890, 891, 892, 893, 894, 895, 896, 897, 898, 899, 900, 901, 902, 903, 904, 905, 906, 907, 908, 909, 910, 911, 912, 913, 914, 915, 916, 917, 918, 919, 920, 921, 922, 923, 924, 925, 926, 927, 928, 929, 930, 931, 932, 933, 934, 935, 936, 937, 938, 939, 940, 941, 942, 943, 944, 945, 946, 947, 948, 949, 950, 951, 952, 953, 954, 955, 956, 957, 958, 959, 960, 961, 962, 963, 964, 965, 966, 967, 968, 969, 970, 971, 972, 973, 974, 975, 976, 977, 978, 979, 980, 981, 982, 983, 984, 985, 986, 987, 988, 989, 990, 991, 992, 993, 994, 995, 996

In many wells, measured enthalpies greatly exceed those of water at the respective silica geotemperature suggesting addition of aquifer steam to the total discharge of the well. In those cases, GEODATA calculates the coexisting steam and water compositions which would be present at the silica temperature and assumes an equilibrium distribution of gases between the two phases. Such excess enthalpy wells have been discarded in the discussion of aquifer chemistry changes.

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The highest temperature wells suggest that the principal upflow lies to the west of the present production field. This appears to be at about 265°C with an initial chloride of 1680 mg/kg. Boiling of this fluid with steam loss leads to a fluid of 260°C and Cl = 1700 mg/kg flowing into the production field.

DATA REDUCTION FOR PRODUCTION WELLS Withdrawal of fluid from an aquifer results in local pressure reduction around wells and subsequently to a field wide pressure decline. Boiling of aquifer fluid sometimes occurs and the fluid sampled in production wells is a variable proportion of the mixture of liquid and vapour. Upon such a pressure drop, influx of cooler waters can occur, both on the scale of a single well and also field wide. Thus the chemical composition of a well at any particular time may reflect all or some of these perturbations, and a data reduction method is required to compare chemical data from production wells.

With exploitation, the water in the production aquifer is steadily renewed by the inflow of both deep recharge and dilution waters and the well chemistry at any time is related to the proportions of these two components. On an enthalpy-chloride mixing diagram, changes in the "apparent" aquifer composition represented by individual well discharges can be resolved into two components - one giving the relative amount of dilution with respect to the original upflow into the field. Changes in the dilution trend then represent changes in the relative proportions of upflow and diluent in the production well feed zones.

Since boiling is a result of both local and fieldwide pressure reduction, it is considered a secondary process in the data reduction. In order to compare chemical data, they are first recalculated to an aquifer condition defined by the quartz geothermometer temperature of the well. These "aquifer" data are then projected on to a reference line, representing field dilution, to obtain boiling corrected chloride concentrations (Cl'). The data reduction process is illustrated in Figure 2. We have defined the dilution line as passing through the initial

fluid composition, $H_i = 1134$ kJ/kg, $Cl_i = 1700$ mg/kg and the assumed diluting water $H_d = 632$ kJ/kg, $Cl_d = 300$ mg/kg. The sample line passes through the points defined by the liquid enthalpy at the silica geothermometer H_w , and the aquifer chloride concentration Cl_w , and the enthalpy of pure steam at the silica temperature H_s , where $Cl = 0$. The intersection of these two lines defines the corrected chloride (Cl') and corrected enthalpy (H'). All available data for the Wairakei wells have been examined in this way.

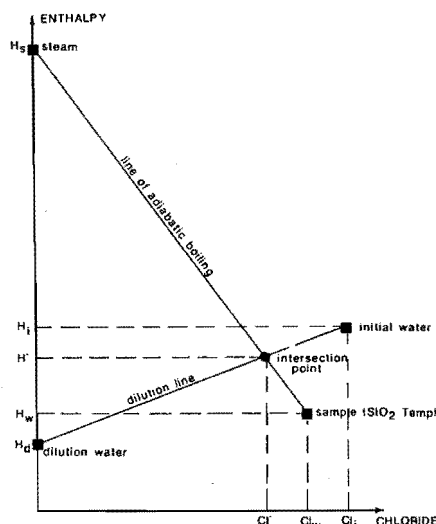
SPATIAL CHANGES IN THE CHEMISTRY We have focussed on the Western borefield in mapping the spatial changes in Cl' for two reasons. The linear arrangement of wells in the Eastern borefield does not permit satisfactory contouring, and wells in the East tend to draw on shallower aquifers which rapidly developed an excess enthalpy condition.

Figure 3 shows mean corrected chloride concentrations for the years prior to 1961 for the Western borefield. The principal fault systems are also shown. Within the constraints of the available data, there is an even distribution, although some dilution occurs in the northeast, trending eventually to the relatively dilute chloride natural discharges in the Geyser Valley.

Figure 2.

The data for 1981-1982 are shown in Figure 4. Declines of 100-200 mg/kg in Cl' are evident in many wells corresponding to enthalpy declines of 40-80 kJ/kg relative to the original state of the field. These data also highlight the southern part of the reservoir as the principal recharge region. The arrow symbols show tracer first-arrival data from McCabe et al (1983) based on injection tests in the late 1970's and early 1980's. These confirm the chloride patterns derived independently. Contoured maps of silica geotemperatures show similar trends.

GROSS CHANGES IN THE AQUIFER The average chloride function for the Western borefield, weighted according to annual well discharges is shown in Figure 5. There is considerable scatter in the data due to wells being taken off production or unable to sustain production pressures, however, some trends are clear. From 1959 to 1963 there is an almost constant average chloride function of ~1585 mg/kg indicating negligible dilution of the water discharged. This is consistent with the formation, during this period, of a steam zone in the upper part of the reservoir, formed by a drop in the level of fluid (Allis, 1981). From 1965 onwards, there is a definite dilution trend evident. The data for 1981 and 1982 have an average Cl' of 1497 mg/kg and this corresponds to a drop of 5.6% since 1959-1963. If this dilution is all due to



inflow of fluid with a chloride concentration of 300 mg/kg, then 6.8% more of the fluid discharged in 1981/82 consisted of this diluting water than in 1959-1963.

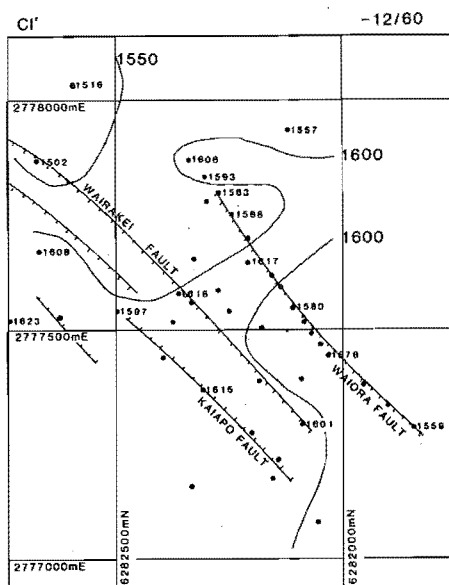


Figure 3.

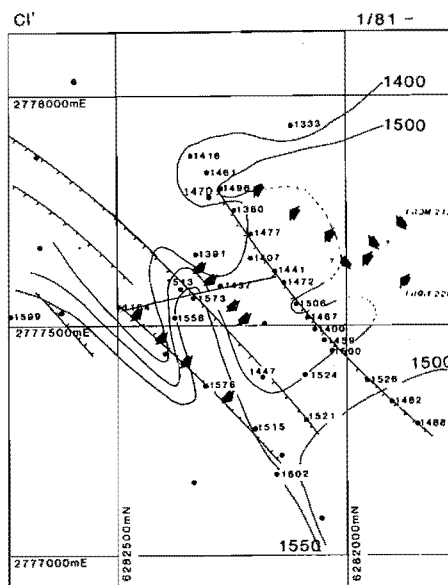


Figure 4.

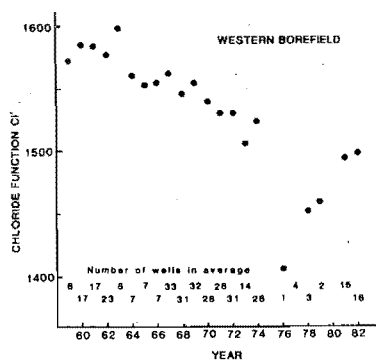


Figure 5.

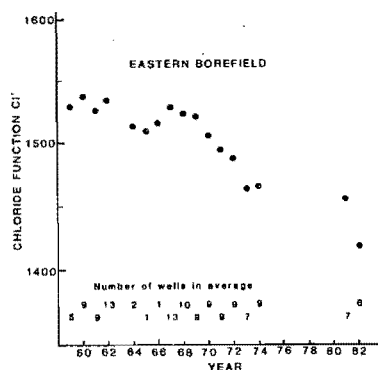


Figure 6.

Figure 6 shows the equivalent calculation for the Eastern borefield. The Cl' is more or less constant until 1969, implying that there is little or no dilution during this time. This probably reflects production resulting from a drop in the average water level and subsequent formation of a steam zone. In 1970, there is a dramatic drop in average Cl' indicating production from more dilute fluids. This trend is confirmed in the data for 1981/82 where the average Cl' is 1437 mg/kg. This represents an increase in dilution of 7.2% by 300 mg/kg Cl fluid over the early years. It would appear that the dilution front which reached the northeastern extremities of the Western borefield in 1963 did not have a significant effect on the Eastern borefield until 1970. However when dilution did commence in the Eastern borefield, it had a more pronounced effect suggesting that the Eastern borefield draws on a proportionately smaller local reservoir than the Western borefield.

CHLORIDE MASS BALANCE Modelling of the Wairakei field to date has been confined to the use of physical data. The chemical database now permits the development of independent models providing additional boundary constraints. Two endmember models are considered. The first model assumes that the reservoir affected by production is small compared with the amount of fluid extracted. The chloride balance can therefore be expressed as:

$$M_R Cl_R + M_D Cl_D + M_I Cl_I = M_P Cl_P + M_O Cl_O$$

where M and Cl refer to mass fluxes and chloride concentrations and the subscripts R , D , I , P , and O refer to deep recharge (R), drainage from the forming steam zone (D), cooler diluting water inflow (I), well production (P), and natural (non-production) outflow (O). The drainage

component refers to hot fluid produced from storage in porous rock following pressure decline. For model calculations referring to any chosen year following the demise of the natural hot water discharges, $M_0 = 0$, and we also assumed that $Cl_R = Cl_D$. Thus:

$$M_R + M_D + M_I = M_P$$

For any particular year, M_P is known and M_D can be estimated. Cl_R is assumed to be constant with time and equal to 1680 mg/kg. Cl_I is assumed to be 300 mg/kg and values for Cl_P have been determined. Consequently the equations can be solved for M_I and M_R and the results are:

	1961	1971	1981
M_R (M tonnes/year)	11.1	43.8	26.9
M_I (M tonnes/year)		3.7	6.7
M_I/M_P		8.7%	12.5%
			15.0%

It can be seen that the contribution of the surface zone water to the production flow has increased from 8.7% in 1961 to 15.0% in 1981. During the initial period of the field history between 1960 and 1970, the main production was from drainage of the forming steam zone as determined by Allis and Hunt (1986). By 1971, this was essentially completed and the deep system responded with a greater flow of recharge water. By 1981, the contribution from surface waters had increased markedly and this caused declining enthalpy of the production field.

A second model assumes that the production reservoir is very large and well mixed throughout, so that there is a long residence time in this reservoir. The notation is the same as that for the first model with the addition of M_S and Cl_S which are the mass and chloride concentration of the large production reservoir. It is assumed that $Cl_P = Cl_S$ and that M_S is constant, implying rapid mixing of the reservoir. M_S has only been constant since 1971, so this model is applicable only to the dilution phase. Again it is assumed that $M_0 = 0$. We consider the period 1971-1981. For this 10 year period the total flow into the reservoir was $M_I^T + M_R^T = M_P^T$ where the superscript T refers to the total flow for the 10 year period. The total chloride in the production reservoir in 1971 was $M_S Cl_S^{1971}$ and in 1981 was $M_S Cl_S^{1981}$. The difference between these two totals must equal the chloride inflows and outflows, i.e.

$$M_S Cl_S^{1981} - M_S Cl_S^{1971} = M_I^T Cl_I + M_R^T Cl_R - M_P^T Cl_P$$

As well, $Cl_S = Cl_P$, $Cl_S^{1981} = 1490$ mg/kg, $Cl_S^{1971} = 1525$ mg/kg, and $M_P Cl_P$ can be calculated by summing over the 10 year period. Together with the mass balance, there is still not enough information to solve for M_P , M_I and M_S . However, for a variety of recharge/dilution ratios (M_P/M_I), estimates of the reservoir size can be made (all units are Mtonnes for the 10 year period). Since there cannot be a negative mass for the reservoir, the maximum ratio of inflow to recharge water is about 1:7. Prior to exploitation, M_R was estimated to be around 12 Mtonnes/year (Allis 1981). If it is assumed that this is constant, then $M_I/M_P = 2.6$ and the mixed reservoir size is estimated to be ~100000 Mtonnes.

M_I^T/M_R^T	M_I	M_R	M_S
6:1	371	62	12469
4:1	346	87	11484
2.6:1	313	120	10182
2:1	288	144	9245
1:1	216	216	6406
1:2	144	288	3567
1:4	87	346	1272
1:7	54	378	0

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