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ORIGINAL RESEARCH

Forecasting a Tribal Population Using the Cohort-Component Method: A Case Study of the Hopi

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Abstract
Population forecasting is a difficult endeavor. When it involves a "small" population, forecasting becomes even more difficult because of the lack of adequate input data to appropriately implement a technique preferred by demographers, the cohort-component method (CCM). Small populations also are subject to high levels of stochastic uncertainty, which can lead to substantial temporal fluctuations in size as well as mortality, fertility, and migration rates over short periods of time. When the population is further defined in terms of characteristics such as tribal membership requirements, the acquisition of relevant age-sex and component data for the discrete population adds even more difficulty because the usual data sources may not have precise data for a given tribe, especially when there is a need for long-term forecasts as is the case in disputes over water allotments. In this case study of the Hopi tribal population, I show that these problems can be overcome, resulting in reasonably accurate forecasts over a long period of time. To do this, I identify three key input data sources: (1) an historic tribal census that serves as the basis for tribal membership; (2) the Social Security Administration's life tables, which are specific to cohorts by year of birth, staring in 1900; and (3) an accurate annual record of tribal membership record that covers a time period that can be used as a benchmark once the forecast is launched from the historic tribal census. For this case study. these three data sources allow me to launch an 80 year CCM forecast of the Hopi Tribal Population from its 1937 tribal census to 2017 and conduct an ex post facto assessment of the accuracy of the forecasted total population in five-year increments from 1992 to 2017 using the annual tribal membership roll for this period; the assessment finds that the forecast matches up well with the tribal membership roll. So without adjustments, the forecast is taken out 20 years more, from 2017 to 2037. The results suggest that accurate long-term forecasts are possible using the cohort-component method for the Hopi, which, in turn, suggests that this same CCM process could be used to develop reasonably accurate long-term population forecasts of other tribes for which a tribal census was conducted that is linked to current tribal membership rolls, especially when these forecasts are required in resolving disputes over water allotments.

Extended author information available on the last page of the article

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Keywords Child-woman ratio · Cohort life table · Inertia · Small population · Tribe · Uncertainty water allotments

Background

Population Forecasting and the Cohort Component Method

Population forecasting has been described as an unavoidable, yet impossible task (Keyfitz, 1987, p. 236). When it involves a "small" population, forecasting becomes even more difficult because of the lack of adequate input data to appropriately implement a technique preferred by demographers, the cohort-component method (Baker et al., 2017; Swanson and Tayman, 1995; Siegel, 1953; Wilson et al., 2021). These issues are exacerbated when long-term forecasts are needed, as is often found in disputes over water allotments, where forecasts are part of the litigation (Maricopa County Superior Court, no date; Greene, 2017). This is a common issue facing Native American tribes and others, especially in the semi-arid southwestern area portion of the USA. (Burton, 1987; Kenney, 2003). It is the origin of this case study describing a method used to develop a long-term forecast of the Hopi tribe (Swanson, 2019), about which more is described in the remainder of this section and especially in the two following sections.

Regardless of the method used, one of the difficulties in forecasting a small population is the fact it is subject to higher levels of stochastic uncertainty than a large population (Coleman, 2001; Swanson & Tayman, 2012, pp. 187–192). In the case of using the cohort-component method (CCM), this stochastic uncertainty can lead to substantial temporal fluctuations in the components of change—fertility, mortality, and migration rates—over short periods of time (Raftery & Ševčíková, 2021; Smith et al., 2013, pp. 53, 92, 124). Another difficulty is that the availability of relevant component data is often problematic (Baker, Swanson, Tayman, and Tedrow 2017). When the population is defined in terms of a tribe, the acquisition of relevant age-sex and component data—births, deaths, and migrants—can be even more difficult to obtain (Swanson, 2008). It is often the case that the usual data sources (The National Center for Health Statistics or its state counterparts and the U.S. Census Bureau) do not have data specific to the tribe of interest (Greene, 2017). This is the situation in this case study of a small population, the Hopi, a tribe with a 2017 membership of 14,422 (Table 1).

Why do these issues make it difficult to use the CCM to forecast a small population? The CCM requires age and sex data (the cohort aspect) as the "launching platform" for a population projection and the components of population change—fertility, mortality, and migration data – to move it forward through time. In short, the CCM is data intensive to start with and when it is applied to small population, particularly a tribe, the lack of data specific to the population of interest means that a lot of data "substitutions" are needed to implement the CCM (Greene, 2017).

The essence of the CCM is captured in the fundamental demographic equation, a simple, but powerful expression which shows how a population changes:

Table 1 Hopi Tribal Population 1989–2017

									As of Year End	
									Reported	Calculated
									Living	Living
Year	Deceased	Relinguished	Disenrolled	Resigned	Removed	Suspended	Denied	Enrolled	Members	Members
1989									6852	
1990	65	6	1	0	0	1	0	237	7017	7017
1991	56	2	0	0	0	0	0	228	7187	7187
1992	60	2	1	0	0	0	0	341	7465	7465
1993	93	2	6	0	0	0	0	393	7766	7757
1994	71	4	6	0	0	0	0	1041	8728	8726
1995	62	5	0	0	0	0	0	811	9474	9472
1996	72	2	0	0	0	0	0	415	9815	9815
1997	76	8	1	0	0	0	0	316	10,047	10,046
1998	80	2	0	0	0	0	0	392	10,357	10,357
1999	94	11	0	0	0	0	0	387	10,640	10,639
2000	63	11	0	0	0	0	0	301	10,866	10,867
2001	70	11	0	0	0	0	0	387	11,172	11,172
2002	70	24	0	0	0	0	0	361	11,439	11,439
2003	89	6	1	0	0	0	0	420	11,764	11,763
2004	89	21	0	0	0	0	0	338	11,994	11,992
2005	86	9	0	0	0	0	0	298	12,197	12,197
2006	97	17	0	0	0	0	0	279	12,363	12,362
2007	94	7	0	0	0	0	0	217	12,479	12,479
2008	78	10	0	0	0	0	0	361	12,752	12,752
2009	105	12	0	0	0	0	0	362	12,991	12,997
2010	91	9	0	0	0	0	0	347	13,244	13,238

Table 1 (continued)

Year	Deceased	Relinguished	Disenrolled	Resigned	Removed	Suspended	Denied	Enrolled	As of Year End Reported Living Members	Calculated Living Members
2011	101	13	0	0	0	0	0	380	13,509	13,510
2012	104	10	1	0	0	0	0	357	13,752	13,751
2013	89	15	0	0	0	0	0	280	13,926	13,928
2014	96	18	0	0	0	0	0	250	14,065	14,062
2015	89	11	1	0	0	0	0	230	14,194	14,194
2016	109	10	0	0	0	0	0	286	14,381	14,361
2017	110	13	0	0	0	0	0	184	14,422	14,422
2018	48	1	0	0	0	0	0	111	14,484	14,484
TotalS	2407	272	18	0	0	0	0	10,310		

Source: Hopi Tribe (2018). Note: The total for 2018 is as of June 12, 2018, not the end of the calendar year

$$P_t = P_o + B_{(n)} - D_{(n)} + I_{(n)} - 0_{(n)} \tag{1}$$

where P_t is the population at the end of the period in question; P_o, the population at the beginning of the period; B is the number of births during the period; D is the number of deaths during the period; I is in-migration during the period; and 0 is out-migration during the period; and n = the length of the period = t – 0.

Equation (1) also can be defined in matrix terms:

$$P_{(0+n)} = AP_{(t)} \tag{2}$$

where A is the transition matrix containing the information on the probabilities of surviving and giving birth. When defined in this manner, Eq. (2) is commonly known as a Leslie Matrix (Leslie, 1945).

To be exactly true, there must be no measurement errors present in [1] (or [2]) (Kintner & Swanson, 1993). If we are interested in projecting a population of interest to a future date, we can use either of these two forms by making assumptions about the future births, deaths, and migration. Especially in the case of births and deaths, however, these assumptions are ordinarily made in the form of fertility and mortality rates, not in the form of the absolute numbers of births and deaths (Smith et al., 2013, pp. 27–32).

Equation (1) can be expanded to include age groups, gender, ethnicity and other characteristics of interest (Smith, Tayman, and Swanson, 2013: 30), such as members of a specific tribe. For populations defined by tribal membership, migration does not enter into the equation because the population is "closed," which simplifies the fundamental demographic equation:

$$P_{t'} = P_o + B - D \tag{3}$$

Equation (3) states that population at a given point in time, P_t, must be equal to the population at an earlier time, P_o, plus the births, B, and less the deaths, D, that occur during the period. When Equation (3) applies, the population in question is described by demographers as being "closed," For tribes that have membership rules based on ancestry, rules that require one to be born into the tribe, such a tribe is closed to "migration" into the tribe. That is, nobody can "join" the tribe by any means other than birth. This is not to say that members may not have been enrolled at birth and subsequently join or that they cannot resign and rejoin. However, joining or rejoining still requires the lineal ancestral descent described in the discussion centered on Table 1, which means that one cannot join by any means other than birth.

Native American Tribes as Populations of Interest

Native Americans are a growing population Liebler & Ortyl, 2014; National Research Council, 1996; Passell, 1996; Thornton, 1996) facing substantial economic and social disadvantages (Deloria et al., 2018; National Research Council, 1996; Pettit, et al, 2014; Robbins, 1992; Smith-Kaprosy et al., 2012). Moreover, this interest in the demographic future of indigenous peoples is not confined to the USA (Raymer et al., 2018; Statistics Canada, 2021; Wilson, 2009). Not surprisingly, the explosion in the growth of the Native American population has generated discussion. In regard to this growth, Passel (1996, p. 79) observes:

> [T]hat for decades through 1960, the American Indian population, as enumerated in U.S. censuses, grew little if at all. From a population of 248,000 in 1890, American Indians increased to 524,000 in 1960. While this does represent a doubling of the population, the average annual growth rate over the entire 70-year period was only 1.1 percent—a very low figure resulting from high fertility and very high mortality. Since 1960, the Native American population has exhibited explosive growth, increasing from 552,000 to 1,959,000, or 255 percent. The average annual growth rate of 4.3 percent, extending over a 30-year period, is demographically impossible without immigration. Previous research (Passel, 1976; Passel & Berman, 1986) has shown that this extraordinary growth was achieved through changing patterns of racial self-identification on the part of people with only partial or distant American Indian ancestry, coupled with relatively high fertility and improving mortality.

Similarly, Thornton (1979, p. 104), observes that the twentieth-century increase in the Native American population reflected in successive U.S. censuses can also be attributed to changes in the identification of individuals as "Native American." He finds that much of the increase in the American Indian population—excluding Eskimo and Aleuts—from 523,591 in 1960 to 792,730 in 1970 to 1.37 million in 1980 to over 1.8 million in 1990 resulted from individuals not identifying themselves as American Indian in earlier censuses but doing so in later ones. Prior to 1960, race was assigned to respondents by enumerators. Self-identification of race and ethnicity was subsequently employed starting with the 1960 census. Both methods are subject to judgment, which can lead to a change in race or ethnicity for the same person from one census to the next (Liebler & Ortyl, 2014; Liebler et al., 2016).

When it comes to developing CCM population projections of Native Americans, there are challenges, not only in the form of the issues described by Liebler & Ortyl, 2014, Liebler et al., 2016, Passel, 1996; Thornton, 1979), but also because of the lack of consistency between the Census Bureau's ethnic and racial classifications and those found in vital statistics (Cannon and Perchesky, 2017; Coulton & Harris, 1998; Devine et al., 2010). This inconsistency introduces errors when applying not only these births and deaths to the Native American population in question but also migration information.

As demonstrated by forecasts of Native American Tribes, there is clearly interest in their demographic future (Campbell, 1996; Greene, 2017; Hollingshaus et al., 2019; Howell, 2020; National Research Council, 1996; Rogers and Gillaspy, 2014). Given this interest, what can be done to overcome the challenges just described as well as the issues faced by these tribes in disputes over long-term water allotments (Burton, 1987; Greene, 2017; Kenney, 2003; Maricopa County Superior Court, no date; Swanson, 2019; Tayman, 2018). One proposed solution follows in the form of a case study.

The Hopi Tribe as a Case Study

In addition to the issues involving census counts, and the form of identification just discussed, with respect to the Hopi Tribe for example, specific decennial census data on it was only first reported in 2010. The Hopi Tribe was not separately grouped in earlier decennial census counts; instead the Tribe was part of the "Pueblo" tribal grouping U.S. Census Bureau, 2012). This lack of historical data represents an obstacle to obtaining age-sex data on the Hopi Tribe. Similarly, the vital statistics data (fertility and mortality) rely on ethnic definitions that may not specifically match the Hopi population as indicated by research on mismatches between the Census Bureau's ethnic and racial classifications and those found in vital statistics (Coulton & Harris, 1998; Devine et al., 2010).

In addition to the self-identification issue, the decennial census is based on the De Jure concept of population (Swanson & Tayman, 2011). This means that in its attempt to count people once and only once, it also attempts to count them "in the right place." (Cork & Voss, 2006). That is, the rules of residency used by the U.S. Census Bureau for decennial census counts may or may not correspond to other definitions of residency, including those used by the Hopi Tribe. In point of fact, the residency rules used by the U.S. Census Bureau for its decennial census are different than the residency rules it uses for its American Community Survey (Judson & Swanson, 2011, pp. 38, 39).

The Hopi are characterized by a sedentary life-style and high-density living arrangements within the reservation (Johansson & Preston, 1976). Much of traditional Hopi culture exists today and includes monogamy, matrilineal descent, and matrilocal residence (Encyclopedia Britannica, no date). There is strong tendency for Hopi to marry (or otherwise form sexual unions) with other Hopi. While the rate of out-marriage has increased (Kunitz, 1974a, 1974b), evidence indicates that the rates of out-marriage remain very low, as is adoption into the Tribe (French & Hanes, 2018).

As of 2020, 7,930 tribal members were estimated to be living off the reservation and 8,775 within it (Swanson, 2019). The reservation itself is wholly contained within the state of Arizona, surrounded by the Navajo Reservation (Hopi Tribe, 2022). Within the 1.5 million acre reservation there are 12 tight-knit villages bound together by relations within and among the 34 living clans living in them (Hopi Cultural Center, no date). Ceremonies are vital to the Hopi and those living off the reservation spend time on the reservation each year in observance of these traditional rituals and ceremonies (Burns, 2107). The time spent on the reservation by these returnees is why it is important to have a forecast of the entire tribal membership in regard to water allotments.

Hopi Tribal membership eligibility criteria are spelled out in Membership Ordinance 33 (Hopi Tribal Council, 1995), which is discussed in detail in the following section.

Data and Method

Along with the lack consistency between, on the one hand, the decennial census, and on the other, vital statistics data, the self-identification issue in conjunction with multi-racial lineage and the residency definitions make it difficult to develop cohort-component forecasts of the Hopi Tribal population using decennial census data and vital statistics data. In addition, the lack of historical decennial census data makes it virtually impossible to use "cohort change ratios," a variant of the cohort-component method that is often employed in conjunction with decennial census data when a population is "small" and vital statistics data are not available (Baker, Swanson, Tayman, and Tedrow 2017). An example of the difficulty of this task is found in recent work by Cannon and Percheski (2017) who discuss some of the obstacles facing an analyst who attempts to assemble valid fertility rates for the American Indian and Alaska Native population from 1980 to 2010. As noted in the preceding section in regard to virtually all Native American tribes, in addition to changing self-identification in terms of race and ethnicity, these obstacles include under-registration in terms of vital event systems and ethnic/race misclassification. These issues point to data that can be used. For data on the Hopi population that can be used to generate a forecast of tribal members on and off the reservation, there are annual counts of tribal members, as can be seen in Table 1 for the period 1989-2017 (Hopi Tribe, 2018). Table 1 provides not only an annual count of tribal members but also the "demographic accounting" underlying each annual count. For example, at the end of 1989/beginning of 1990 there were 6,852 members. Before the end of 1990 there were 65 members who died, six who relinquished their membership, zero who resigned, zero who were removed, zero who applied for membership and were denied, and 237 who were enrolled. This leads to a net gain of 165, which yields the 7,017 members shown at the end of 1990/beginning of 1991 and includes the one member who was suspended during 1990.

In addition to the annual count of total Hopi members for the period, 1989–2017, the 1937 Tribal Census (National Archives and Record Service (1965) provides the age, sex, and other characteristics of the Hopi population in 1937. Neither of these data sources suffers from the racial/ethnic identification and residency issues affecting decennial census data; nor are they subject to the decennial census /vital statistics mis-match problem. The annual membership data and the 1937 Tribal Census are linked via membership rules, as will be discussed shortly.

The December 31, 1937, Tribal Census Roll lists a (corrected) official total of 3325 Hopi Tribal members (National Archives & Record Service, 1965, p. 531 (microfilm page number)). The Census Roll lists 1735 males and 1590 females with 3209 residing on the Hopi reservation, 13 on another BIA Jurisdiction (Indian Reservation), and 103 elsewhere. The Census Roll contains information on births, deaths, supplemental 1938 Census counts, and a tribal census count for January 1st, 1937 (National Archives & Record Service, 1965). Those included as members in the 1937 census were full quantum (4/4), a requirement

Table 2 1937 Tribal Roll Census Population by Age & Sex

ADJUSTED (USING CORRECTED TOTAL),			
ALL MEMBERS ARE FULL BLOOD QUANTUM, 4/4)			
Age	Male	Female	Total
0–4	230	221	451
5–9	177	200	376
10–14	186	184	370
15–19	152	151	303
20–24	168	185	354
25–29	105	108	213
30–34	116	118	234
35–39	103	77	180
40–44	84	61	145
45–49	72	48	120
50–54	53	48	102
55–59	51	40	91
60–64	81	56	137
65–69	52	37	89
70–74	32	16	48
75–79	16	11	28
80–84	9	4	13
85–89	10	6	16
90+	37	16	53
Total	1735	1590	3325

Source: National Archives and Record Service (1965). "Hopi Tribe Census 1937." Hopi Indian Agency, Keams Canyon, AZ. National Archives Microfilm Publications, microcopy 595, roll 195, Indian Census Rolls, 1885–1940. Washington, DC. The National Archives, General Services Administration

that was relaxed in later years as described shortly. Table 2 provides an estimate of the 1937 Hopi Population by age and sex using a count by age and sex that was "controlled" to the corrected totals by sex for the December 31st, 1937, Tribal Census Roll (National Archives & Record Service, 1965, p. 531 (microfilm page number).

The counting (by hand) of the Hopi population by age and sex from the 1937 Tribal Census schedules as shown on the microfiche, was tedious. Because of the potential for error, this process became even more tedious because I went through the age and sex count multiple times and concluded the age-sex count was accurate only when the most recent two were exact matches by age and sex. However, even this process did not yield a count that when summed matched the "official" count by sex. My "final" age-sex count yielded 1689 males and 1545 females whereas the "official" count by sex showed 1735 males and 1590 females. The final age and sex counts, shown in Table 2, were "controlled" to the official counts by sex, which eliminated this discrepancy. Although my final age-sex count did not match the "official" count by sex, as a person with a background in primary data collection that includes organizing, conducting and supervising municipal and county census counts, I found the census schedules displayed on the microfiche to be professionally organized and completed (see the Discussion section for more on the tribal census count data). I suspect that my count was less than the official count because a small number of schedules, no more than three pages, were "missing" – not recorded on the microfiche.

From the "estimated" age-sex distribution controlled to the official 1937 Tribal Census data shown in Table 2, I launched a cohort-component (CCM) forecast that takes the form of the fundamental population equation for a closed population, as found in Equation [3]. It uses age and sex data from the 1937 Hopi Tribal Census that covers both the "cohort" requirement and the fertility component. The mortality component is provided by the Social Security Administration's "Cohort Life Tables" (Bell & Miller, 2005). Because the Hopi population is "closed," these two sources provide the components of population change that are required for a cohort-component forecast of the Hopi Tribal Population, fertility and mortality.

As alluded to earlier, Hopi Tribal membership eligibility criteria are spelled out in Membership Ordinance 33 (Hopi Tribal Council, 1995). Ordinance 33 states that an individual is eligible for Hopi Tribal membership if they are a lineal descendant of a Hopi or Tewa Indian listed in the December 31st, 1937, Census Roll (National Archives & Record Service, 1965) and are one-fourth (1/4) degree or more Hopi or Tewa blood or one-fourth (1/4) or more Hopi-Tewa blood combined (Hopi Tribal Council, 1995, p. 2). These criteria are consistent with earlier eligibility criteria prior to the adoption of Ordinance 33 (Hopi Tribal Council, 1995). Thus, all Hopi Tribal members can be traced back to one or more ancestors listed in the 1937 Tribal Census Roll. These criteria (the minimum blood quantum requirement (1/4) and the requirement that a member can be lineally traced back to one or more ancestors in the 1937 Tribal Census Roll), demonstrate that the Hopi Tribal population is "closed" from a demographic perspective.

An important entry in Table 2 is the population (by sex) aged 0–4. This age group represents the combined effects of fertility and mortality on infants (age zero to 1 year) and children aged 1 to 4. I note this because the infant mortality rate (the death rate to those under 1 year of age) is typically much higher than the childhood mortality rate (the death rate to those aged 1 to 4 years). However, as is found in the ex post facto test (Table 4 and it discussion), the 0–4 year grouping appears to have little, if any effect on the accuracy of the forecast. This age group is also not affected by migration because the population is closed. By taking the ratio of the population aged 0–4 to the females who are of reproductive years and culturally eligible to form sexual unions, one can calculate a measurement that incorporates both fertility and the effects of infant and child mortality relative to the population of females likely to have produced this age group (Baker et al., 2017, pp. 25, 26, 45–62, 80–81). Females aged 20–39 were selected due to consideration of reproductive years and eligibility to form sexual unions. This selection encompasses an age group that is twenty years wide, which is consistent with the five-year width of the 0–4 age group (dividing the age ranges results in a whole number). This consistency is important for forecast cycle length and age group width (Baker et al., 2017; Smith, Tayman, and Swanson, 2001). In 1937, for males aged 0–4, the ratio to females aged 20–39 is 0.4713 = 230/488. For females aged 0–4, the ratio is 0.4933 = 221/488. These ratios are needed to launch a demographic forecast of Hopi Tribal population. Note that these ratios are exclusive to the Hopi and incorporate no external information on fertility and mortality.

A CCM forecast also requires information on the survivorship of Hopi aged five years and over. An external information source was used because no survivorship data specific to the Hopi in 1937 exists. However, the U.S. Social Security Administration has assembled "life tables" specific to cohorts by year of birth from 1900 to 2100 (Bell & Miller, 2005). Evidence suggests that Hopi mortality in 1937 was higher than the Social Security Administration's (SSA) Life Tables constructed for the birth cohort of 1940 (Johansson & Preston, 1976; Kunitz, 1974a, b). Therefore, the 1935 SSA birth cohort life tables by sex for the entire US population were used to survive Hopi males and females aged 0–4 in 1937 to "extinction," which means until all members of the cohort have died. (The SSA cohort life tables allow for survivorship to 120 years, at which time all members have died.) For Hopi aged 10–14 and 15–19 in 1937, the 1920 SSA birth cohort life tables were used to survive each individual to extinction; and for Hopi aged 20–24 through 90+in 1937, the 1910 SSA birth cohort life tables were used to survive them to extinction.

In using the 1937 child-woman ratios by sex to generate the populations by sex aged 0–4 in 1942, 1947, 1952, and 1957, it is assumed that fertility and infant/child mortality remained constant. This assumption is consistent with the "baby boom" period of high fertility and information on Hopi fertility and mortality (Johansson & Preston, 1976; Kunitz, 1974a, b). Starting in 1957, child-woman ratios by sex are trended downward by interpolating (using a geometric model) between the 1957 ratios and the ratios found in Table QT-P1, from Summary File 1 in the 2010 US Census for "Hopi Alone" as taken from the Hopi CCD (Reservation). The 2010 ratio for males aged 0–4 to females aged 20–39 is 0.36 = 306/850 and the 2010 ratio of females aged 0–4 to females aged 20–39 is 0.3576 = 304/850.

The trend between 1957 and 2010 was then extrapolated in five-year increments to 2037. This is consistent with the decline of fertility levels observed in the USA from 1957 to 2017 (where they are believed to have reached levels below which they will fall). In using ratios that decline until 2017 it is assumed that declines in Hopi fertility from 1957 to 2037 as well as declining infant/child mortality rates, which also is consistent with the decline in U.S. infant mortality rates during this same period.

An important assumption underling this approach is the use of child-woman ratios. The CCM assumes that the populations underlying fertility is "female dominant," which means that all Hopi females are producing children that are eligible for Hopi Membership. Because the model is based on the 1937 Tribal Census, the membership criteria requiring a direct descent from this Census is met for blood quantum members who are required to have at least ¼ Hopi/Tewa blood. The CCM implicitly assumes that all males and females who bear children are full blooded Hopi/Tewa. This assumption is founded on research which indicates that the Hopi population historically had very low rates of "out-marriage" (1974b; French & Hanes, 2018;

Johansson & Preston, 1976; Kunitz, 1974a; National Archives & Record Service, 1965) and as mentioned in the preceding section, there is a strong tendency for Hopi to marry (or otherwise form sexual unions) with other Hopi. Moreover, as detailed in Table 4 and the corresponding discussion, the forecasts produced by the CCM track very well with recorded Hopi Tribal membership in 2002, 2007, 2012, and 2017. This confirms that the models assumptions regarding Hopi marriage patterns and blood quantum are reasonable.

Results

Using Table 1 and the preceding information, a demographic forecast of the Hopi Tribe population was launched using five-year age groupings (up to the terminal open-ended age of 90) by sex and a five-year projection cycle. Using the SSA birth cohort life tables as described in the preceding section, Hopi age groups from 0–4 to 90 + were survived forward until 1942. Using the 1937 child-woman ratios in conjunction with the "survived" population of females from 1937 to 1942, cohorts for ages 0–4 by sex were generated for 1942. This completed the estimated 1942 population by age and sex. Using the SSA life tables for 1940, the 1942 population was survived to extinction and the estimated population for ages 0–4 in 1947 was generated. The same SSA birth cohort life tables just described were used to survive age groups 5–9 to 90 + in 1937 forward to 1942. This process was repeated, moving forward in five-year increments from 1942 to 1957, with the birth cohorts being survived using the immediately preceding SSA birth cohort life table. (For example, the 1950 SSA birth cohort life table was used to survive to extinction those aged 0–44 in 1952 and those aged 0–4 in 1957.)

The process described for moving the Hopi Tribal population from 1942 to 1957 was used to survive it from 1957 to 2002 using SSA birth cohort life tables as follows: For the 1957, 1962, and 1967 birth cohorts, the 1960 SSA birth cohort life table was used; for the 1972 and 1977 cohorts, the 1970 SSA birth cohort life table was used; for the 1982 and 1987 birth cohorts, the 1980 SSA birth cohort life table was used; for the 1992 and 1997 cohorts, the 1990 SSA birth cohort life table was used; and so on to the 2032 and 2037 cohorts, for which the 2030 SSA birth cohort life table was used. The decisions on which SSA cohort life tables to use with Hopi birth cohorts was made in accordance with my judgment on which were likely to reflect most accurately the Hopi experience. In making this judgment I used information found in Kunitz (1974a) and Johansson and Preston (1976) as a guide.

The annual Hopi membership data for 1989 to 2017 (Table 1) provide the opportunity to evaluate (as well as calibrate, if needed) the accuracy of the demographic forecast data generated in the form of an ex post facto test (Swanson, 2018; Swanson et al., 2010). However, because the annual membership data are only for the total population, the accuracy of the age-sex CCM forecasts cannot be assessed. However, as an example of these age-sex forecasts done in five-year increments from the launch year of 1937 to 2017, Table 3 provides the 2017 Hopi population by age and sex generated by the CCM.

Table 3 2017 Hopi Tribal Population Forecast by Age & Sex

Age	Male	Female	Total
0–4	747	742	1489
5–9	700	694	1393
10–14	660	653	1314
15–19	620	613	1233
20–24	578	572	1150
25–29	541	535	1076
30–34	499	496	995
35–39	475	472	947
40–44	402	402	803
45–49	388	388	775
50–54	342	350	693
55–59	320	326	646
60–64	249	262	512
65–69	220	238	458
70–74	182	208	390
75–79	134	163	297
80–84	73	105	178
85–89	26	59	86
90–94	8	18	26
95–99	1	3	4
100–104	0	1	1
105–109	0	0	0
110–114	0	0	0
115–119	0	0	0
Total	7,165	7,301	14,466

Sums may not be precise due to minor rounding error

Table 4 Comparison of Forecast Results with Tribal Membership

Year	Cohort Component Model	Tribal Membership Data	Difference (CCM Membership)	Percent Difference
1992	9663	7465	2198	29.44%
1997	10,522	10,047	475	4.37%
2002	11431	11439	– 8	– 0.07%
2007	12,389	12,479	– 90	– 0.72%
2012	13,398	13,752	– 354	– 2.58%
2017	14,466	14,422	44	0.30%

As just noted, because the annual membership data only show the total counts, not by age and sex, I assess the accuracy of the CCM forecasts for the total population only. Table 4 shows this, a comparison of the forecasted total population found in Table 2 to the total Hopi population found in the Tribal Membership Data (Table 1) for 1992, 1997, 2002, 2007, 2012, and 2017. Table 4 shows that the CCM over-estimates total tribal membership in 1992 by 29.4%, but improves dramatically by 1997 (4.7%), and then tracks very closely with the membership data from 2002 through 2017. There are two leading reasons for this change subsequent to 1992.

First, it is likely that the over-estimated number for 1992 reflects to some degree the fact that mortality among the Hopi in the 1930s and 1940s was higher than estimated by the earliest SSA birth cohort life table available to apply to those aged 20–24 through 90 in 1937, the 1900 SSA file. The bulk of the overestimation was in the oldest age groups, which is generally consistent with mortality information found in in Kunitz (1974a) and Johansson and Preston (1976). Kunitz (1974a, pp. 9–10) quotes the findings of a 1908 report that the Hopi suffered much from epidemics and goes on to note that smallpox epidemics occurred within the tribe in the 1890s. Kunitz (1974a, p. 10) also states that the tribe was affected by the 1918 influenza pandemic. Johansson and Preston (1976, p. 20) observe that Hopi children were exposed to enormously high mortality levels around 1900. Those who survived would have had reduced life expectancies (Elo & Preston, 1992). When this cohort passed away, the CCM generated numbers that moved very much closer to the reported tribal members. It is therefore reasonable to believe that the SSA birth cohort life tables used subsequent to 1950 accurately reflect Hopi mortality. Similarly, the results indicate that use of child-woman ratios for 1937 through 1997 accurately reflects the combined effects of fertility and infant/child mortality for Hopi.

Second, as can be seen in Table 1, there was a substantial increase in Tribal enrollment in 1994 and 1995 compared to previous and subsequent years. As suggested by the “demographic accounting” this increase is due to members who were eligible (by virtue of birth) but for one reason or another had not enrolled (or re-enrolled) until 1994 and 1995. This surge in membership has to do with the Hopi-Navajo Relocation Act (U.S. GAO, 1995) which was aimed at resolving a dispute over tribal boundaries. In order to qualify for relocation benefits, one had to be certified, which involved establishing tribal membership. Thus, those Hopi who were not tribal members and desired relocation benefits, joined in order to be eligible for these benefits. This suggests that the second part of the reason that the forecast of 1992 over-estimated tribal members was that there were Hopi who were eligible to be members but had had not joined the tribe until the enactment of the Hopi-Navajo Relocation Act. Had those eligible been members in 1992, the difference between the forecast and the membership number would have been substantially smaller.

With an understanding of the reasons for the poor fit in 1992 and the close fit of the forecast to the membership data from 1997 to 2017, there is no need to make adjustments to the forecast (Swanson et al., 2010), so the process just described was continued 20 years beyond 2017 to 2037. Tables 5 through 8 show the total population by age and sex for 2022, 2027, 2032, and 2037, respectively.

The results suggest that the CCM is capable of providing reasonable forecasts for not only the Hopi Tribal population, but others with a tribal census roll that is linked to tribal membership and accurate tribal membership data that can be used to calibrate/evaluate the cohort-component method described here (Tables 6, 7, 8).

Table 5 2022 Hopi Tribal Population Forecast by Age & Sex

Age	Male	Female	Total
0–4	781	778	1559
5–9	746	741	1488
10–14	699	693	1393
15–19	659	653	1311
20–24	617	612	1229
25–29	575	571	1145
30–34	538	534	1072
35–39	495	493	989
40–44	470	469	939
45–49	395	398	793
50–54	380	383	763
55–59	332	343	675
60–64	306	317	623
65–69	230	248	478
70–74	194	218	412
75–79	149	180	329
80–84	97	130	227
85–89	41	70	111
90–94	7	19	26
95–99	1	4	5
100–104	1	4	5
105–109	0	0	1
110–114	0	0	0
115–119	0	0	0
Total	7,715	7,859	15,573

Sums may not be precise due to minor rounding error

Discussion

Before addressing the population forecast itself, a brief explanation of the use of population forecasts in water allotment litigation is in order. In general, water demand is typically calculated by multiplying the per capita usage by the expected number of users (Miro et al., 2018, pp. 4, 5). In the case of the Hopi and others involved in water allotment issues, water is finite but demand is not. If there are parties competing for the same water, part of the process used to decide how to allocate water is the expected number of users. Hence, the use of a population forecast. There are of course, refinements, which can be based on the type of customer (residential, commercial, and industrial), usage categories (single-family, multi-family) and source (water wholesaler or water retailer). However, per capita usage and the number of users is the usual starting point (Miro et al., 2018), which is the situation in the Hopi case (Maricopa County Superior Court (No date).

Table 6 2027 Hopi Tribal Population Forecast by Age & Sex

Age	Male	Female	Total
0–4	821	819	1640
5–9	781	777	1558
10–14	746	741	1487
15–19	698	693	1390
20–24	656	651	1307
25–29	614	610	1224
30–34	572	569	1141
35–39	535	532	1067
40–44	490	490	980
45–49	463	465	928
50–54	386	393	780
55–59	370	377	747
60–64	316	332	648
65–69	286	302	588
70–74	203	227	430
75–79	161	191	352
80–84	108	144	252
85–89	57	88	146
90–94	12	23	35
95–99	1	4	6
100–104	0	1	1
105–109	0	1	1
110–114	0	0	0
115–119	0	0	0
Total	8,275	8,430	16,705

Sums may not be precise due to minor rounding error

Turning to the actual forecast, while a small population such as the Hopi presents difficulties in terms of forecasting, it has, fortunately, an important commonality with larger populations: inertia. Raftery and Ševčíková (2021) observe that because of inertia, it is possible to make reasonable long-term population forecasts. They further note that the effective time unit for population forecasting is the "generation," which is about 27 years. Thus, the 80 year horizon from 1937 to 2017 is slightly less than three generational time units (81 years) and the 20 year forecast horizon from 2017 to 2037 is less than a single generational time unit. In the case of the Hopi, the high degree of accuracy of the 2017 forecast (which had a relative error of only 0.30%) suggests that inertia carried the day, so to speak, over uncertainty across a three generation time-unit period.

It is important to recall that migration does not enter into a discussion of inertia and uncertainty because the Hopi tribal population is closed. Raftery and Ševčíková (2021) state that estimating migration is one of the biggest outstanding problems in demography. By not having to deal with migration, only two of the drivers of

Table 7 2032 Hopi Tribal Population Forecast by Age & Sex

Age	Male	Female	Total
0–4	859	869	1727
5–9	820	818	1638
10–14	780	777	1558
15–19	744	740	1484
20–24	695	691	1386
25–29	652	650	1302
30–34	611	609	1220
35–39	568	567	1135
40–44	530	529	1059
45–49	482	486	968
50–54	454	459	913
55–59	375	386	761
60–64	356	366	722
65–69	293	315	609
70–74	257	280	537
75–79	168	199	367
80–84	120	155	276
85–89	64	98	162
90–94	17	30	47
95–99	2	5	8
100–104	0	1	1
105–109	0	1	1
110–114	0	0	0
115–119	0	0	0
Total	8,848	9,032	17,880

Sums may not be precise due to minor rounding error

uncertainty in a forecast are present in the Hopi forecasts, fertility and mortality. As such, the main source of uncertainty in the 2037 population forecast is the potential for changes in the number of births and deaths from 2017 to 2037 while the secondary source is the stochastic fluctuations in these births and deaths. However, as we have seen in terms of the actual changes in fertility and mortality and their stochastic uncertainty over the 80 period from 1937 to 2017, it is clear that with the one exception noted regarding the effect of underestimating mortality in regard to the 1992 forecast, fertility and mortality were accurately represented by the CCM per the ex post facto accuracy tests for the remaining five time points (1997, 2002, 2007, 2012, and 2017), where the average relative error is only 0.33%. Given this, I argue that the Hopi tribal population forecast over the following twenty year period, from 2017 to 2037 is very highly likely to be reasonable.

Whether or not a similar argument would hold for other small tribes (or even large tribes such as the Navajo) that could be forecasted using the type of data and the CCM approach employed in this case study is an open research question. However,

Table 8 2037 Hopi Tribal Population Forecast by Age & Sex

Age	Male	Female	Total
0–4	899	901	1801
5–9	858	868	1726
10–14	820	818	1638
15–19	779	776	1555
20–24	741	739	1480
25–29	691	690	1382
30–34	649	648	1297
35–39	645	646	1291
40–44	562	563	1126
45–49	523	525	1048
50–54	473	480	953
55–59	442	451	893
60–64	359	374	734
65–69	334	350	684
70–74	261	291	552
75–79	219	250	469
80–84	126	162	288
85–89	74	109	182
90–94	19	33	52
95–99	3	8	11
100–104	0	1	1
105–109	0	0	0
110–114	0	0	0
115–119	0	0	0
Total	9478	9685	19,163

Sums may not be precise due to minor rounding error

the potential appears to be high given that many tribal census counts were conducted over the period from 1890 to 1940 (National Archives, 2014), which are listed by tribe and date at https://www.archives.gov/research/census/native-americans/1885-1940.html, with the following introduction:

> The Indian Census Rolls, 1885-1940 (M595, 692 rolls) contain census rolls that were usually submitted each year by agents or superintendents in charge of Indian reservations, to the Commissioner of Indian Affairs, as required by an act of July 4, 1884 (23 Stat. 98). The data on the rolls vary, but usually given are the English and/or Indian name of the person, roll number, age or date of birth, sex, and relationship to head of family.
>
> Beginning in 1930, the rolls also include the degree of Indian blood, marital status, ward status, place of residence, and sometimes other information. For certain years--1935, 1936, 1938, and 1939--only supplemental rolls of additions and deletions were compiled. Most of the 1940 rolls have been retained by the Bureau of Indian Affairs (BIA) and are not included in this publication.

> There is not a census for every reservation or group of American Indians for every year. Only persons who maintained a formal affiliation with a tribe under federal supervision are listed on these census rolls.

It is the tribes that conducted census counts subsequent to 1933 that appear to have the highest potential to be forecasted using the CCM and data described in this Hopi case study. This is because of the Indian Reorganization Act of 1934 (48 Stat. 984), whereupon tribes were encouraged to specifically set up a constitution that gave recognized criteria for determining membership and enrollment. Included in this list would be the Oglala Sioux, among many others, for example (National Archives, 2014).

It is unfortunate that I was only able to assess the accuracy of the total population forecast. If the annual Hopi age-sex specific membership data were available (e.g., in tabular form), the accuracy of the age-sex aspect of the forecasts also could have been assessed—another research question.

In conclusion, this case study suggests that this approach is worth considering where long-term forecasts are required of a Native American tribe, such as is found in disputes over water allotments (Burton, 1987; Greene, 2017; Kenney, 2003; Maricopa County Superior Court; Swanson, 2019). It is also worthwhile to note that the CCM process applied to historical tribal census done between 1934 and 1940 generates "estimates" up to the current point in time. Such estimates would give a perspective on the Native American population that could be useful given its "non-demographic growth," as identified by Passell (1996), Thornton (1979) and others, which was discussed earlier in this paper. These estimates also may be useful in assessing the accuracy of the 2020 census counts of the tribes comprising the Native American population. Swanson (2022), for example finds it highly likely that tribal members residing on the Hopi Reservation were substantially undercounted by the US Census Bureau.

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